# Quadriceps Femoris Muscle Torques and Fatigue Generated by Neuromuscular Electrical Stimulation With Three Different Waveforms

Background and Purpose. Neuromuscular electrical stimulation is used by physical therapists to improve muscle performance. Optimal forms of stimulation settings are yet to be determined, as are possible sex-related differences in responsiveness to electrical stimulation. The objectives of the study were: (1) to compare the ability of 3 different waveforms to generate isometric contractions of the quadriceps femoris muscles of individuals without known impairments, (2) to compare muscle fatigue caused by repeated contractions induced by these same waveforms, and (3) to examine the effect of sex on muscle force production and fatigue induced by electrical stimulation. Subjects. Fifteen women and 15 men (mean age=29.5 years, SD=5.4, range=22-38) participated in the study. Methods. A portable batteryoperated stimulator was used to generate either a monophasic or biphasic rectangular waveform. A stimulator that was plugged into an electrical outlet was used to generate a 2,500-Hz alternating current. Phase duration, frequency, and on-off ratios were kept identical for both stimulators. Participants did not know the type of waveform being used. Torque was measured using a computerized dynamometer: a maximal voluntary isometric contraction (MVIC) of the right quadriceps femoris muscle set at 60 degrees of knee flexion was determined during the first session. In each of the 3 testing sessions, torque of contraction and fatigue elicited by one waveform were measured. Order of testing was randomized. Torque elicited by electrical stimulation was expressed as a percentage of average MVIC. A mixed-model analysis of variance was used to determine the effect of stimulation and sex on strength of contraction and fatigue. Bonferroni-corrected *post hoc* tests were used to further distinguish between the effects of the 3 stimulus waveforms. Results. The results indicated that the monophasic and biphasic waveforms generated contractions with greater torque than the polyphasic waveform. These 2 waveforms also were less fatiguing. The torques from the maximally tolerated electrically elicited contractions were greater for the male subjects than for the female subjects. Discussion and Conclusion. Muscle torque and fatigue of electrically induced contractions depend on the waveform used to stimulate the contraction, with monophasic and biphasic waveforms having an advantage over the polyphasic waveform. All tested waveforms elicited, on average, stronger contractions in male subjects than in female subjects when measured as a percentage of MVIC. [Laufer Y, Ries JD, Leininger PM, Alon G. Quadriceps femoris muscle torques and fatigue generated by neuromuscular electrical stimulation with three different waveforms. Phys Ther. 2001;81:1307-1316.]

Key Words: Fatigue, Neuromuscular electrical stimulation, Torque, Waveform.

Yocheved Laufer Julie Deanne Ries Peter M Leininger Gad Alon ranscutaneous neuromuscular electrical stimulation is commonly used by physical therapists in muscle strength rehabilitation.<sup>1-4</sup> There appears to be a correlation between the force of electrically induced contractions and gains in muscle force during voluntary contractions.<sup>5,6</sup> Gains in force have been reported using contraction intensities of 30% to 50% of each subject's maximal voluntary isometric contraction (MVIC).<sup>7</sup>

Commercial stimulators provide many different waveforms and pulse settings capable of producing contractions at these therapeutic levels.<sup>2,8–10</sup> Researchers have attempted to identify preferred stimulation settings in terms of comfort,<sup>10,11</sup> force of contraction,<sup>8,9</sup> and muscle fatigue, which is defined as a decrease in the forcegenerating ability of a muscle resulting from recent activation.<sup>12,13</sup>

The results of a study by Snyder-Mackler et al<sup>9</sup> indicated that differences exist among the torque-generating capabilities of various stimulators, with phase charge an important determining factor. The stimulation variables that are thought to have the greatest impact on muscle fatigue include pulse amplitude and duration, pulse train frequency, and the on-off time ratio of the train.<sup>13</sup> However, because the number of the factors considered in the different studies is extremely variable, it is difficult to make a definitive conclusion concerning the optimal settings that can elicit the strongest contractions with minimal fatigue.

