High Voltage Electrical Stimulation in the Augmentation of Muscle Strength: Effects of Pulse Frequency

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ABSTRACT. Balogun JA, Onilari OO, Akeju OA, Marzouk DK. High voltage electrical stimulation in the augmentation of muscle strength: effects of pulse frequency. Arch Phys Med Rehabil 1993;74:910-6.

• This study was designed to determine the effects of pulse frequency (20pps, 45pps, 80pps) on subjects' voltage tolerance, delayed muscle soreness, and muscle strength gained following 6 weeks of electrical stimulation. Thirty healthy men (mean age = 22 years) were randomly assigned to three groups. Subjects in group 1 (n = 10), group 2 (n = 10), and group 3 (n = 10) had their right quadriceps femoris muscles electrically stimulated with a high-voltage pulsed galvanic stimulator preset at pulse frequencies of 20pps, 45pps, and 80pps, respectively. The left limb of each subject served as the control. For all the groups, the duty cycle of the stimulator was set at 10 seconds on and 50 seconds off during the stimulation. At each training session, the maximal tolerable voltage for each subject was monitored. Ten maximum contractions was allowed at each training session. Muscle soreness perception was evaluated 48 hours after stimulation using a 10-point visual analog scale. Electrical stimulation was administered three times a week for 6 weeks. For each subject, the average voltage output and muscle soreness rating were computed at the end of each week. With a cable tensiometer, the knee extension isometric force of both limbs was evaluated before training and at the end of the second, fourth, and sixth weeks of the study and 3 weeks after training. Repeated measure's analysis of variance was used to determine significant differences in the dependent variables. The results showed that the maximum voltage tolerance, muscle soreness ratings, and muscle strength gained by the three groups are not significantly ($p > .05$) different. The right and left knee extension isometric force increased ($p < .05$) by 24% and 10%, respectively, at the end of the sixth week of training. The gain in muscle strength was still sustained 3 weeks after training. The findings revealed that the stimulator used in this study can improve the strength of normal innervated muscles, but none of the three pulse frequencies selected offered any clinical advantage.

Strength increase in normal innervated muscles is achieved traditionally by active exercise that incorporates external resistance or the use of neuromuscular electrical stimulation (NMES). The evaluation of the effectiveness of NMES and active exercise in muscle strengthening has received considerable attention in the literature. The majority of the existing studies reveal that NMES is as effective, but not superior to, the traditional methods of muscle strengthening.[1] However, the degree of muscle soreness associated with NMES is less than the traditional exercise regimen.[2,3] In medical rehabilitation, NMES is particularly recommended when volitional muscle contraction is not possible due to underlying weakness and/or pain.

The recent interest in the use of NMES for strength augmentation has led to the proliferation of many electrical stimulators for which claims of favorable results have been reported.[2-16] On the contrary, other studies found no increase in muscle strength following NMES.[17-19] The latter finding was attributed to the low force output during the NMES as a result of the sensory discomfort and muscle soreness experienced by the subjects.[1] To be effective in increasing strength, an electrical stimulator must be capable of producing strong tetanic muscular contractions and yet activate a low pain response.[20]

It is generally assumed that the characteristics of an electrical stimulator can be modified to minimize discomfort/pain by altering the wave form, pulse duration, and pulse frequency.[21-23] To date, no widely accepted protocol exists for clinicians using NMES to increase muscle strength. Specifically, the optimum pulse frequency (ie, pulse repetition rate) for muscle strength is yet to be identified.[24] However, it is widely believed that the pulse frequency must be high enough to cause tetanic contraction during treatment. In practice, most clinicians select pulse frequencies between 15 to 100pps.[21,25]

Pulse frequency selection during NMES is critical because it determines the peak force output and the rate of force fatigue during treatment.[26] In a recent study, Binder-Macleod and McDermond[27] investigated the force-frequency relationship following voluntary and electrically induced contractions, and concluded that pulse frequency greater than 60pps is most appropriate for muscle strengthening. They did not, however, evaluate their subject's perception of the varying (pulse frequency) stimuli. It is plausible that the pulse frequencies used for muscle strengthening are tolerated differently by the subjects. Similarly, the post-stimulation muscle soreness caused by each pulse frequency may also be different.

