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Neuromuscular Electrical Stimulation for Quadriceps Muscle Strengthening After Bilateral Total Knee Arthroplasty: A Case Series

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RESEARCH REPORT

Study Design: A case series.
Objectives: The purpose of this case series was to assess the effect of high-intensity neuromuscular electrical stimulation (NMES) on quadriceps strength and voluntary activation following total knee arthroplasty (TKA).
Background: Following TKA, patients exhibit long-term weakness of the quadriceps and diminished functional capacity compared to age-matched healthy controls. The pain and swelling that results from surgery may contribute to quadriceps weakness. The use of high-intensity NMES has previously been shown to be effective in quickly restoring quadriceps strength in patients with weakness after surgery.
Methods and Measures: All patients were treated for 6 weeks, 2 to 3 visits per week, in outpatient rehabilitation. Five patients (NMES group) participated in a voluntary exercise program for both knees and NMES for the weaker knee. Three patients (exercise group) participated in a voluntary exercise program for both knees without NMES. For each treatment session, 10 isometric electrically elicited muscle contractions were administered at maximally tolerated doses to the initially weaker leg of the NMES group. Quadriceps strength and muscle activation were repeatedly assessed up to 6 months after surgery using burst superimposition techniques.
Results: At 6 months, the weak NMES-treated legs of 4 of 5 patients in the NMES group had surpassed the strength of the contralateral leg. In contrast, none of the weak legs in the exercise group were stronger than the contralateral leg at 6 months. Changes in quadriceps muscle activation mirrored the changes exhibited in strength.
Conclusion: When NMES was added to a voluntary exercise program, deficits in quadriceps muscle strength and activation resolved quickly after TKA. *J Orthop Sports Phys Ther* 2004;34:21-29.

Key Words: *geriatric, inhibition, rehabilitation, total knee replacement*

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Simultaneous bilateral total knee arthroplasty (TKA) has become an increasingly common surgical procedure for patients with bilateral knee osteoarthritis or rheumatoid arthritis.[1,5,9,20,21,23] Typically, patients are only permitted to undergo simultaneous bilateral TKA if they are in excellent health due to the increased risk for complications from 2 surgical procedures (eg, longer anesthesia times).[1,20,23] When patients are appropriately chosen for the procedure, outcomes are comparable to patients who undergo a staged bilateral knee replacement,[23] yet the total rehabilitation time is less.[20]

Patients after TKA are often plagued with quadriceps femoris weakness and functional deficits that continue for years after surgery.[2,4,15,39] These limitations in strength and function are thought to result from a combination of preexisting weakness before surgery and pain and swelling postsurgery.[18,22,26] After bilateral TKA, patients are doubly affected by this persistent quadriceps weakness, which may result in serious functional limitations. Quadriceps weakness has been correlated with slower walking speeds, longer stair-climbing times, and increased risk of falls.[8,40] One source of this weakness is voluntary activation deficits, which result from a failure of recruiting all available motor units or a reduction in the maximal motor unit discharge rate from those motor units which are recruited.[19] Voluntary activation deficit can be quantified by superimposing a supramaximal electrical stimulus on a maximally contracting muscle.[10,19,34,36,37,41] Using this technique, voluntary activation deficits have been reported in patients with osteoarthritis or following knee surgery, including TKA.[18,25,27,28,35] Voluntary activation deficits can result from pain,[27] effusion,[12] and joint damage,[16] all of which are potentially present in patients after TKA. Voluntary exercise programs have had limited success in restoring quadriceps strength when a substantial voluntary activation deficit is present.[17]

Studies of various younger adult populations have demonstrated that neuromuscular electrical stimulation (NMES), at sufficient intensities, can be combined with volitional exercise to more effectively increase muscle strength and functional performance than volitional exercise alone.[11,31,33] A recent case report suggested that incorporating high-intensity NMES into an outpatient rehabilitation program for muscle strengthening offers promise for restoring quadriceps strength.[21] NMES has the potential to override muscle activation deficits resulting from impairments in central nervous system processing. In addition, NMES activates a greater proportion of type II (fast-twitch) muscle fibers when compared to volitional exercise at a comparable intensity.[3,7,13,30,38] Type II fibers are essential for higher levels of force production and their activation may translate to improved functional performance.

