0363-5465/86/1401-0018$02.00/0
THE AMERICAN JOURNAL OF SPORTS MEDICINE, Vol. 14, No. 1

The effect of muscle stimulation during resistive training on performance parameters*

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ABSTRACT

This study compared changes in movement velocity, force, and work from bilateral quadriceps muscle stimulation during resistive squatting exercise to identical exercise without stimulation. Both the group undergoing resistive training over 24 sessions ($N = 9$) and the group receiving the same treatment in conjunction with stimulation during the last 12 sessions ($N = 9$) showed significant improvements in measures of movement velocity, force, total work, power, sprint time, and vertical jump distance when compared to a control group receiving no treatment ($N = 9$). All subjects were baseline tested and tested at 3, 6, and 7 week intervals. Both experimental groups improved significantly for all measures, but the electrical stimulation group did not produce more significant changes overall than those with resistive training alone. However, when compared to control measures, the effect of electrical stimulation-augmented responses among some measures was more pronounced than the effect of resistive training alone.

Within the past decade considerable interest has developed in the use of muscle stimulation to either restore function or enhance performance. For the most part, faradic current applied to the quadriceps muscle group following knee ligament surgery[5,8] or among patients with chondromalacia patallae[6] has produced improvement in isokinetic or isometric knee extension strength. This type of stimulation applied to normal quadriceps muscle has produced equivocal results. Some investigators[2,3,12,16] indicate that electrical stimulation can improve isometric strength significantly beyond changes observed in control groups, yet these findings have not been observed by others.[13]

While differences in electrode location, stimulating parameters, and training schedules could account for some of the discrepancies observed, these diverse results are nevertheless somewhat disconcerting in light of much publicized claims by Kots[10] that stimulation delivering modulated and interrupted sinusoidal currents at a medium frequency of 1600 to 2500 cycles per second, can produce remarkable and prolonged changes in muscle strength, provided maximal muscle tetany without induction of pain is achieved. At least one attempt to replicate these claims has been unsuccessful.[9] Taken in perspective, research has indicated that electrical muscle stimulation alone is no more effective than traditional exercise programs.[13]

At the same time, the work of Currier et al.[2] is of particular interest because normal subjects attempted maximal voluntary isometric contractions during superimposed low frequency faradic stimulation of the quadriceps muscle. In that study the group receiving electrical stimulation with isometric training showed a 21% increase in knee extension torque compared to a 19% improvement among subjects simply undergoing isometric exercise alone. Although the Currier study[2] used stimulation during isolated joint movements in a comparatively static sitting posture, stimulation with dynamic movement would be more directly relevant to sports. Such an approach might be more compatible with the overall motor program used by an athlete to enhance performance. For example, electrical stimulation to the quadriceps during squat exercises performed against specific loads might ultimately affect vertical displacement, a dynamic activity of importance to high jumpers or volleyball players.

We have attempted to determine whether bilateral maximal quadriceps stimulation during dynamic squat exercises against resistive loads enhances strength or velocity meas-

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* Presented at the 1984 American College of Sports Medicine Annual Meeting, May 25, 1984, San Diego, California.
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ures of movement or other important performance characteristics such as sprint speed or vertical displacement.

METHODS

Subjects

Twenty-seven men gave their informed consent to participate in this study. All were high performance athletes (professional tennis instructors) or men who participated regularly in recreational sports. Subjects were randomly assigned to three groups of nine. Group E (age range, 34 to 52 years; mean age, 41.7; SD, 6.78) received only the resistive training. Group E/S (age range, 26 to 37 years; mean age, 33.2; SD, 3.87) received electrical stimulation with the training. Group C (age range, 24 to 44 years; mean age, 35.8; SD, 6.24) served as the control group, with each subject continuing his normal prestudy regimen. Subjects in all groups underwent testing at the same time intervals: baseline (Time 1); after 3 weeks (Time 2); after 6 weeks (Time 3); and after 7 weeks (Time 4). Groups E and E/S received 12 training sessions between Times 1 and 2 and another 12 training sessions between Times 2 and 3. Test measures taken at Time 4 constituted a 1 week followup to cessation of treatments. This follow-up testing was included to determine whether performance measures change after cessation of exercise or exercise/stimulation treatments. Members of groups E and E/S underwent identical training protocols at specified times on Monday, Tuesday, Thursday, and Friday for 4 weeks. During training sessions 13 to 24 (Weeks 4 through 6) Group E/S received bilateral quadriceps stimulation with each resistive exercise movement.