The effect of portable stimulators as compared with house current–driven stimulators is another issue of concern.<sup>2</sup> Portable stimulators are less expensive and can be easily used in a home program, whereas the more expensive house current–driven stimulators are used primarily in clinics. Therefore, a comparison of efficacy between the 2 types of stimulators has implications for use by physical therapists.

According to the manufacturers, both types of stimulators can provide most stimulus settings. Yet, the highintensity and high-frequency (2,500 Hz) alternating current is traditionally available primarily in clinical stimulators, whereas monophasic and biphasic waveforms are available in all types of stimulators.<sup>2</sup> The results of recent studies2,14 support the use of a highintensity clinical electrical stimulator and do not support the use of low-intensity or battery-operated stimulators for increasing the force of the quadriceps femoris (QF) muscles following anterior cruciate ligament reconstruction. In these studies, however, different stimulus characteristics and protocols were used for the batteryoperated and line-powered stimulators. These differences, although not related to the source of current operating the stimulators, may have affected the results. The clinical stimulator used in these studies was set to deliver a 2,500-Hz triangular alternating current with a 200-microsecond phase duration, a burst rate of 75 bursts per second, and an on-off time ratio of 11/120seconds, whereas the battery-operated stimulator was set at a phase duration of 150 microseconds, a frequency of 55 Hz, and an on-off time ratio of 15/50 seconds. These differences may have affected both muscle torque and fatigue during the training sessions which in turn affected the gains in muscle strength. Therefore, we believe that the results indicating the superiority of clinical stimulators can be questioned.

The effect of electrical stimulation is determined by the intrinsic tissue properties of the individual.<sup>15</sup> Yet, very few researchers have investigated the individual's sex as a factor that may influence the force of electrically induced muscle contractions. The results of a recent

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Dr Laufer, Ms Ries, and Dr Alon provided concept/research design and facilities/equipment. Dr Laufer provided writing and data analysis. Dr Laufer, Ms Ries, and Mr Leininger provided data collection. Dr Laufer and Ms Ries provided project management, and Ms Ries provided clerical support. Ms Ries and Mr Leininger provided subjects, and Ms Ries provided institutional liaisons.

The Institutional Review Board of Marymount University, Arlington, Va, approved the study.

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Table 1.Stimulation Characteristics

Type of Waveform	Power Source	Waveform Shape	Phase Duration (µs)	Frequency	Maximal Peak Intensity (mA)
Monophasic	Battery	Rectangular	200	50 Hz	150
Biphasic	Battery	Symmetric rectangular	200	50 Hz	150
Polyphasic	House current	Alternating sinusoidal, 2,500 Hz	200	50-Hz bursts <sup>a</sup>	100

<sup>a</sup> Each burst and each between-burst interval was 10 milliseconds, with 25 alternating pulses per burst.

study<sup>16</sup> indicate that plantar-flexion torque elicited by electrical stimulation was lower in female subjects than in male subjects both at pain threshold and at maximally tolerated stimulation levels. To our knowledge, the effect of a person's sex on electrically induced fatigue has not been adequately investigated. Should sex play a role in contraction force and muscle fatigue, this variable should be considered in future studies examining the effectiveness of stimulation therapy.

The objectives of our study were: (1) to examine the ability of 2 different waveforms delivered by portable stimulators and one waveform delivered by a clinical stimulator to induce maximally tolerated isometric contractions of the QF muscle in individuals without known neuromuscular or musculoskeletal impairments (the stimulators differed in power source and waveform but not in phase duration, frequency, or on-off ratio of pulse trains) (2) to compare muscle fatigue induced by repeated contractions achieved by the same waveforms, and (3) to examine the effect of the individual's sex on maximally tolerated muscle contraction and fatigue induced by the 3 waveforms.

## **Methods**

#### **Subjects**

Fifteen female subjects with a mean age of 28.2 years (SD=5.2, range=22–35) and 15 male subjects with a mean age of 30.7 years (SD=5.5, range=24–38) volunteered to participate in the study. All subjects reported having no known neuromuscular or skeletal impairment. Each subject received a detailed explanation of the study and gave informed consent prior to participation.