Applying high-intensity electrical stimulation to only 1 limb following bilateral TKA provides an ideal opportunity for investigating the efficacy of NMES, as each patient provides a control limb for comparison. The purpose of this case series was to assess the effect of adding high-intensity NMES to a volitional strengthening program following TKA. The hypothesis was that adding NMES to a 6-week, voluntary exercise program would be more effective in improving quadriceps activation and strength than voluntary exercise alone.

METHODS

Patients

Eight patients with simultaneous, primary bilateral total knee replacements (Table 1) were recruited from local surgeons who performed tricompartmental cemented TKA with a medial parapatellar approach. Patients were excluded from the study if they were diagnosed with diabetes mellitus, uncontrolled blood pressure, neurological disorders, neoplasms, or had a body mass index (BMI = weight [kg]/height [m^2]) of greater than 40 (morbidly obese).

Patients were assigned to 1 of 2 intervention groups: (1) "Ex legs" or (2) "NMES legs." Patients in the Ex legs group received the same intervention for both legs, which consisted of voluntary exercises for strengthening of the lower extremity. Patients in the NMES legs group participated in a voluntary exercise program for the leg that was stronger at initial evaluation, and NMES was added to the voluntary exercise program for the leg that was weaker at initial evaluation (Table 2). The Human Subjects Review Committee at the University of Delaware approved the study and all subjects gave informed consent.

Intervention

Intervention began 3 to 4 weeks following TKA, after staples were removed. All patients were scheduled for treatment at the University of Delaware Physical Therapy Clinic 3 times a week for 6 weeks (total of 18 visits) and were allowed to miss up to 4 visits. All in-clinic and home exercise interventions were documented in patient data booklets to ensure consistency of care and patient compliance. Rehabilitation for all patients included interventions to reduce pain and inflammation, improve incision mobility, restore knee flexion and extension range of motion, improve bilateral lower-extremity strength

TABLE 1. Patient demographics for patients with bilateral total knee arthroplasty.

Patient	Height (m)	Weight (kg)	BMI	Age (y)	Gender	Group
1	1.75	103.4	33.8	64	M	NMES
2	1.78	97.1	30.8	67	M	NMES
3	1.85	93.0	27.1	75	M	NMES
4	1.68	88.9	31.5	64	M	NMES
5	1.85	99.8	29.2	63	M	NMES
6	1.73	118.8	39.7	76	F	Exercise
7	1.73	93.0	31.1	69	M	Exercise
8	1.78	87.5	27.8	61	M	Exercise

Abbreviations: BMI, body mass index (weight [kg]/height [m^2]); F, female; M, male; NMES, neuromuscular electrical stimulation.

TABLE 2. Groups designations and corresponding interventions.

Group Name/Leg	Intervention
NMES group	
Weak NMES legs	Volitional exercise, NMES
Strong NMES legs	Volitional exercise
Exercise group	
Weak Ex legs	Volitional exercise
Strong Ex legs	Volitional exercise

Abbreviation: NMES, neuromuscular electrical stimulation.

using high-intensity voluntary exercises, and improve functional performance (see Table 3). Each patient was evaluated and treated on the basis of individual impairments, as the guidelines for intervention in Table 3 permitted.

NMES The weak NMES legs received identical intervention to all other legs except that 10 NMES-elicited quadriceps contractions were added to each treatment session. For the NMES intervention, patients were seated on an electromechanical dynamometer (KinCom; Chattanooga Corporation, Chattanooga, TN), and a measuring arm, which restrained the movement of the leg, was secured to the lower leg (Figure 1). The knee was positioned at 60° of knee flexion and all contractions were isometric. The patient's maximal voluntary isometric contraction (MVIC) was determined before the NMES intervention using the average peak force of two 5-second isometric contractions.

