Differences in Quadriceps Femoris Muscle Torque When Using a Clinical Electrical Stimulator Versus a Portable Electrical Stimulator

Background and Purpose. There have been conflicting views and evidence reported in the literature concerning differences in muscle torque-generating capacities between clinical (“plug-in”) console devices whose power source is provided by an electrical outlet (60 Hz, alternating current-driven) and portable electrical muscle stimulators (smaller, battery-operated stimulators). The purpose of this study was to compare the torque-generating capacity of the quadriceps femoris muscle during neuromuscular electrical stimulation (NMES) between a clinical neuromuscular electrical stimulator (VersaStim 380) and a portable neuromuscular electrical stimulator (Empi 300PV).

Subjects. Forty volunteer subjects with no known knee, neurological, or cardiovascular pathology (22 male, 18 female) participated in the study.

Methods. All subjects were tested with the clinical and portable stimulators on 2 separate days. Peak isometric torque of the quadriceps femoris muscle was measured using a Biodex dynamometer. Peak isometric quadriceps femoris muscle torque achieved during NMES and the average quadriceps femoris muscle torque integral produced over 10 NMES contractions were measured for each stimulator. Subjects also rated the amount of pain they experienced during the 10 NMES contractions using a numeric pain scale. Paired t tests were used to compare mean differences in measured variables between stimulator conditions.

Results. There were no differences in the peak torque or numeric pain ratings during the electrically stimulated contractions between stimulator conditions. The Empi 300PV produced a greater average torque integral compared with the VersaStim 380 during 10 electrically stimulated contractions (Empi 300PV = 988.6 ± 330.4 N·m·s, VersaStim 380 = 822.7 ± 292.6 N·m·s).

Discussion and Conclusion. The portable Empi 300PV stimulator produced comparable levels of average peak torque at comparable levels of discomfort to those produced by the VersaStim 380 clinical stimulator. The Empi 300PV maintained greater amounts of torque production during a 10-contraction training session compared with the VersaStim 380. Based on these data, we believe that the Empi 300PV has the potential to produce adequate levels of torque production for NMES quadriceps femoris muscle performance training. Further study is needed to determine the effectiveness of using the Empi 300PV for quadriceps femoris muscle performance training.

Key Words: Electrical stimulation, Muscle performance, Quadriceps femoris muscle.

Christian L Lyons, Joel B Robb, James J Irrgang, G Kelley Fitzgerald
Physical therapists commonly utilize neuromuscular electrical stimulation (NMES) to improve torque production of the quadriceps femoris muscle. Use of NMES has been shown to be effective in improving quadriceps femoris muscle torque production in subjects without known knee, neurological, or cardiovascular pathology\(^1\)–\(^4\) and subjects who have undergone anterior cruciate ligament reconstruction.\(^5\)–\(^8\) There are 2 general types of electrical stimulation devices that are used for muscle performance training. The term “clinical stimulator” has been used to describe “plug-in,” console devices whose power source is provided by an electrical outlet (60 Hz, alternating current-driven). The term “portable stimulator” is used to describe smaller, battery-operated stimulators. In studies that have demonstrated the effectiveness of NMES for improving quadriceps femoris muscle torque production, clinical stimulators were used to apply the NMES.\(^1\)–\(^8\) In contrast, in studies that were unable to demonstrate a treatment effect when using NMES for quadriceps femoris muscle performance training, portable stimulators were used to deliver the stimulus during training.\(^9\)–\(^11\) There is some evidence to suggest that portable stimulators generate less torque during electrically stimulated muscle contraction compared with clinical stimulators, and this may explain, in part, the apparent differences in treatment effect between these types of stimulators.\(^12\)

Conversely, Laufer et al.\(^13\) suggested that waveform, not current source, was the cause of discordance in torque production between “portable stimulators” and the “house current-driven stimulators.” By holding phase duration and pulse frequency constant, these researchers showed that the portable units’ monophasic or biphasic waveforms were actually able to generate greater quadriceps femoris muscle contractions than the

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CL Lyons, PT, MS, OCS, SCS, ATC, is Assistant Chief, Physical Therapy Element, MacDill Hospital, 6th Medical Group, MacDill Air Force Base, Fla.

JB Robb, PT, MS, SCS, ATC, CSCS, is Assistant Chief of Physical Medicine, RAF Lakenheath, 48th Medical Group, Lakenheath, United Kingdom.