It is important to consider the subject's perception of stimuli in evaluating NMES; after all, sensory discomfort and muscle soreness are considered the major limiting factors in the use of electrical current to promote muscle

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strength.[1,5,10] From clinical perspective, an ideal electrical stimulator must not only be capable of increasing muscle strength, but must be well tolerated during stimulation and cause minimal muscle soreness.[28,29] Currently, no prospective study has evaluated the relative effectiveness of the different pulse frequencies (15 to 100pps) recommended for muscle strengthening.

This study was primarily designed to determine the effects of three (20pps, 45pps, and 80pps) pulse frequencies, on subjects (1) maximum tolerable voltage during stimulation, (2) poststimulation muscle soreness, and (3) muscle strength following 6 weeks of training. A secondary concern was to determine whether the strength gained following NMES is retained 3 weeks after the cessation of treatment. We hypothesized that 80pps pulse frequency will be more effective in improving the strength of normal innervated muscles.

METHODS

Subjects

Nondisabled male undergraduate students at Obafemi Awolowo University, Ile-Ife, Nigeria, participated in this study. Thirty-eight subjects initially volunteered for the study, but 8 of them did not complete the 6 weeks training and their data were excluded. Four subjects withdrew from the study due to scheduling conflicts and loss of interest. Three subjects (2 subjects assigned to 45pps group and 1 subject assigned to 20pps group) withdrew as a result of discomfort/pain from the treatment. One subject assigned to 20pps group withdrew following complaints of pain in the knee joint. The remaining sample size was 30 subjects.

Informed consent was obtained before data collection. Criterion for selection was based on absence of any known musculoskeletal injuries affecting the lower extremities and nonparticipation in strength training program 6 months before the study. No financial compensation was offered for participating in the study.

Limb dominance was ascertained after a brief interview. Subjects were asked "Which leg do you preferentially use to kick a ball while playing soccer?" The leg the subject indicated was considered the dominant limb for that subject.[30] All the subjects in the study were right-limb dominant. Their physical characteristics are presented in table 1. The subjects in each group are comparable in age, weight, height, and body adiposity. Some (40%) of the subjects were involved in recreational activities before the study (eg, soccer, basketball), but not one of them was an elite athlete.

Instrumentation

A high-voltage galvanic stimulator[a] (HVGS) with monophasic (twin-peak pulse) wave form and pulse duration of 65 to 75 microseconds was used in this study. The intensity amplitude of the HVGS ranges from 0 to 500V, and the pulse frequency options on the myostimulator ranges from 4 to 80pps. Within the pulse frequency options available on the HVGS, we selected stimulating frequencies (20pps, 45pps, 80pps) commonly recommended for muscle strengthening by most clinicians.[21,25]

The knee extension isometric strength of the subjects was evaluated with a cable tensiometer. In our previous studies,[30,31] we found the knee extension strength measurements with the cable tensiometer to be highly reproducible ($r = .90$; $p < .001$). Similarly, the output of the cable tensiometer used in this study was found to be valid when calibrated against known weights ($r = .99$; $p < .001$).

Research Design

A 3 (groups) × 2 (limbs) × 5 (time frames) experimental protocol was used in this study. Subjects were randomly assigned to three groups. Subjects in group 1 ($n = 10$), group 2 ($n = 10$) and group 3 ($n = 10$) had their dominant (right) quadriceps muscle stimulated with the HVGS preset at pulse frequencies of 20pps, 45pps, and 80pps, respectively. For consistency purposes and to minimize intersubject variability, the nondominant (left) limb of each subject served as the control. Electrical stimulation was administered three times a week for 6 weeks.

At each training session, the intensity of the stimulator was adjusted to the current that could be maximally tolerated by each subject and 10 contractions were allowed at that current intensity. Muscle soreness perception was evaluated 48 hours after stimulation using a 10-point visual analog scale. For each subject, the isometric force of both quadriceps muscles was evaluated pretraining (before the first NMES), at the end of the second, fourth, and sixth week of the NMES; and 3 weeks after training. The subjects were instructed to maintain their normal daily activities but not to engage in any other exercise training program during the study.