Self-adherent, flexible electrodes (7.6×12.7 cm) were placed over the subject's quadriceps to apply the electrical stimulation.[29] A clinical neuromuscular electrical stimulator (Versastim 380; Electromed Health Industries, Miami Beach, FL) was set to deliver a 2500-Hz alternating current, modulated at 50 bursts per second, with a ramp-up time of 2 to 3 seconds.[29] The intensity was set to the maximum intensity tolerated by the patient during each session. The patient was instructed to relax during stimulation and prevent cocontraction of the hamstrings as well as inadvertent voluntary quadriceps muscle contraction. The intensity was increased as tolerated throughout each session. Ten 10-second isometric contractions were elicited with an 80-second rest between each contraction.[29] The electrically elicited knee extension peak force produced by each contraction of the quadriceps muscle was recorded by customized software (LabVIEW V 4.0.1; National Instruments, Austin, TX) on a personal computer.

Testing Procedure

Quadriceps strength and voluntary muscle activation were tested. Testers were isolated from the subjects' interventions and were not aware of which patients received the NMES intervention. Testing was performed in the 3rd (initial evaluation), 6th (midtraining), 9th (posttraining), 12th (3-month follow-up), and 24th (6-month follow-up) weeks after TKA. To minimize apprehension and discomfort during testing, patients were allowed to choose which leg was tested first during the initial evaluation. The order of testing remained the same for each subsequent testing session.

Quadriceps Strength and Activation Testing

Patients were seated on the electromechanical dynamometer with their hips flexed to approximately 85° and their knees flexed to 75°. The axis of the dynamometer was aligned with the axis of rotation of the knee joint and the bottom of the force transducer pad was positioned against the anterior aspect of the leg proximal to the lateral malleolus. The lower leg, thigh, and pelvis were stabilized using inelastic straps with Velcro closures. Two 7.6×12.7-cm self-adhesive neuromuscular stimulation electrodes were secured to the thigh. The anode was placed over the motor point of the rectus femoris and the cathode was placed over the motor point of the vastus medialis.

Strength testing began by instructing all patients to perform three 3- to 5-second voluntary isometric contractions at an intensity that they perceived as 50% to 75% of their maximal effort. These contractions served to familiarize the patient with the apparatus and to warm up the muscle. In addition, the quadriceps femoris muscle was stimulated several times at intensities that would elicit muscle contractions to familiarize the patient with the sensation of electrical stimulation. After the patient was familiar with the procedure and the muscle warmed up, testing began by having the patient attempt a 3- to

FIGURE 1. Experimental setup for neuromuscular electrical stimulation (NMES) treatment. Patients were seated and stabilized with the hip flexed to 85° and the knee flexed to 75°. Two 7.62×12.70-cm electrodes were placed over the vastus medialis and proximal rectus femoris of the quadriceps.

TABLE 3. Rehabilitation program.

Range of motion (ROM)	• Exercise bike (10-15 min), started with forward and backward pedaling with no resistance until enough ROM for full revolution; progression: lower seat height to produce a stretch with each revolution. • Active-assistive ROM for knee flexion, sitting or supine, using other leg to assist. • Knee extension stretch with manual pressure (in clinic) or weights (at home). • Patellar mobilizations: 3×30 superior/inferior; medial/lateral, as necessary.
Strength	• Quad sets, straight leg raises (without quad lag), hip abduction (sidelying), standing hamstring curls, seated knee extension, standing terminal knee extensions from 45° to 0°, step-ups (5.08-15.24-cm block), wall slides to 45° knee flexion; 1 to 3 sets of 10 repetitions for all strengthening exercises. • Criteria for progression: exercises are to be progressed (eg, weights, step height, etc) once the patient can complete the exercise correctly and feels maximally fatigued at the end of each set. • Progression: 0.454-0.907-kg weights added to exercises, step-downs (5.08-15.24-cm block), front lunges, wall slides towards 90° knee flexion.
Pain and swelling	• Ice and compression as needed.
Incision mobility	• Soft tissue mobilization until incision moves freely over subcutaneous tissue.
Functional activities	• Ambulation training with assistive device as appropriate with emphasis on heel strike, push-off at toe-off and normal knee joint excursions. • Emphasis on heel strike, push-off at toe-off and normal knee joint excursions when able to walk without assistive device. • Stair ascending and descending step over step when patient has sufficient concentric/eccentric strength.
Monitoring vital signs	• Blood pressure and heart rate are monitored at initial evaluation and as appropriate.