JJ Irrgang, PT, PhD, ATC, is Associate Professor, School of Health and Rehabilitation Sciences, University of Pittsburgh, Pittsburgh, Pa.

GK Fitzgerald, PT, PhD, OCS, is Associate Professor, Department of Physical Therapy, School of Health and Rehabilitation Sciences, University of Pittsburgh, 6035 Forbes Tower, Pittsburgh, PA 15260 (USA) (kfitzger@pitt.edu). Address all correspondence to Dr Fitzgerald.

All authors provided concept/idea/project design and writing. Ms Lyons and Mr Robb provided data collection, and Dr Irrgang and Dr Fitzgerald provided data analysis. Ms Lyons, Mr Robb, and Dr Fitzgerald provided project management. Ms Lyons and Mr Robb provided subjects. Dr Fitzgerald provided facilities/equipment.

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This study was approved by the University of Pittsburgh Institutional Review Board.

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The Empi 300PV unit is a portable stimulator that produces a constant current with a peak output of 100 mA and a programmable pulse duration of 0 to 400 microseconds. The Empi 300PV unit utilizes a symmetrical biphasic waveform similar to that of the portable unit used by Laufer et al to produce effective quadriceps femoris muscle contractions. Before attempting to use this device in our NMES quadriceps femoris muscle performance training programs for our patients, we elected to compare the torque-generating capabilities of this device with those of a clinical stimulator (VersaStim 380). When used in our clinic for muscle stimulation, the VersaStim 380 constant-current device is set to utilize a triangular waveform with a typical Russian frequency setting of 2,500 Hz and a pulse duration of 400 microseconds. The VersaStim 380 was set at 75 bursts per second with a 6.7-millisecond burst duration. We used the VersaStim 380 as the comparison device because this device has been shown to be effective in enhancing recovery of quadriceps femoris muscle torque production in patients who have undergone anterior cruciate ligament reconstruction both in our own experiments and in other studies as well.

The primary purpose of this study was to compare the torque produced during electrically stimulated isometric quadriceps femoris muscle contractions between the clinical and portable stimulators. A secondary aim was to compare differences in self-reported pain during NMES between the 2 types of stimulators.

Method

Subjects

The subjects were 40 volunteers (22 male, 18 female) without a history of knee surgery or knee injury, cardiovascular disease, or neurologic disease. We also excluded individuals who had a recent history of prolonged corticosteroid use (greater than 3 months in the past year) because we believed that they may be at greater risk for tendon injury during maximal voluntary contractions. The mean age of the subjects was 30.4 years (SD = 9.9, range = 21–60). Average subject body mass index was 24.4 kg/m² (range = 19.4–33.07). The average number of days per week that subjects reported engaging in exercise was 3.4 days per week (range = 0–7). All subjects signed a written informed consent form approved by the University of Pittsburgh Institutional Review Board prior to participation in the study.

Testing Procedures

Subjects underwent 2 separate test sessions, one for each stimulator. The order of testing with the stimulators was counterbalanced to eliminate any systematic effects due to the order of testing. For example, if subject 1 was tested with the clinical stimulator during the first session, then subject 2 would be tested with the portable stimulator during his or her first session, and so on.

For the portable stimulator, new batteries were used for each subject during testing. This was done to minimize any potential problems with reduced current output from the portable stimulator due to low battery output with continued use.

Each test session consisted of 6 components: a warm-up period, setup, determination of maximal voluntary isometric contraction (MVIC), a dosing phase, a resting period, and a testing phase. Limb selection for testing was determined by a coin flip before the first test, and the same limb was used for both sessions for each subject.

First Test Session

Warm-up period. Each subject was provided a 5-minute warm-up on an exercise bicycle, cycling at approximately 80 revolutions per minute and a low resistance, prior to each test session.

Setup. Following the bicycle warm-up, a maximum voluntary isometric quadriceps femoris muscle torque test was performed. A Biodex dynamometer (Biodex Multijoint System 3) was used to measure quadriceps femoris muscle torque. Torque data from the dynamometer were transferred to a second computer for processing. A custom-made program, using LabVIEW software, was developed for data processing for this study. The program also allowed for display of torque data and torque markers on the computer monitor during testing. The torque produced during the MVIC was used as a reference for determining the percentage of the MVIC torque that was generated during electrical stimulation of the muscle for each electrical stimulator.