Electrical stimulation

Muscle stimulation was achieved through bipolar, flexible rubber electrodes placed on each quadriceps muscle. Maximal muscle response was usually achieved with electrodes placed over the midbelly of the rectus femoris and near the insertion of the vastus medialis. Constant current was provided from a battery operated dual channel programmable stimulator (EMPI, Inc., Fridley, MN). Current was delivered in modified monophasic rectangular pulses at 75 Hz, a frequency found comfortable by most subjects. The equipment has variable voltage with peak amplitude up to 62 mA in monophasic mode. Rise time of the "on" phase of current was virtually instantaneous with activation of the unit, which was programmed to stimulate throughout the duration of dynamic movement.

Each subject in the E/S group individually set the amplitude of the electrical stimulation to the maximal tolerable amount before beginning each set. The stimulation was applied during the pressing phase of the squat and increased before each exercise if the subject had accommodated to the intensity used during the previous set.

Resistive training

All testing and training sessions were performed using the Ariel 4000 computerized exercise machine (CEM; Computerized Biomechanical Analysis, Inc., Amherst, MA). The CEM system incorporates a closed-loop mechanism allowing real time feedback control of force, speed, and bar displacement based on the unique characteristics of the individual. The processor unit provides resistance at the bar by controlling the flow rate in the hydraulic mechanism which maintains bar speed and resistance. The CEM is capable of monitoring speeds at varying resistance levels or resistance at different velocity patterns. Results can be reported in English or metric units. For this study, speed is reported in degrees per second, force in pounds, and power in foot-pounds per second. The CEM can also control the amount of work performed and indicates the fatigue level reached by the involved muscle group(s).

During training the CEM was programmed to control different speed settings for five sets of squat. The exercise mechanism used in this study provides positive resistance during the concentric contraction phase of the squatting motion. Resistance is set to match the individual effort at a predetermined controlled speed throughout the range of motion. The squat exercise format required subjects to begin in a sitting position and raise resistive loads placed at the shoulders as knees and hips were actively extended. All five sets were programmed to allow a maximum of 5000 foot-pounds of work at each set in the following manner:

Set 1—The exercise bar was restricted to move at a maximum speed of 75 deg/sec along an arc of the exercise bar which is 56 inches in length.

Set 2—The speed of movement was set for a linear deceleration from 50 to 10 deg/sec.

Set 3—The speed of movement was set for a linear acceleration from 25 to 75 deg/sec.

Sets 4 and 5—The movement was restricted to 35 deg/sec.

During testing the CEM was programmed to measure three basic functions: bar speed, force, and work. Bar speed was measured under three different settings of constant resistance: 2.2 kg, 20% of an individual's maximal force for 1 repetition (1RM) and 40% of the individual's 1RM, respectively. The force (strength) was measured under three different speed settings. One measurement, 75 deg/sec, was the average maximal speed of the subjects when tested for speed with no resistance at the bar. The setting of 25 to 75 deg/sec in a linear increment was representative of subjects' acceleration during the speed test with no resistance at the bar, and 15 deg/sec was the average starting speed of the subjects tested. The endurance test was set to measure the amount of work performed during 1 minute of maximal effort at a bar speed of 35 deg/sec.

Test parameters

All subjects underwent the same test protocol. During testing, individuals in Group E/S were not stimulated. Eighteen measurements were made during testing sessions:

FR15avg—The greatest average force (pounds) measured throughout the range of motion over six repetitions at a constant bar speed of 15 deg/sec.

FR15max—The greatest peak force measured at a specific point throughout the range of motion over six repetitions at a constant bar speed of 15 deg/sec.

FR75avg—The greatest average force measured throughout the range of motion over six repetitions at a constant bar speed of 75 deg/sec.

FR75max—The greatest peak force measured at a specific point throughout the range of motion over six repetitions at a constant bar speed of 75 deg/sec.

FR25avg—The greatest average force measured throughout the range of motion over six repetitions with the exercise bar accelerating linearly from 25 to 75 deg/sec.

FR25max—The greatest peak force measured throughout the range of motion over six repetitions at a linear acceleration from 25 to 75 deg/sec.

SP5avg—The greatest average velocity measured throughout the range of motion over six repetitions with constant resistance set at 2.2 kg.