#### Instrumentation

A portable electrical stimulator (Staodyn EMS)\* was used to elicit a muscle contraction with either a monophasic rectangular waveform or a biphasic symmetric rectangular waveform. A house power-driven stimu-

\* Staodyn Inc, 1225 Ken Pratt Blvd, PO Box 1379, Longmont, CO 80502.

lator (Dynatron 650)<sup>†</sup> was used to elicit muscle contractions with a polyphasic waveform. Table 1 presents a summary of the characteristics of the electrical stimulation settings used. An oscilloscope was used in an effort to ensure accurate setting of stimulus frequency and pulse duration of the portable stimulator. Four 7.6-  $\times$ 12.7-cm  $(3 \times 5\text{-in})$  oval, reusable, self-adhering electrodes (PALS)<sup>‡</sup> were used with each participant. A dynamometer (Kin-Com)<sup>§</sup> was used to assess torque generated by the right QF muscle group during MVIC and during all electrically induced isometric QF muscle contractions. The reliability of force, angle, and velocity measurements obtained with the Kin-Com dynamometer has been studied, and the obtained intraclass correlation coefficients of above .99, in our opinion, indicate that the measurements of force and angle with this dynamometer are highly replicable.<sup>17</sup> The application of the Kin-Com dynamometer to the measurement of torque in electrically induced contractions also has been done.<sup>18,19</sup> We, therefore, did not examine the reliability of our torque measurements.

## Procedure

Each subject participated in 3 sessions, with at least 48 hours between sessions but no more than 7 days between sessions. Subjects were assigned to 1 of 6 groups. Group assignment determined the order in which they were tested using the 3 different electrical stimulation waveforms. Assignment to group was by order of inclusion in study and by sex (3 female subjects and 3 male subjects in each group). Participants were not informed of the type of waveform being used during each testing session. The right QF muscle was used for all tests.

During the initial session, the MVIC of the right QF muscle was measured. This measurement was followed by an electrically induced maximally tolerated contraction (MTC) test and by a fatigue test using 1 of the 3 waveforms. The procedure for each of the ensuing

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<sup>&</sup>lt;sup>‡</sup> Axelgaard Manufacturing Co Ltd, 1667 S Mission Rd, Fallbrook, CA 92028.

<sup>&</sup>lt;sup>§</sup> Chattanooga Group Inc, 4717 Adams Rd, PO Box 489, Hixson, TN 37343.

sessions was similar to the procedure for the initial session, with the following exceptions: (1) MVIC was determined at the initial session only, and (2) the type of waveform being used for the electrical stimulation component of the protocol differed and was determined by group assignment.

MVIC test. The Kin-Com was used to measure MVIC at an angle of 60 degrees of knee flexion. We attempted to ensure accurate application of the measurement technique, as recommended in previous studies.<sup>18,19</sup> The subjects' leg, thigh, and pelvis were stabilized by the seating system pads and belts. The backrest was set at 110 degrees of posterior incline, and the inferior portion of the shin pad was adjusted at 5.1 cm (2 in) superior to the right medial malleolus. The fulcrum of the lever arm was aligned with the most inferior aspect of the lateral epicondyle of the right femur. Gravity correction was performed at 10 degrees of right knee flexion to eliminate inadvertent pull of the hamstring muscle group. We did not do reliability testing for this correction. All alignment and seating information was documented so that we would be consistent in all testing sessions. We used a carpenter's level and a universal goniometer in an effort to ensure that the arm of the dynamometer was horizontal when the knee was supposed to be in full extension. The speed of the dynamometer was set at  $0^{\circ}/s$ .

Subjects did 3 consecutive 3-second MVIC trials of the right QF muscle group, with 57 seconds of rest between trials. The dynamometer sampled the torque data at a frequency of 100 samples per second. The mean of the data output was used to represent torque. Subjects were instructed to keep their arms crossed over their chest and were given verbal coaching to "kick as hard as you can" during the 3-second contractions. Subjects were not allowed to view the measurements on the computer screen. The torque for each contraction was averaged for the 3 trials, and this average was used as the MVIC.