Subjects were seated on the dynamometer with the dynamometer force pad secured to the distal aspect of the lower leg, just superior to the malleoli. A thigh strap, waist strap, and 2 chest straps were then secured to stabilize the subject in the dynamometer chair. The dynamometer’s axis of rotation was aligned with the lateral femoral epicondyle, and the knee was extended from 90 degrees to 0 degrees to ensure that the axis of...
rotation of the knee was aligned with the axis of rotation of the dynamometer. The knee was then positioned in 60 degrees of flexion. The torque produced from the weight of the limb was recorded with the patient at rest and entered into the computer programming for gravity correction.

**Determination of MVIC.** Practice prior to testing was provided by having each subject produce voluntary isometric contractions of the quadriceps femoris muscle against the force pad of the dynamometer at 50%, 75%, and 100% of his or her perceived maximum voluntary effort. Following the practice session, the subject performed 3 MVICs (6 seconds in duration) of the quadriceps femoris muscle, and the average torque produced during the 3 contractions was recorded as the maximum voluntary isometric quadriceps femoris muscle torque output. Analysis of the 40 subjects’ MVICs from day 1 versus day 2 of testing indicated that this procedure yields reliable quadriceps femoris torque measurements. An intraclass correlation coefficient (ICC [2,k, where k=3]) of .97, with a 95% confidence interval of .94 to .98, was obtained for test-retest reliability of the MVIC data.

**Dosing phase.** After each subject completed the maximum voluntary isometric torque test, we determined the maximum stimulus amplitude that the subject could tolerate during NMES in the dosing phase. For this measurement, the subject remained seated in the dynamometer chair, positioned as described for the maximum voluntary isometric torque test. Two electrodes (6.98- × 12.7-cm Durastick self-adhesive electrodes) were placed on the distal medial and proximal lateral portions of the subject’s anterior thigh. Prior to application of the electrodes, the skin over the electrode placement site was cleansed with alcohol swabs. To ensure consistent electrode placement for the second test session, a clear plastic sheet was placed over the subject’s anterior thigh, and tracings were made of the subject’s patella and patellar tendon as well as the 2 electrodes on the clear plastic sheet.

Once the electrodes were placed, an electrical stimulus from the designated stimulator was applied to the subjects’ resting muscle. The stimulus characteristics used for each stimulator during testing are provided in the Table. The stimulus characteristics for the VersaStim 380 were the same as those we have previously found to be effective in enhancing quadriceps femoris muscle torque production.8 The stimulus characteristics for the Empi 300PV were selected based on our clinical observations that these parameters, in general, yielded the greatest amount of quadriceps femoris muscle torque production with the least discomfort. During the dosing phase only, we displayed a torque marker line on the computer monitor at 50% of the subjects’ MVIC torque. Subjects were told, “Relax and let the stimulation do the work” when the stimulus was applied. We informed the subjects that, during electrical stimulation, we wanted the torque curve produced by the muscle stimulation to exceed the level of the marker on the screen if possible. During this phase, the stimulus intensity was gradually increased until subjects indicated to the tester that their limit of tolerance for the stimulus had been achieved (they did not want any further increase in the stimulus amplitude) regardless of whether the torque curve exceeded the level of the torque marker. This process was repeated for 2 additional trials, and the highest tolerable stimulus amplitude that was achieved during the 3 trials was recorded and used as the stimulus amplitude for subsequent testing.

**Resting period.** Following the dosing phase to determine the NMES stimulus amplitude for testing, subjects were given a 5-minute rest period during which they were allowed to get up from the Biodex dynamometer. The electrodes remained in place during the rest period. Once the 5-minute rest cycle was completed, the subjects

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1 Chattanooga Group, 4717 Adams Rd, Hixson, TN 37343.
were repositioned on the dynamometer seat in preparation for testing.

**Testing phase.** The testing phase consisted of 11 contractions: 1 contraction to ramp the stimulus up to a subject’s maximum tolerated stimulus intensity (determined as described earlier) and 10 contractions at this stimulus intensity. Each electrically stimulated contraction was 10 seconds in duration and was followed by a 50-second rest period. During each 10-second stimulation period, the subject was told to “relax and let the stimulation do the work.” For this phase of testing, the data screen was turned from the subject to prevent the subject from seeing the torque measurements being recorded.