5-second MVIC while receiving verbal encouragement from the tester and visual feedback from the dynamometer's real time force display. During the contraction, a 135-V, 10-pulse, 100-pps train (1000-microsecond pulse duration) was delivered to the muscle to assess whether the subject was indeed maximally activating the quadriceps muscle (burst superimposition technique).[19,24,34,37] A S8800 stimulator with a SIU8T stimulus isolation unit (Grass Instruments, Inc., Quincy, MA) was driven by a personal computer that uses customized software (LabVIEW V 4.0.1) to control the timing parameters of the stimulation protocol. Data were digitized at 200 Hz and analyzed with customized software (LabVIEW V 4.0.1). With full voluntary muscle activation, no increase in force was measured. If a subject was unable to activate the quadriceps muscle fully, MVIC testing was repeated up to 2 additional times and the maximal force noted during these 3 tests was used for analysis. Each attempt at achieving an MVIC was separated by 5 minutes to minimize the effects of muscle fatigue. The greatest maximal voluntary effort achieved during the testing session for each leg was used for analysis. The burst superimposition technique has been shown to be highly reliable in subjects without pathology, with repeated testing that demonstrated an intraclass correlation coefficient of 0.98 (mean age, 24.2 years; age range, 17-32 years).[32]

Data Management and Analysis

Because of the limited number of subjects included in this study, the data are presented individually and qualitatively to describe trends in outcomes.

Quadriceps Strength The force (N) of the quadriceps MVIC was normalized to body mass index (N/BMI) for all comparisons to account for variations in force production that are a result of differences in body size. Three sets of comparisons were made for the 8 individuals: (1) comparison within the NMES legs and Ex legs groups (strong versus weak legs); (2) comparison of weak legs between groups (weak NMES legs versus weak Ex legs); (3) comparison of strong legs between groups (strong NMES legs versus strong Ex legs).

The average percent increase in normalized quadriceps muscle strength was also used to describe strength gains of the individuals. The percent increase was calculated using the following relationship:

$$\text{Percent increase in strength} = \frac{\text{6-month MVIC (N)} - \text{initial MVIC (N)}}{\text{initial MVIC (N)}} \times 100$$

Quadriceps Voluntary Muscle Activation Voluntary quadriceps muscle activation was calculated by measuring the peak volitional and electrically elicited forces during the MVIC test. The central activation ratio (CAR) was used to quantify voluntary muscle activation.[19] The CAR is calculated by dividing the maximum voluntary force produced before the electrical stimulus by the maximum force produced during the superimposition of the electrical stimulus. A CAR of 1.0 signifies complete activation. In contrast, a CAR of less than 1.0 suggests incomplete voluntary muscle activation. The same comparisons outlined earlier for quadriceps strength were made for voluntary activation.

The percent increase in quadriceps voluntary activation was also used to describe improvements in activation of the individuals. The percent increase was calculated using the following relationship:

$$\text{Percent increase in CAR} = \frac{\text{6-month CAR} - \text{initial CAR}}{\text{initial CAR}} \times 100$$

NMES Dose The daily NMES dose was calculated as a ratio of the highest electrically elicited knee extension force obtained in a session by the maximal MVIC achieved on that same day. The NMES doses are reported as average doses obtained over the 6 weeks of treatment.

RESULTS

Compliance

The average number of sessions was 17. No patient missed more than 3 sessions.

Quadriceps Strength and Voluntary Muscle Activation

Strong Versus Weak Legs The percent increases in quadriceps strength for the weak NMES legs ranged from 221% to 451% as compared to 50% to 152% for the strong NMES legs; whereas the percent increases in quadriceps strength for the weak Ex legs ranged from 41% to 148% as compared to 30% to 71% for the strong Ex legs (Table 4). Initially, the average quadriceps strength of almost all legs receiving NMES was less than that of the legs that received only voluntary exercise for strengthening (Table 5).