MTC test. During the initial session, a 5-minute rest period was allowed between the MVIC test and the MTC test. Each subject's right thigh was cleaned with alcohol and fitted with 4 PALS electrodes. Two stimulation channels were used, and electrode placement was determined by palpation as follows: one electrode was placed directly over the distal bulk of the vastus medialis muscle, one electrode was placed over the distal vastus lateralis muscle, one electrode was placed over the rectus femoris muscle, and one electrode was placed over the proximal portion of the vastus lateralis muscle. Following testing, the final locations of electrodes relative to surface anatomy landmarks were traced onto a clear transparency in an attempt to ensure identical electrode placement for subsequent testing trials. Once the electrodes were in place, subjects were placed in the Kin-Com in the same

position as was used for the MVIC testing. Using a series of no more than 6 to 8 brief (3–5 seconds) electrically stimulated contractions with increasing intensity, a maximal tolerated intensity was determined for each waveform. After each increase in intensity that induced a visibly stronger contraction, the participant was asked, "Can you tolerate any further increase in intensity?" Some electrode placement modification was allowed to maximize subject comfort once the electrical stimulation was begun.

Maximal tolerated intensity was identified as the intensity of stimulation received when the subject said that he or she could no longer tolerate an increase in intensity. Following a 2- to 3-minute rest period, torque output of the QF muscle group elicited by the maximal tolerated intensity was recorded by use of the Kin-Com at a sampling frequency of 100 Hz. Three consecutive 7-second (including 2-second ramp up time) contractions were elicited, with 60 seconds of rest between contractions. Subjects were instructed to keep their arms crossed over their chest and to try to relax during the electrically stimulated contraction. They were not able to view the measurements of their torque on the computer screen. The torque for each contraction was averaged for the 3 trials, and this average was used to represent the MTC.

Fatigue test. After a 15-minute rest period, the fatigue component of the protocol was done, using the maximally tolerated stimulation intensity previously identified and identical positioning in the Kin-Com. The fatigue test consisted of a series of 7-second electrical stimulations (including 2-second ramp up time) separated by 2-second rest periods. This pattern was repeated for 48 contractions or until the QF muscle group generated zero torque. The reliability of measurements obtained with this fatigue test protocol has been examined previously in the QF muscle of individuals without impairments, and the intraclass correlation coefficients ranged between .75 and 1.0.20 Care was taken here to replicate the technique used in the previous study. Although contractions were elicited throughout the test protocol, there were some limitations in the computer programming of the Kin-Com dynamometer. Thus, torque measurements were saved for 21 contractions spaced throughout the test. The same contractions were saved for all subjects and tests. As in other portions of the study, subjects were instructed to keep their arms crossed over their chest and to try to relax during the electrically stimulated muscle contractions; they were not able to view the torque measurements displayed on the computer screen.

	ырпаз	IC		Polypn	asic	
Range	X	SD	Range	X	SD	Range
5.3-63.4	32.7	17.1	8.4–74.8	25.5	11.2	9.9–51.7
	5.3–63.4 16.6–73.8	5.3–63.4 32.7 16.6–73.8 43.3	5.3–63.4 32.7 17.1 16.6–73.8 43.3 14.1	5.3-63.4   32.7   17.1   8.4-74.8     16.6-73.8   43.3   14.1   16.2-63.7	5.3-63.4   32.7   17.1   8.4-74.8   25.5     16.6-73.8   43.3   14.1   16.2-63.7   36.3	5.3-63.4 32.7 17.1 8.4-74.8 25.5 11.2   16.6-73.8 43.3 14.1 16.2-63.7 36.3 11.6

38.0

## Table 2.

Contraction Torque (Expressed as Percentage of Maximal Voluntary Isometric Contraction) by Stimulators and Sex