The peak quadriceps femoris muscle torque induced during each of the 10 stimulated contractions was recorded and then averaged and expressed as a percentage of each subject’s MVIC. This method was used because previous research demonstrated that the stimulus amplitude should produce at least 25% to 50% of the individual’s MVIC when using NMES for quadriceps femoris muscle performance training.1.3–14 We wanted to observe whether the average peak torque achieved this level during testing for both stimulators.

The torque integral (in newton-meter-seconds) over the 10-second contraction was calculated for each of the 10 contractions. From these data, we calculated the average torque integral produced over the 10 contractions for each subject. This variable was used to determine whether there were differences between stimulators in the amount of torque that is produced over the course of a treatment session consisting of 10 contractions, each of 10 seconds’ duration.

To determine whether there were differences between stimulators in self-reported pain during stimulation, subjects also rated the level of pain they experienced during each contraction on an 11-point (0–10) numeric pain rating scale, where 0 represents “no pain” and 10 represents the “worst pain imaginable.” The pain rating was recorded after each electrically elicited contraction and then averaged for analysis. Eleven-point numeric pain rating scales have been shown to yield reliable measurements of pain in people with a variety of lower-extremity musculoskeletal conditions (ICC=.86, 95% confidence interval=.65–.94).15

**Second Test Session**
Subjects returned within 1 week of the first test session to repeat the testing procedures with the second stimulator. The procedures for this session were the same as described for the first test session, including the warm-up, determination of a subject’s MVIC, determination of a subject’s maximum tolerated stimulus amplitude, and the average peak quadriceps femoris muscle torque, average torque integral, and average numeric pain ratings during the 10 electrically stimulated contractions. The MVIC torque acquired during this session was used as the reference for determining the percentage of MVIC torque that was produced during electrical stimulation of the muscle for this session. This was done to reduce any possible training or fatigue effect that may have occurred from the first testing phase and to ensure that the percentage of MVIC was accurate for the subject’s MVIC on that day of testing.

**Data Analysis**
Means and standard deviations for electrically stimulated peak isometric quadriceps femoris muscle torque, the average torque integral produced during the 10 electrically stimulated contractions, and the numeric pain ratings for the 10 electrically stimulated contractions were calculated for each of the stimulator conditions. Paired t tests were used to compare mean differences in each of these variables between stimulator conditions. An a priori power analysis using a paired t test at alpha equal to .05 and—assuming a minimum important difference of 10% in torque output between stimulator conditions, with a common standard deviation of the difference equal to 20% (0.50 effect size)—indicated that we would need approximately 33 subjects to find a difference between stimulator conditions with a statistical power of 0.80.

**Results**
A summary of the mean differences between stimulator conditions for all variables are provided in Figures 1 through 3. There were no differences in the peak torque (Empi 300PV=60.5%±18.7% of MVIC, VersaStim 380=56.0%±16.2% of MVIC; Fig. 1) or numeric pain ratings (Empi 300PV=4.6±2.3, VersaStim 380=4.9±1.9; Fig. 3) during the electrically stimulated contractions between stimulator conditions (P>.05). The Empi
300PV produced a greater average torque integral (988.6 ± 330.4 N·m·s) compared with the VersaStim 380 (822.7 ± 292.6 N·m·s) during the 10 electrically stimulated contractions (Fig. 2, P = .01). The data suggest that the Empi 300PV performed better than what has been previously reported by Snyder-Mackler et al.12 for portable, “battery-powered” electrical stimulators in terms of producing quadriceps femoris muscle torque. The portable stimulator used by Snyder-Mackler et al produced an average torque of only 8.9% of MVIC. One possible explanation is that we used large electrodes (6.98 × 12.7 cm) for both the portable and clinical stimulators in our study. The large electrodes might allow for greater tolerance of current by the subject, and thus our subjects may have received greater amounts of current before reaching the maximum level of tolerance.

Laufer et al.13 reported achieving average torque outputs ranging from 33% to 43% of MVIC during muscle stimulation with a portable stimulator, depending on whether a monophasic or biphasic waveform was used. They used electrodes that were similar in size to those used in our study (7.6- × 12.7-cm). It may be possible that differences in peak torque output during muscle stimulation reported by Laufer et al.13 and those found in our study may be explained, in part, by differences in stimulus characteristics. Laufer et al.13 used a pulse rate of 50 pulses per second, a phase duration of 200 microseconds, and a maximum peak stimulus amplitude of 150 mA for both monophasic and biphasic waveforms, whereas the Empi 300PV used in our study used a symmetrical, synchronous cycling waveform with a pulse rate of 75 pulses per second, a pulse duration of 250 microseconds, and a maximum peak stimulus amplitude of 100 mA.