Procedure

On arrival in the laboratory, the age of each subject was recorded and their height and weight measured. The subjects sat on a treatment table with back rest and both lower limbs allowed to hang over the edge of the treatment table. Electrical stimulation was administered to the right quadriceps femoris muscles following the protocol and electrode pad placement arrangement described by Laughman and associates.[10] The electrodes of the HVGS consisted of cotton-padded lead plate. To enhance passage of current during stimulation, the three electrodes were soaked in tepid water before treatment. Subsequently, the proximal (cathode) electrode (11.2 × 11.2cm) was placed at the femoral triangle; the lower edge of the distal (cathode) electrode (11.2 × 11.2cm) was placed 7cm to the upper margin of the patella. The large dispersive (anode) electrode (13.8 × 19.4cm) was placed at the lumbosacral region. The electrodes were maintained in position with velcro strap (10.2cm wide). In a pilot study, we found this electrode arrangement effective in eliciting strong contraction of the quadriceps femoris muscle group.

Irrespective of the group assignment, the duty cycle of the HVGS was set at 10 seconds on and 50 seconds off during stimulation. Subsequently, the pulse frequency of the HVGS was preset to the appropriate frequency depending on the group to which the subject was assigned. During treatment, the current intensity was gradually increased until the subject verbally indicated that he could no longer

Table 1: Physical Characteristics of the Subjects in Each Group

Variables	Group one (20pps)		Group two (45pps)		Group three (80pps)		
	Mean	SD	Mean	SD	Mean	SD	*F*-ratio
Age (years)	22.0	1.7	22.0	1.9	23.1	1.2	1.53 (ns)
Weight (kg)	60.8	4.1	59.2	5.4	63.4	5.5	1.75 (ns)
Height (m)	1.755	0.069	1.731	0.055	1.740	0.050	0.446 (ns)
Body mass index ($kg \cdot m^{-2}$)	19.7	1.4	19.7	1.4	20.9	1.9	1.919 (ns)

Abbreviations: SD, standard deviation; NS, not significant ($p > .05$).

tolerate further rise in current. At this point, the maximum voltage indicated on the voltmeter of the HVGS was recorded for the subject and current intensity was maintained at the subjects' level of tolerance.

Knee extension movement was observed during electrical stimulation. No external weight was applied to the limb to provide resistance during the contraction[10] because the movement initiated was adequately counterbalanced by gravity. The degree of knee extension depends on the intensity of current tolerated by the subject. Subjects were instructed not to assist the contraction produced by the electrical stimulation, but no objective measurement was taken to monitor compliance with the instruction. Ten maximum contractions were allowed at each training session. Overall, each subject had 18 stimulation sessions.

In order to motivate the subjects to endure maximum electrical stimuli, we provided information on their peers' voltage tolerance, but, to ensure confidentiality, names were not released. None of the subjects reached the maximum (500) voltage output of the HVGS during the 6 week training period.

Forty-eight hours following NMES, the subjects were required to rate the soreness experienced in their quadriceps muscles using a 10-point visual analog scale described by Balogun.[29] The subjects were instructed that zero on the scale corresponds to complete absence of soreness, whereas 10 represents severe soreness that is accompanied by distressing pain. At each session, the subjects rated their muscle soreness before the NMES.

The quadriceps femoris strength of the subjects was evaluated according to the procedures described by Richard and Currier.[32] During testing, the subject's hip was maintained at 120° extension and the knee positioned at 60° flexion. An ankle cuff was affixed and attached to the cable tensiometer. The other end of the tensiometer was anchored to the base of the testing table. The peak isometric force (kgf) was recorded when the subject exerts maximum effort during knee extension following the command "pull." Both right and left limbs were evaluated at the different time frames. For each limb, three trials were made, but the highest reading was recorded. A minimum of three minutes' rest was allowed between each trial. At regular intervals during the study, the output of the cable tensiometer was calibrated against standard known weights.

Data Analysis

For each subject, the average maximum tolerable voltage for each week was computed to track the pattern of subjects' acceptance of the HVGS. Similarly, the average of the muscle soreness ratings for each week was obtained.