SP5max—The greatest peak velocity within the range of motion over six repetitions with constant resistance set at 2.2 kg.

SP20avg—The greatest average velocity measured throughout the range of motion over six repetitions with constant resistance set at 20% of FR15avg.

SP20max—The greatest peak velocity measured at a specific point throughout the range of motion over six repetitions with constant resistance set at 20% of FR15avg.

SP40avg—The greatest average velocity measured throughout the range of motion over six repetitions with constant resistance set at 40% of FR15avg.

SP40max—The greatest peak velocity measured at a specific point throughout the range of motion over six repetitions with constant resistance set at 40% of FR15avg.

Work—The total amount of work (foot-pounds) performed during 60 seconds of squat exercise at a constant bar speed of 35 deg/sec.

Reps—The total number of repetitions performed during 60 seconds of squat exercise at a constant bar speed of 35 deg/sec.

Power—The average work (foot-pounds) performed for each repetition (WORK/REPS).

Fatigue—The muscular fatigue level reached at the last repetition expressed as the ratio (%) between the average force of the last repetition over the highest average force attained during 60 seconds of work.

Sprint—The best time (seconds) measured for a 25 yard dash (three trials).

Jump—The best vertical jump (centimeters) measured as the vertical height difference between maximal standing reach and maximal jumping reach for three attempts.

The vertical jump ability was measured with the Vertax, which incorporates a set of horizontal bars spaced at 0.5 inch intervals for 2 feet. The lower edge of the bars is adjusted to the subject's maximum reach and this point is used as a zero reference point.

Each subject performed a 75 foot sprint on a synthetic surface running track. Time was measured manually to the nearest 0.01 sec with a quartz stop watch. All measurements were made by the same investigator.

Statistical analysis

A two-factor analysis of variance model with repeated measures on one factor was used for each response variable.[4] The Bonferroni multiple comparison procedure was used to determine where significant differences within groups (Table 1) and between groups (Table 2) relative to baseline occurred. A preset statistical significance level of 0.05 was established.

RESULTS

Table 1 shows all data for which within group significant improvements were observed during or after training compared to baseline (Time 1). These data are represented by dots. Rarely did Group C show changes when compared to either experimental group (C versus E, C versus E/S). Both Group E and Group E/S made significant increases in velocity, force, power, work, and displacement, and a significant reduction in sprint time measures when compared to Group C (E versus C, E/S versus C), or to one another (E versus E/S, E/S versus E). The symbol ">" indicates a significant increase between Times 2 and 3 or 3 and 4, except for sprint time where a significant reduction in time occurred between Times 2 and 3, E versus C. Thus, Group E/S showed a significant increase in power production after 12 sessions of electrical stimulation (E/S versus E, Time 3 versus Time 2) when compared to changes at the same time interval for Group E (E versus E/S). Group E/S also showed a significant increase in the number of repetitions (reps) to complete the squat exercise against a constant bar speed of 35 deg/sec attained at followup (Time 4) when compared to baseline (dot at Time 4, E/S versus E). Such an increase was not maintained by Group E (no dot at Time 4, E versus E/S).

Data in Table 2 examine between-group changes from baseline measures and use the same symbols as in Table 1. Both Groups E and E/S showed substantial improvements in most measurements from baseline compared to the amount of change occurring in Group C. Compared to Group C, Group E/S also produced significantly faster velocity (SP5avg, SP5max, SP20avg, SP20max, SP40avg) and more repetitions between Times 2 and 3.

Group E/S underwent significantly greater improvement

TABLE 1
Within group comparison among test variables for significant changes ($P < 0.05$) from baseline and between test times

Variable (Time:)	E vs C			C vs E			E/S vs C			C vs E/S			E vs E/S			E/S vs E		
	2	3	4	2	3	4	2	3	4	2	3	4	2	3	4	2	3	4
SP5avg	.	>.	>.	.			.	>.	.	.			.	.	.	.	.	.
SP5max	.	.	.	.	.		.	.	.	.	.		.	.	.	.	.	.
SP20avg	.	.	.			.	.	.	.				.	.	.	.	.	.
SO20max	.	.	.				.	.	.				.	.	.	.	.	.
SP40avg		.	.				.	.	.					.	.			.
SP40max		.	.											.	.			
FR15avg		>.	.					>.	.				.	>.	.	.	>.	.
FR15max		>.	.					>.	.						.			
FR75avg	.	>.	.				.	>.	.				.	>.	.	.	>.	.
FR75max	.	>.	.				.	.	.					.	.	.	.	.
FR25avg		>.	.				.	>.	.					.	.	.	.	.
FR25max		>.	.				.	>.	.					>.	.	.	>.	.
No. Reps	.	.					.	.	.					.			.	.
Power	.	.	.				.	>.	.				.	.	.	.	>.	.
Jump	.	>.	.				.	>.	.				.	.	.	.	.	.
Sprint[a]	.	>.	.				.	.	.				.	.	.	.	.	.
Work	.	>.	.				.	.	.				.	.	.	.	.	.