After 3 weeks of treatment (midtraining), the quadriceps strength of the weak NMES legs showed a dramatic improvement in 4 out of 5 patients and was almost identical to, or had surpassed, the strength of the contralateral strong NMES legs. At 6 months, 4 out of 5 patients with initially weak NMES legs remained stronger than their initially stronger contralateral leg (Table 5). Only 1 of the initially weak Ex legs showed a similar initial jump in quadriceps strength within the first 3 weeks of training (patient 6), and none of the weak Ex legs were stronger as compared to their contralateral leg at 6 months (Table 5).

Quadriceps strength testing demonstrated consistent linear or curvilinear increases in strength for all legs over the course of 6 months, with the exception of patient 6 (Table 5). Patient 6 showed the greatest amount of variability in force production during consecutive testing sessions and had greater oscillations in strength than the other patients.

Quadriceps voluntary activation for the legs receiving stimulation underwent a concurrent increase compared to the legs that did not undergo NMES during the first 3 weeks of treatment (Table 6). Quadriceps voluntary activation did not change as dramatically during the remaining testing sessions as it did during the first 3 weeks of training for patients in the NMES group.

Weak NMES Legs Versus Weak Ex Legs Initial quadriceps strength of the weak NMES legs was less for patients 1 through 5 than that of the weak Ex legs of patients 7 and 8 (Table 5). Patient 6 was the exception to this observation and had quadriceps weakness that was comparable to that of the weak NMES legs. By midtraining, quadriceps strength of the weak NMES legs had almost equaled or surpassed that of the weak Ex legs in all patients except patient 3. Quadriceps strength of the weak Ex legs improved by midtraining. Both the weak NMES legs and weak Ex legs continued to show improvements in strength through the 6-month follow-up, but the weak NMES legs demonstrated the greatest overall improvement (Table 5).

Voluntary muscle activation of the quadriceps increased for all the weak NMES legs within the first 3 weeks of treatment (Table 6). In comparison, the weak Ex legs only had 1 substantial change in quadriceps voluntary activation in patient 8, which

RESEARCH REPORT

TABLE 4. Percent change in quadriceps strength and voluntary activation from initial evaluation to 6-month follow-up.

	Increase in Quadriceps Strength (%)		Increase in CAR (%)	
Patient	**Weak Legs**	**Strong Legs**	**Weak Legs**	**Strong Legs**
1*	451	76	39.0	−1.6
2*	302	121	87.0	11.0
3*	233	152	66.0	52.0
4*	351	133	34.0	5.0
5*	221	50	34.0	−3.0
6†	41	30	−6.0	−14.0
7†	80	67	−0.8	−4.0
8†	148	71	54.0	3.0

Abbreviation: CAR, central activation ratio.
*Neuromuscular electrical stimulation group.
†Exercise group.

TABLE 5A. Force normalized to body mass index (N × [kg/m^2]$^{-1}$) for the initially weaker leg of all patients.

Patient	Initial Evaluation	3 Weeks	6 Weeks	3 Months	6 Months
1*	5.0	24.6	25.3	26.1	27.4
2*	3.8	12.3	12.6	13.7	15.1
3*	5.9	7.0	12.4	12.7	19.5
4*	7.8	19.8	21.4	26.0	35.4
5*	5.5	13.7	16.0	16.5	17.6
6†	5.2	9.8	5.4	9.3	7.4
7†	10.5	12.7	14.8	18.6	18.9
8†	9.5	10.3	14.5	20.9	23.4

* Weak NMES legs, received neuromuscular electrical stimulation and voluntary exercise for strengthening.
† Weak Ex legs, received only voluntary exercise for strengthening.

TABLE 5B. Force normalized to body mass index (N × [kg/m^2]$^{-1}$) for the initially stronger leg of all patients.