A two-factor (groups and time frames), repeated measure's analysis of variance (ANOVA) was used to determine significant differences in the voltage output and muscle soreness rating data; and a three-factor (groups, limbs, and time frames) repeated measures ANOVA was used to determine significant differences in the quadriceps strength data. When significant *F* ratios were found in the ANOVA, the specific differences among the group means were further probed with the Scheffe' post hoc test. The Scheffe mean group comparison test uses the *F*-sampling distribution and, similar to the ANOVA, is robust concerning nonnormality and heterogeneity of variance.[33] The level of significance was fixed at .05 α level. The statistical analysis was performed on a Macintosh Plus[b] microcomputer using the StatView 512+ program.[c]

RESULTS

The result of the two factors ANOVA for voltage tolerance showed no significant *F*-ratio among groups ($F = 0.51$; $p > .6077$) or for groups × time frame's interaction effect ($F = 0.22$; $p > .9942$) but significant main effect was found for time frames ($F = 110.32$; $p < .0001$). During training, the maximum voltage tolerance for the three pulse frequencies increased until the fourth week, after which it plateaued (fig 1). The result of the Scheffe' post hoc analysis for the time frames data (table 2) indicated that the subjects were able to tolerate more electrical stimuli as the training progressed; but after the fourth week of training the subjects' showed no further increase. When compared to baseline data (week 1), the voltage tolerance of the subjects increased by 55% at the end of the training.

The two factors ANOVA for the muscle soreness ratings data did not show significant *F*-ratio for groups ($F = 1.07$; $p > .3573$) or time frames ($F = 1.63$; $p > .1552$). Similarly, the groups × time frame interaction effect was not statistically significant ($F = 0.59$; $p > .8185$). The above findings suggest that muscle soreness rating by the three groups are similar during the duration of the study (fig 2).

The result of the three factors for ANOVA the knee extensor isometric force measurements are presented in table 3. The group's main effect is not statistically significant ($F = 1.79$; $p > .1771$). That is, the effect of the three pulse frequencies on muscle strength is comparable (fig 3). However, significant *F*-ratio was found for limbs ($F = 12.24$; $p < .0009$). The limbs × time frame interaction effect is plotted in figure 4. The result of the Scheffe' post hoc analysis (table 4) revealed that before training, the knee extensor

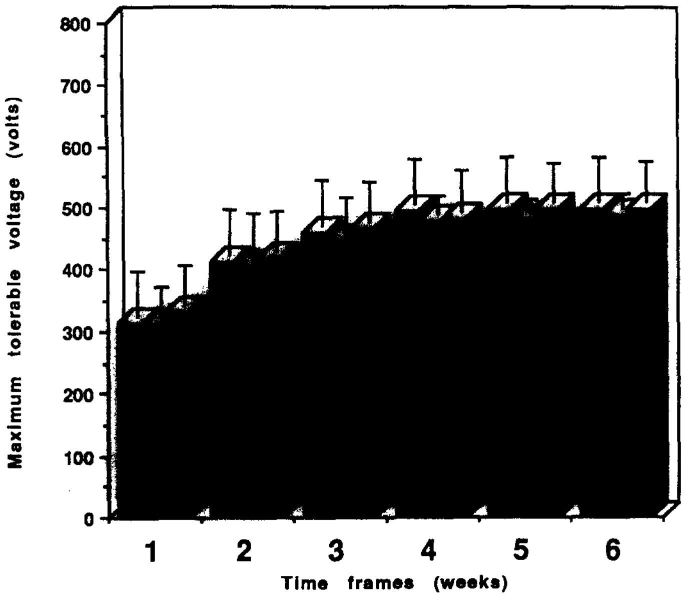

Fig 1—Mean voltage tolerance at the end of each week of training. Error bars are standard deviations. ■, 20pps; ▨, 45pps; □, 80pps.