# Data Analysis

Overall mean

The average torque produced by each stimulator during each MTC test was expressed as a percentage of average MVIC. A mixed-model analysis of variance (ANOVA) with waveform type as the repeated factor and the subject's sex as the within factor was used to determine the effect of electrical stimulation waveform and sex on strength of contraction. Bonferroni-corrected post hoc tests were used to further distinguish between the effects of the 3 stimulus waveforms. To analyze the effect of stimulus waveform type on muscle fatigue, the torque of each contraction during a fatigue test was expressed as a percentage of MVIC. The percentage of MVIC and the time since the start of fatigue test were plotted. The created curves appeared to be characterized by a decay function, and the areas under the curves were calculated by using a computerized integrative computational method, namely, a "polygon-based" algorithm. The areas under the curve, thus representing the sum of torque (ST) generated across contractions, were compared using the ANOVA and Bonferroni-corrected post hoc tests. Next, because ST is affected by the rate of decrease in torque as well as by the relative strength of the initial contraction, the average torque of each contraction was normalized to the initial contraction produced by the stimulator. Thus, the first contraction of each subject for each stimulator was considered 100%, and consecutive contractions were expressed as a percentage of the initial contraction. The areas under the curves obtained by plotting normalized values versus time since the start of the fatigue test represented the rate of decay (RD). These areas were calculated similarly to the ST areas and were compared using the ANOVA and Bonferronicorrected *post hoc* tests. The SAS program<sup>#</sup> was used for all statistical analyses.

17.1

36.6

## Results

One male subject tolerated maximum output with all 3 waveforms. Another male subject achieved maximal output with the biphasic waveform, and 2 others achieved maximal output with the polyphasic waveform. In all other tests of maximum electrically elicited contractions, subjects' complaints of discomfort and inability to toler-

# Table 3.

16.6

Bonferroni-Corrected Post Hoc Comparison Among Waveforms

Waveform	т	Р	Corrected P
Monophasic vs biphasic	0.55	.583	NSª
Monophasic vs polyphasic	2.14	.036	.109
Biphasic vs polyphasic	2.69	.009	.028

30.9

12.6

<sup>a</sup> NS=not significant.

ate higher current amplitude limited the strength of QF muscle contraction.

Table 2 presents the means, standard deviations, and ranges of contraction torque (expressed as a percentage of MVIC) elicited by the 3 waveforms grouped by sex. The ANOVA indicated that torques of the monophasic, biphasic, and polyphasic waveforms  $(36.6 \pm 17.1,$  $38.0\pm16.6$ , and  $30.9\pm12.6$ , respectively) were different (F=4.05; df=2,56; P=.02). A difference in torque also was found between the female subjects and the male subjects  $(30.35\pm15.4 \text{ and } 40.00\pm13.6, \text{ respectively})$ (F=4.70; df=1,28; P=.04). Interaction of sex and stimulus was not significant. Table 3 summarizes the results of the Bonferroni-corrected post hoc comparison of the 3 stimulus waveforms. The results indicate that the effect was probably due to the difference between the force of the contraction elicited by the biphasic stimulus waveform and that elicited by the polyphasic stimulus waveform.

Figure 1 presents the torques (expressed as a percentage of MVIC) during the fatigue test for each of the 3 waveforms. Table 4 presents the mean areas under the curve and the standard deviations of torque measurements (expressed as percentage of MVIC) plotted against time for female and male subjects stimulated with the 3 waveforms (ST). Comparison of areas under the curve for ST indicated an effect for stimulus waveform (F=37.13; *df*=2,54; *P*=.0001), with no effect due to sex or interaction. Bonferroni-corrected post hoc tests indicated greater areas under the curve for the monophasic and biphasic stimulation  $(5,631.1\pm2,824.2)$ and 5,572.6±2,465.0, respectively) as compared with the polyphasic stimulation  $(2,362.4\pm1,227.5)$ (t=7.37)P=.0003 and t=7.49, P=.0003, respectively), with no

<sup>#</sup> SAS Institute Inc, PO Box 8000, Cary, NC 27511.



#### Figure 1.

Mean quadriceps femoris muscle torque of all subjects during fatigue test for each waveform (expressed as a percentage of maximal voluntary isometric contraction [%MVIC]).