Patient	Initial Evaluation	3 Weeks	6 Weeks	3 Months	6 Months
1*	12.9	20.3	21.1	22.3	22.7
2*	11.8	17.3	20.3	23.3	26.0
3*	7.1	10.4	13.5	16.9	17.8
4*	13.1	20.8	18.7	24.8	30.6
5*	9.8	11.2	17.8	15.5	14.8
6†	6.4	7.5	7.6	6.1	8.3
7†	11.3	12.8	15.0	14.9	18.9
8†	16.6	16.1	17.4	19.7	28.3

* Strong NMES legs, contralateral leg received NMES and voluntary exercise for strengthening.
† Strong Ex legs, contralateral leg received only voluntary exercise for strengthening.

occurred later in training than for the weak NMES legs. It should be noted that the central activation of 2 of the 3 weak Ex legs was initially higher than for the weak NMES legs, possibly offering a lesser opportunity for improvement.

Strong NMES Legs Versus Strong Ex Legs The strong legs of individuals in both groups had comparable initial quadriceps strength (Table 5). At 6 months, the strong NMES legs had average strength gains that were greater (range, 50%-152%) than the strong Ex legs (range, 30%-71%) (Table 4). The voluntary muscle activation in the strong legs did not change as much throughout the testing period as it did for the weak legs (Table 6).

NMES Dose

The NMES dose ranged from 29% to 53% (Table 7). While the patient with the highest NMES dose (53%) had the greatest increase in quadriceps strength (451%), the small sample size of this case series does not afford the opportunity to make inferences regarding a dose-response relationship.

DISCUSSION

This case series suggests that adding NMES to a rehabilitation program after TKA may facilitate quadriceps strength gains more rapidly than voluntary exercise alone. In addition, the results of this case series suggest that a full 6 weeks of NMES treatment may not be necessary to achieve the benefits of the treatment, given that the most dramatic improvement took place in the first 3 weeks. The improvement in quadriceps activation in those legs that received NMES in the first 3 weeks was accompanied by a concomitant increase in quadriceps strength. NMES provoked a large and rapid increase in quadriceps force production in the weakest patients, who traditionally have modest results with voluntary exercise programs.[17]

The timing and the degree of change in voluntary muscle activation from the initial evaluation to the midtraining test corresponded to the initial rapid changes in quadriceps strength. This suggests that during the initial phases of NMES treatment, much of the initial change in quadriceps strength can be explained by a resolution of activation deficits. After midtraining, additional improvements in the strength between both subgroups were more likely a product of muscle hypertrophy because voluntary muscle activation remained fairly constant in many of the individuals from midtraining to the 6-month follow-up.

A similar pattern of strength gains emerged when the weak NMES legs were compared to the weak Ex legs, with greater improvements in quadriceps strength and voluntary activation for the weak NMES legs than for the weak Ex legs. Strength gains for the weak Ex legs were modest and did not seem to correspond as well with changes in voluntary muscle activation, as was the case in the weak NMES legs. We believe that NMES may have initially contributed to improved quadriceps strength by facilitating muscle activation. Given the small sample size, we cannot rule out the possibility that the higher initial activation levels for the weak Ex legs allowed less room for improvement than for the weak NMES legs.

Muscle activation of both legs in patient 6 (Ex legs group) was high compared to expected values following surgery.[25,35] Patient 6 reported no pain with muscle contraction or during functional activities at any point after surgery. The lack of pain may be partially responsible for the high muscle activation initially after surgery. It is also interesting to note the larger fluctuations in strength of the weak voluntary exercise leg for this patient and the minimal improvement in overall quadriceps strength over the course of 6 months. Patient 6 had a high self-report of knee function initially and a low expectation to improve her function. Low expectations with concomitant low motivation may explain some of the inconsistency in improvement.

Although the number of patients included in this case series is small, the varying degrees of initial weakness present with the burst superimposition test was consistent with that present in patients with unilateral TKA tested identically (n = 28).[35] We have no reason to believe that the initial weakness measured is not an accurate reflection of their quadriceps strength.