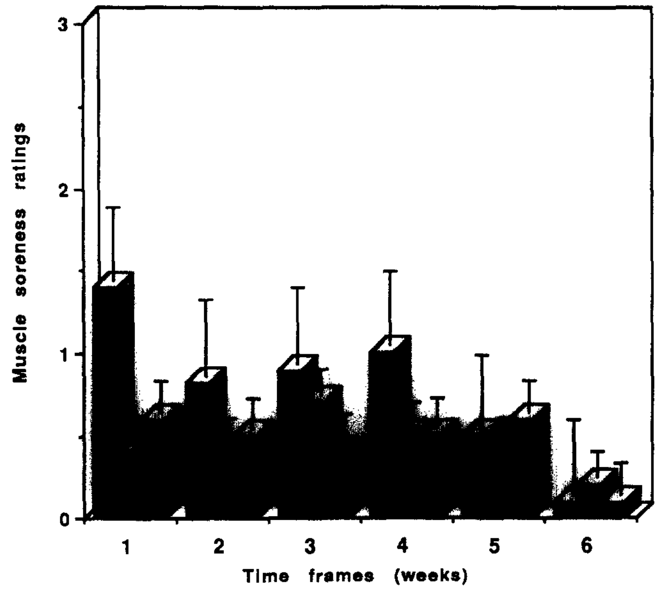

Fig 2—Mean muscle soreness ratings at the end of each week. Error bars are standard deviations. ■, 20pps; ▨, 45pps; □, 80pps.

isometric force of both lower limbs are similar ($p > .05$); however, at the end of the second, fourth, and sixth weeks of NMES, the right lower limb became stronger ($p < .05$) than the left limb. Three weeks following cessation of NMES, the right limb was still stronger ($p < .05$) than the left limb. At the end of the 6 weeks of NMES, the right and left quadriceps femoris strength increased by 24% and 10%, respectively.

DISCUSSION

The primary objective of this study was to evaluate the relative effectiveness of pulse frequencies commonly recommended by clinicians for muscle strengthening. We found, contrary to our hypothesis, that none of the three (20pps, 45pps, 80pps) pulse frequencies that we included in our design offered an apparent advantage in terms of muscle strength gained. Our findings may be due to the narrow range of pulse frequency that we selected.

Although we did not monitor the torque-generating capacity of our stimulator, other investigators have found electrical stimulation to be capable of producing force equal to 30% to 35% of the maximal voluntary contraction,[10,19] or force equal to the maximum voluntary contraction.[34] From the existing literature, it appears that the torque produced during NMES is determined by the pulse parameters (wave forms, pulse duration, and pulse rate) of the stimulator and method of electrode arrangement.[18] In the present study, we obtained significant increase in muscle strength following 6 weeks of NMES; the strength gained was still retained 3 weeks following cessation of training. The 24% increase in the right quadriceps strength corroborates the result of majority of studies using electrical stimulation to augment muscle strength (table 5), but it is discordant with studies that showed that electrical stimulation is not capable of increasing strength in normal innervated muscles.[17-19] The mechanism by which electrical stim-

Table 2: Summary of the Scheffé Post Hoc Analysis for Voltage Tolerance

Contrasts	Mean Difference	Scheffé *F*-test*
Week 1 vs Week 2	−94.4	22.0*
Week 1 vs Week 3	−139.3	48.0*
Week 1 vs Week 4	−166.6	68.5*
Week 1 vs Week 5	−173.4	74.3*
Week 1 vs Week 6	−177.6	77.9*
Week 2 vs Week 3	−44.9	5.0*
Week 2 vs Week 4	−72.1	12.9*
Week 2 vs Week 5	−79.0	15.4*
Week 2 vs Week 6	−83.1	17.1*
Week 3 vs Week 5	−34.1	2.9*
Week 3 vs Week 6	−38.2	3.6*
Week 3 vs Week 4	−27.2	1.8†
Week 4 vs Week 5	−6.8	0.1†
Week 4 vs Week 6	−11.0	0.3†
Week 5 vs Week 6	−4.2	0.0†

* Statistically significant at 0.05 α level.
† Not significant.

Table 3: Summary of the Three-Factor Repeated Measures ANOVA for Quadriceps Isometric Force

Source	*df*	Sum of Squares	Mean Squares	*F*-ratio	*p* value
Groups (A)	2	1186.7	593.4	1.788	0.1771
Limbs (B)	1	4062.7	4062.7	12.240	0.0009
A × B	2	265.9	132.9	0.401	0.672
Subjects within groups	54	17923.0	331.9		
Time frames (C)	4	4369.1	1092.3	78.110	0.001
A × C	8	157.0	19.6	1.404	0.1962
B × C	4	562.4	140.6	10.056	0.0001
A × B × C	8	43.7	5.5	0.39	0.925
C × subjects within groups	216	3020.2	14.0		

Abbreviation: *df* = degree of freedom.