#### Table 4.

Mean Area Under the Curve and Standard Deviation (Percentage × Seconds) of Fatigue Tests When Torque Is Expressed as Percentage of Maximal Voluntary Isometric Contraction (Sum of Torque [ST]) and When Torque Is Normalized to Initial Contraction (Rate of Decay [RD])

	Monophasic		Biphasic		Polyphasic	
	X	SD	X	SD	X	SD
ST						
Female Male	5,881.9 5,397.2	3,552.9 2,027.1	5,495.3 5,655.4	2,858.1 2,067.8	1,862.5 2,862.3	1,002.4 1,257.3
RD						
Female Male	17,493.4 14,820.3	5,470.1 3,564.1	17,552.7 14,416.7	2,746.1 3,369.5	7,372.2 8,668.2	4,118.3 3,396.9

detectable difference between the monophasic and biphasic stimuli.

Figure 2 presents normalized mean values of torque during the fatigue test for each stimulus waveform type for the female and male subjects. Table 4 presents the mean areas under the curve and standard deviations of torque measurements normalized to initial contraction plotted against time for female and male subjects stimulated with the 3 waveforms (RD).

Comparison of areas under the curve representing RD indicated an effect for waveform (F=57.02; df=2,54; P=.0001), with no effect for sex. Bonferroni-corrected *post hoc* tests revealed greater areas under the curve for the monophasic and biphasic stimulation (16,110.8±4,700.2 and 16,038.8±3,403.7, respectively) as compared with the polyphasic stimulation (8,020.2±3,767.3) (t=7.37, P=.0003 and t=7.49, P=.0003, respectively), with no detectable difference between the monophasic and biphasic stimuli. These results indicate a

faster rate of torque decay with the polyphasic stimulator. However, in this comparison, there was an interaction of sex and stimulation waveform (F=3.73;df=2,54; P=.03). Results of an analysis of sex differences within each of the 3 stimulus waveform types are presented in Table 5. The results indicated that the female subjects had greater areas under the curve than male subjects when fatigued by the biphasic stimulator (17,552.7±2,746.1 and 14,416.7±3,369.5 for female and male subjects, respectively). A trend in the same direction was observed for the monophasic stimulator (17,493.4±5,470.1 and 14,820.3±3,564.1 for female and male subjects, respectively), whereas there was no difference between sexes for the polyphasic stimulator.

# Discussion

The results of our study indicated that, when phase duration and pulse/train frequency were held constant at 200 microseconds and 50 Hz, respectively, the maximally tolerated QF muscle contraction elicited by a stimulator using a household-powered source with a 2,500-Hz alternating polyphasic waveform was weaker than the contraction elicited by a portable stimulator with either a monophasic or biphasic waveform.

Snyder-Mackler et al,9 who compared percentage of MVIC elicited by a 2,500-Hz alternating current (phase duration=200 microseconds), a biphasic symmetrical current (phase duration=200 microseconds), and a 4,000-Hz alternating current (phase duration=150 microseconds), found the torque generated by the latter type of current to be the lowest. These results were interpreted to support the contention that torquegenerating capabilities are proportional to phase charge. Although phase duration was held constant in our study, the actual phase charge of the sinusoidal alternating current was 65% to 70% of that of the square monophasic or biphasic waveform. This may seem to support the view that torque generation is proportional to phase charge. However, the results of a study by Kantor et al<sup>10</sup> indicated that square waveforms exhibit a faster discharge of current than high-frequency alternating current, which results in a much shorter effective phase duration for the monophasic and biphasic pulses. Thus, without actual measurement of phase charge, it is impos-



Monophasic

300

400

400

300

300

Seconds

Normalized mean quadriceps femoris muscle torque during the fatigue test of female and male

Seconds

Polyphasic

Seconds

**Biphasic** 

400

500

500

500

100

80

60

40

20

0

100

80

60

40

20

0

100

80

60

40

20

Figure 2.

0

0

subjects for each waveform.