Another factor that might explain differences between the results of our study and those of previous studies1,13,16 is that our subjects were not encouraged to tolerate a target level of stimulus intensity (ie, 50% of MVIC). Because the subjects in our study were given visual feedback in the dosing phase to encourage them to achieve 50% of MVIC, they may have been motivated to tolerate more neuromuscular stimulation to produce greater levels of torque production than what was previously reported.1,13,16 Previous researchers1,13,16 have masked subjects during all phases of stimulation, which may have limited the degree of “stimulus toleration.” Asking subjects to tolerate 50% of MVIC of quadriceps femoris muscle torque production is not an unrealistic expectation, as several previous studies2,4,17,18 have yielded electrical stimulation torque production of 60% to 87% of MVIC.

A potential confounder that needed to be considered in our study is that subjects may have attempted to voluntarily contract their quadriceps femoris muscle to meet the 50% of MVIC benchmark during the dosing phase of the study. We attempted to minimize this problem from...
occurring by instructing subjects to “relax and let the machine do the work” during application of the stimulus. In addition, we prevented the subjects from viewing the computer monitor during the testing phase of the study to eliminate the visual feedback they would receive regarding torque production during this phase. During the dosing phase, not all subjects achieved the 50% of MVIC benchmark before indicating they had reached the maximum tolerable level of stimulation. Therefore, we are confident that use of voluntary contraction to assist subjects in achieving the 50% of MVIC benchmark was minimized.

The torque integral produced by the Empi 300PV was greater than that of the VersaStim 380. Although these units produced similar percentages of MVIC, the Empi 300PV unit was able to maintain the torque production more consistently over the 10-second contraction than the VersaStim 380. The difference we observed in torque integral supports the findings of Laufer et al13 where the battery-powered units producing monophasic and biphasic waveforms were less fatiguing than the clinical, house current-driven units producing Russian stimulus. Laufer et al13 offered possible explanations of de facto higher-frequency stimulation and more fast-fatigable motor unit recruitment as the source of increased fatigue with the polyphasic Russian setting.

The pain level reported for each stimulator was an important consideration of this study. A patient must be able to tolerate an adequate level of stimulation to produce a training effect. If sufficient torque cannot be achieved, the use of electrical stimulation for strengthening may not be appropriate. In addition, it is in the clinician’s and patient’s best interest to use a stimulation tool that is able to generate a training effect at a comfortable level of stimulation. Our results show an average of just over 4 on a 0- to 10-point numeric pain scale for each unit at the perceived maximum tolerated stimulus, which we consider to be a modest level of discomfort. Based on our results, we conclude that there is no difference between the pain levels reported over the 10 electrically elicited contractions produced by the VersaStim 380 and Empi 300PV units.

We recorded the stimulus intensity used for each stimulator during testing and found that there was a difference between stimulators in the percentage of the instrument’s maximum current capacity used during stimulation. The percentage of the instrument’s current capacity during testing was greater for the Empi 300PV (X=90.1%, SD=12.8%, range=60%-100%) compared with the VersaStim 380 (X=34.0%, SD=7.0%, range=23.2%-57%). A potential implication is that, although the 2 stimulators may be comparable in producing torque, the Empi 300PV may not have enough reserve current capacity to maintain an adequate level of torque as a patient increases the quadriceps femoris muscle torque output with training. In contrast, as individuals progress with treatment, they may not need as much current from the stimulator to produce adequate levels of torque during training. Further study is needed to determine whether the Empi 300 PV can sustain adequate levels of torque production as a training program is progressed over time.

Conclusion
The portable Empi 300PV stimulator can produce comparable levels of average peak torque at comparable levels of discomfort to that produced by the VersaStim 380 clinical stimulator when a subject’s maximum tolerance for the stimulus is used as the criterion to set the stimulus intensity. The Empi 300PV stimulator resulted in the maintenance of greater torque production over 10 electrically elicited contractions compared with the VersaStim 380. Based on these data, we believe that the Empi 300PV has the potential to produce adequate levels of torque production for NMES performance training of the quadriceps femoris muscles. Further study is needed to determine the effectiveness of using the Empi 300PV for quadriceps femoris muscle performance training.

References