The comparisons between the weak legs of individuals in both groups was included in the analysis, as it discredits the argument that the remarkable strength gains in the weak NMES legs were simply a result of a bias for greater potential improvement due to selecting only the initially weak leg to receive NMES. In fact, it could be argued that those legs which are weak, with corresponding large voluntary activation deficits, represent more of a "worse case" scenario for clinicians. This would bias against finding greater gains in strength and activation with voluntary strengthening protocols.

When comparing the strong NMES legs to the strong Ex legs, cross-education from the NMES intervention may explain the greater strength gains in the strong legs of the NMES group. The only difference in the treatment protocol between each group of strong legs was that the strong legs in the NMES group had a contralateral weak leg that received NMES intervention. Research has shown that both unilateral voluntary and unilateral electrically elicited strength training carries over into strength gains in the untrained limb.[6,14] For electrically elicited

TABLE 6A. Central activation ratios for the initially weaker leg of all patients.

Patient	Initial Evaluation	3 Weeks	6 Weeks	3 Months	6 Months
1*	0.61	0.97	0.85	0.86	0.84
2*	0.34	0.69	0.60	0.74	0.64
3*	0.57	0.70	0.84	0.68	0.95
4*	0.74	0.95	0.90	0.97	1.00
5*	0.71	0.91	0.95	0.94	0.96
6†	1.00	1.00	0.93	0.99	0.94
7†	0.93	0.91	0.91	0.93	0.92
8†	0.57	0.53	0.87	0.78	0.87

* Weak NMES legs, received neuromuscular electrical stimulation in addition to voluntary exercise program for strengthening.
† Weak Ex legs, received only voluntary exercise for strengthening.

TABLE 6B. Central activation ratios for the initially stronger leg of all patients.

Patient	Initial Evaluation	3 Weeks	6 Weeks	3 Months	6 Months
1*	0.86	0.96	0.84	0.87	0.84
2*	0.63	0.69	0.66	0.75	0.70
3*	0.60	0.71	0.82	0.86	0.91
4*	0.95	0.98	0.93	1.00	1.00
5*	0.88	0.80	0.96	0.85	0.85
6†	0.95	0.90	0.74	0.80	0.82
7†	0.95	0.91	0.93	0.87	0.92
8†	0.79	0.69	0.87	0.85	0.82

* Strong NMES legs, contralateral leg received neuromuscular electrical stimulation in addition to voluntary exercise program for strengthening.
† Strong Ex legs, contralateral leg received only voluntary exercise for strengthening.

TABLE 7. Relationship between neuromuscular electrical stimulation (NMES) dose and increase in quadriceps strength for weak NMES legs. NMES dose is an average of each daily NMES treatment dose: electrically elicited quadriceps force (N)/maximum voluntary quadriceps force (N).

Patient	NMES Dose (%)	Increase in Quadriceps Strength (%)
1	38	221
2	37	233
3	29	351
4	49	302
5	53	451

strength training, the degree of carryover varies, often depending on the intensity of NMES used for treatment. Hortobagyi et al[14] found that a training intensity of 80% of MVIC for both voluntary exercise and electrical stimulation resulted in 15% and 19% cross-education, respectively.

The results of this case series cannot be used to describe a relationship between NMES dose and quadriceps strength gains because there were too few subjects included for such analysis. Interestingly, the patient with the largest NMES dose achieved the greatest quadriceps strength gains, which is consistent with prior research[33] indicating that larger NMES doses result in greater quadriceps strength gains. Additional research is needed to establish a dose-response relationship in patients with TKA.

CONCLUSION

This case series supports the use of high-intensity NMES to promote quadriceps strength gains in outpatient rehabilitation following TKA. The quadriceps muscle that received this form of electrical stimulation demonstrated dramatic increases in strength early in rehabilitation (the first 3 weeks of NMES) that coincided with a concomitant increase in voluntary activation. Further research is required with larger sample sizes and evaluation of functional carryover of quadriceps strengths gains with NMES treatment used in this study. When NMES was added to a voluntary exercise program, deficits in quadriceps muscle strength and activation resolved quickly after TKA and were maintained over a 6-month follow-up period.

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