% Normalized

0

% Normalized

0

100

100

100

200

200

200

% Normalized



Women

Women

Women

🛚 Men

Men

Men

Several factors may explain the differences between the study outcomes. First, we examined the strength of QF muscle contraction in subjects without impairments, whereas other authors examined recovery of QF muscle following surgery. Second, in our study, phase duration, frequency, and on-off times were held constant for all stimulators. In studies by Snyder-Mackler et al,2,14 the clinical stimulator delivered a current with a phase duration of 200 microseconds, a burst rate of 75 bursts per second, and an on-off time ratio of 11/120 seconds, whereas the battery-operated stimulator delivered a current with a phase duration of 300 microseconds, a frequency of 55 Hz, and an on-off time ratio of 15/50 seconds. It has been shown that higher pulse frequencies and shorter on-off ratios result in more muscle fatigue.13 Therefore, these differences in current

Therefore, these differences in current characteristics, although not dependent on the type of power driving the current, could very well have affected muscle contraction force and fatigue.

In the studies by Snyder-Mackler et al,<sup>2,14</sup> the portable stimulator group trained at higher current intensities, and all except 7 subjects used all available amperage (100 mA). The higher peak intensities required by the

# Table 5.

Comparison Between Sexes of Area Under the Curve (Percentage  $\times$  Seconds) When Torque Is Normalized to Initial Contraction

Stimulation Waveform	df	F	Р
Monophasic	1,54	3.44	.07
Biphasic	1,54	4.40	.04
Polyphasic	1,54	0.85	NSª

<sup>a</sup> NS=not significant.

portable stimulator group support the finding that a polyphasic waveform utilizes a lower peak intensity to achieve the same threshold of stimulation as monophasic and biphasic waveforms.<sup>10</sup> Such peak intensities may be necessary due to the shorter effective phase charge of the low-frequency current, and they are consistent with the relationship between phase duration and current amplitude observed in neuromuscular electrical stimulation. In our study, only 2 subjects used all available amperage of the portable stimulator, and 3 subjects used all available amperage of the clinical stimulator. However, our portable stimulator provided a 150-mA peak intensity, and the clinical stimulator provided a 100-mA peak intensity. The lower amperage (100 mA) provided by the portable stimulator of the previous studies may not have allowed for training with truly maximally tolerated contractions, which, in turn, resulted in less effective strengthening. Portable stimulators can be manufactured to produce higher amperage and, as our study demonstrated, can generate greater average muscle contraction torques than the clinical stimulator. Further research is necessary to determine whether portable stimulators can be as effective as clinical stimulators in enhancing the recovery of atrophied muscle.

The results of our study suggest that MTCs generated by all 3 waveforms are, on average, weaker in women than in men. Our results also demonstrated large variability in both groups. Thus, the torques generated by some female subjects were just as high as those generated by any male subject, although some male subjects could generate only very low torques. These results are in agreement with the findings of a recent study<sup>16</sup> in which it was demonstrated that plantar-flexion forces elicited by electrical stimulation were lower in female subjects than in male subjects at both pain threshold and at maximally tolerated stimulation levels. The results of our study and the study by Alon et al<sup>16</sup> indicate that the ability of electrical stimulation to generate muscle contraction forces may be sex-dependent. Should this be the case, studies concerning the effectiveness of electrical stimulation should incorporate separate analyses for female and male subjects. A range of socio-psychological as well as biological-physiological differences between sexes has been offered to explain this differential

effect.<sup>16,23</sup> However, further research is necessary to substantiate these findings and to determine the factor(s) that may explain this difference between sexes and whether this should affect practice.

The QF muscle torques revealed repeatable patterns of decline of torque during the fatigue tests for all 3 stimulation waveforms. A sharper decline occurred over the first 5 to 20 contractions, and a much more moderate decline occurred during the remaining contractions. Although the rate of fatigue during electrical stimulation of skeletal muscle is much greater than that seen during volitional contractions,<sup>24</sup> this pattern of decline is similar to that observed in voluntary contraction fatigue tests<sup>25</sup> and has also been reported for electrically induced fatigue tests.<sup>20</sup> These patterns are similar despite the fact that the first contraction is 100% of MVIC in the voluntary fatigue tests, whereas initial contractions are much lower in the electrically induced tests. It has been suggested that the early recruitment of large, fast, and rapidly fatiguing motor units (Type FF) obtained during electrical stimulation may explain the rapid rate of fatigue generally reported with neuromuscular electrical stimulation.19