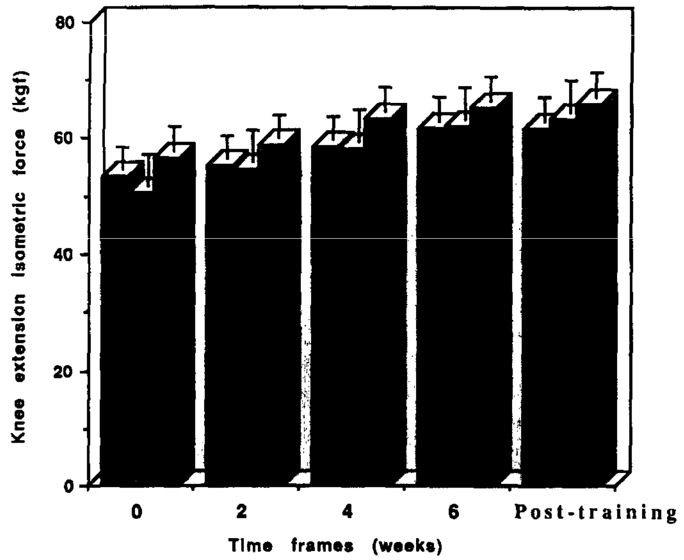

Fig 3—Influence of pulse frequency on quadriceps femoris strength. Error bars are standard deviations. ■, 20pps; ▨, 45pps; □, 80pps.

ulation operates to produce increase in muscle strength is still not well understood, but two major theories have been proposed.[35,36] The first theory suggests that electrical stimulation improves muscle strength in the same way as active exercise by substantially increasing the muscle functional load. The second theory proposed that electrical stimulation augments muscle strength because it targets and trains the type II muscle fiber more effectively than does active exercise.

In our study, the left quadriceps femoris muscles of the subjects were not stimulated directly, yet we obtained a significant (10%) increase in the left knee extensor strength at the end of the 6 weeks training. This paradoxical finding would argue against increased functional load as the underlying mechanism through which electrical stimulation promotes muscle strength but supports the second theory of preferential recruitment of the type II muscle fiber. We attributed the increase in left quadriceps strength to a combination of factors, such as crossover effect[37] and motor learning due to repeated testing.[38] We used nondisabled subjects with intact motor innervation; therefore, there might have been an overflow of excitation to the left extremity during electrical stimulation; thus, leading to subconscious contraction of the muscles. According to Shaver,[37] crossover phenomenon is caused by diffusion of motor impulses from the 70% to 85% of contralateral descending nerve fibers of the pyramidal system to the remaining 15% to 30% of the ipsilateral descending nerve fibers.

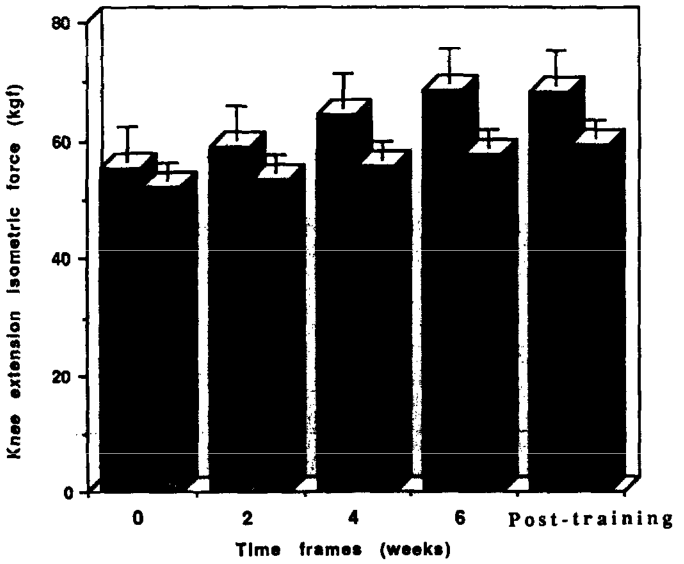

Fig 4—Changes in quadriceps femoris muscles strength with training. Error bars are standard deviations. ■, right limb; ▨, left limb.

Table 4: Summary of the Scheffé Post hoc Analysis for Quadriceps Isometric Force

	Right Limb		Left Limb			
Time Frames	Mean	SD	Mean	SD	Mean Difference	Scheffé *F*-value*
Pretraining	55.3	8.0	52.4	7.9	2.9	2.057
Week 2	59.1	7.7	53.5	8.4	5.7	7.350*
Week 4	64.4	9.4	55.9	9.9	8.5	11.601*
Week 6	68.4	9.4	57.7	9.1	10.7	19.937*
Posttraining	68.2	9.2	59.2	9.1	9.0	14.876*

Abbreviation: SD, standard deviation.
* Statistically significant at 0.05 α level.
† Not significant ($p > .05$).

Contrary to our expectation, we found that pulse frequency has no effect on the maximum voltage tolerance and delayed muscle soreness. Our subjects initially found the electrical stimuli uncomfortable, but with repeated application, they adjusted (ie, become accommodated) to the stimulation and tolerated greater current intensities as training progressed (fig 1). The response to the electrical stimuli over time (fig 1), seems to parallel the gain in muscle strength (fig 3). For example, both voltage tolerance and gain in muscle strength peaked at the end of the fourth week of training. In this study, we monitored voltage tolerance instead of current tolerance because an ammeter is not available on the HVGS that we used. Because it is the current and not the voltage that brings the nerve to threshold, our findings on the subjects' adjustment to electrical stimulation must be interpreted with caution.

During the first week of training, the muscle soreness experienced by subjects in the 20pps group appeared higher than the other (45pps, 80pps) stimulating groups (fig 2). Because of the wide variability between subjects, the above observed trend is however, not statistically significant. It is possible that the use of a sensitive instrument, such as pressure algometer,[39] in the assessment of soreness may have revealed significant difference between groups. Further study is needed to support our speculation.

Clinical Implication

We found the high-voltage electro-galvanic stimulator and the protocol used in this study effective in augmenting strength of normal innervated muscles. However, none of the three pulse frequencies evaluated offered any apparent

Table 5: Findings of Previous Studies on the Effects of Electrical Stimulation and Active Exercise on Muscle Strength

Authors	Duration of Study (weeks)	Number of Treatment Sessions	Strength Gain With NMES	Strength Gain With Active Exercise	Pulse Wave Form/ Pulse Frequency
Currier et al (1979)	2	10	21%*	19%†	Square wave, 25pps
Erikson et al (1981)	5	5	16%	27%†	Square wave, 200pps
Romero et al (1982)	5	10	21%	—	Faradic, 2,000pps
Halbach & Straus (1982)	3	15	22%	42%‡	Half wave, 50pps
Currier and Mann (1983)	5	15	25%*	30%†	Sine wave, 2,500pps
McMiken et al (1983)	3	12	22%	25%†	Square wave, 75pps
Laughman et al (1983)	5	25	22%	18%†	Sinusoidal, 2,500pps
Mohr et al (1985)	5	15	0.7%	14.7%†	Twin peak, 50pps
Present study	6	18	24%	—	Monophasic, 20 to 80pps

* NMES combined with static isometric exercise.
† Isometric exercise training.
‡ Isokinetic exercise training.

advantage in terms of muscle strength gained or preferential acceptance of the stimuli. The above findings may not be directly applied to patient populations because we used only young healthy subjects in our design. Follow-up studies should be undertaken using patients with musculoskeletal injuries affecting the lower extremities. Our present findings suggest that NMES may be useful in the rehabilitation of patients where active exercise is not feasible due to protective pain, immobilization, or weakness of the affected muscles.

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Suppliers

a. ElectroMed Health Industries, 11601 Biscayne Boulevard, Miami, FL 33181.
b. Apple Computer Incorporated, 20525 Mariani Avenue, Cupertino, CA 95014.
c. Brain Power Incorporated, 24009 Ventura Boulevard, Suite 250 Calabasas, CA 91302.