The results of our study demonstrated that the polyphasic waveform caused greater fatigue in the QF muscle than the monophasic and biphasic waveforms. Comparison of the ST among the stimulation waveforms indicated that the torque across contractions was lower when the QF muscle was stimulated by the polyphasic waveform. Comparison of measurements obtained for the area under the normalized curves (RD) indicated that this lower overall torque across contractions was due not only to the lower initial torque of the polyphasic waveform but also, at least in part, to a faster rate of decay following stimulation with the polyphasic waveform as compared with the other 2 waveforms. Thus, the number of contractions before the torque fell below 50% of the initial contractions was 8, 10, and 5 for the monophasic, biphasic, and polyphasic waveforms, respectively.

Comparisons of the areas under the ST and RD curves indicated no overall differences in rate of fatigue between the female and male subjects. However, the observed interaction effect suggests that the rate of fatigue is lower for women than for men when the contractions are generated by the monophasic and biphasic waveforms. When contractions were induced by the polyphasic waveform, the rate of fatigue was equally as rapid in female subjects as in male subjects. To the best of our knowledge, no previous studies compared the effect of sex on electrically induced fatigue, and further research is needed to examine this issue.

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The dramatic difference between the fatiguing effect of the polyphasic waveform and that of the other 2 waveforms is difficult to explain. Two of the 3 variables considered to have the greatest effect on muscle fatigue (stimulation frequencies and on-off ratios) were the same in all settings.<sup>13,26</sup> Furthermore, stimulation intensity, which is the third variable, was apparently lower in the polyphasic stimulator, as the average initial MTC induced by this waveform was weaker than that induced by the other waveforms. A weaker initial contraction should have resulted in a lower rate of fatigue.<sup>13</sup>

The polyphasic waveform, as used in our study, consisted of fifty 10-millisecond-long bursts, with each burst containing 25 repetitions of 400-microsecond sinusoidal cycles. It is theoretically possible, therefore, that even when one assumes an absolute refractory period of 4 milliseconds, each burst elicited 2 to 3 action potentials. Thus, the polyphasic waveform could have resulted in a *de facto* much higher frequency of stimulation than the other waveforms. As higher frequency is strongly related to muscle fatigue, this, in turn, may have resulted in the faster rate of fatigue for this stimulator.

Another possibility relates to the high frequency (2,500 Hz) of the carrier waveform. The human body exhibits nonlinear, resistive-capacitive, frequency-dependent conduction characteristics.<sup>27</sup> Thus, the different carrier frequency may have affected the depth of current penetration and, in turn, the type of muscle fibers stimulated. The more type FF motor units recruited, the faster the expected muscle fatigue. Whatever the cause for the greater fatigue generated by the polyphasic waveform, the clinical implications are the same. Whenever this type of current is used for muscle strengthening, a relatively large on-off ratio is necessary in order to defer muscle fatigue.

#### Conclusions

This study demonstrated that maximally tolerated electrical stimulation with the polyphasic waveform elicited weaker electrically induced contractions of the QF muscle in individuals without impairments than stimulation with the monophasic and biphasic waveforms, provided phase duration and stimulation frequency were held constant. In addition, stimulation with the polyphasic waveform resulted in more rapid muscle fatigue. These results suggest that waveform is an important consideration in the choice of an appropriate muscle stimulation regimen. The study also demonstrated that this consideration appears to be more important than the source of power operating the stimulator. Although these results warrant further verification with patients, they suggest that it should be possible to establish home treatment protocols with battery-operated stimulators providing monophasic or biphasic waveforms, which could be just

as effective as the more expensive treatment with a clinical stimulator. The results of our study also indicate sex-related differences in electrically induced contractions and in muscle fatigue patterns. Thus, further studies concerning the effectiveness of neuromuscular electrical stimulation should consider differences between sexes in response to treatment. Such studies could enhance the development of the most effective treatment regimens.

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