[a] Sprint variable indicates significant *reductions* in sprint time.

TABLE 2
Between group comparisons among test variables for significant changes ($P < 0.05$) from baseline and between test times

Variable (Time:)	E vs C			E/S vs C			E/S vs E		
	2	3	4	2	3	4	2	3	4
SP5avg	.	.	.	.	>.	.			
SP5max		.	.		>.	.			
SP20avg		.	.	.	>.	.			
SP20max		.	.		>.	.			
SP40avg			.		>	.			
FR15avg		.	.		.	.			
FR15max		.	.			.			
FR75avg		.	.	.	.	.	.		
FR75max		.	.	.	.	.			
FR25avg		.	.	.	.	.	.	.	.
FR25max		.	.		.	.	.		
No. Reps				.	>.	.			
Power	.	.	.	.	.	.			
Jump	.	.	.	.	.	.			
Sprint[a]	.	.	.	.	.	.			
Work	.	.	.	.	.	.			

[a] Sprint variable indicates significant *reduction* in sprint time.

than did Group E in force produced through a linear acceleration from 25 to 75 deg/sec (FR25avg) during squat movements at each testing interval compared to baseline (E/S versus E). These differences are visually depicted in Figure 1. Groups E and E/S showed parallel improvements in reduced sprint time, increased vertical displacement, and work and power production (Fig. 2). Only the mean difference between baseline and the 3 week test (Times 1 and 2) for work production was significantly different (Group E/S, $P < 0.05$). For all other measures shown in Figure 2, Group E/S showed greater mean changes over time than did Group E, when differences from baseline to any other test time were compared, but these were not statistically significant ($P > 0.05$).

DISCUSSION

The results from this experiment suggest that a specific resistive exercise program with electrical stimulation or a resistive exercise program alone are equally effective in producing strength changes under variable velocity loads or in improving other functional measures such as sprint time, vertical jump height, or power and work production. For most test measures, however, the group receiving electrical stimulation had greater baseline values and showed more substantial, but statistically insignificant, absolute changes over time. These greater baseline values and changes with treatment among Group E/S members were probably not primarily due to fiber composition alterations with exercise and electrical stimulation, although no attempt was made to

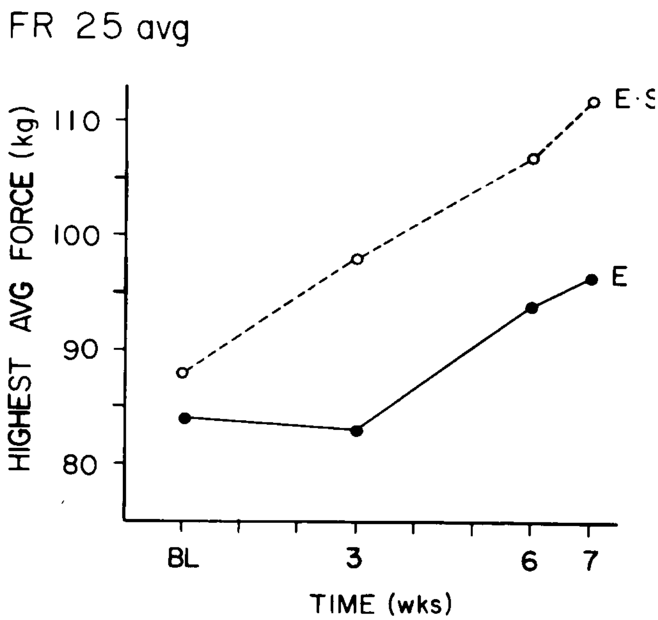

Figure 1. Mean changes in variable FR25avg from baseline to each test session for Group E and Group E/S. Times: 3, 6, and 7 weeks correspond to test sessions 2, 3, and 4, respectively.

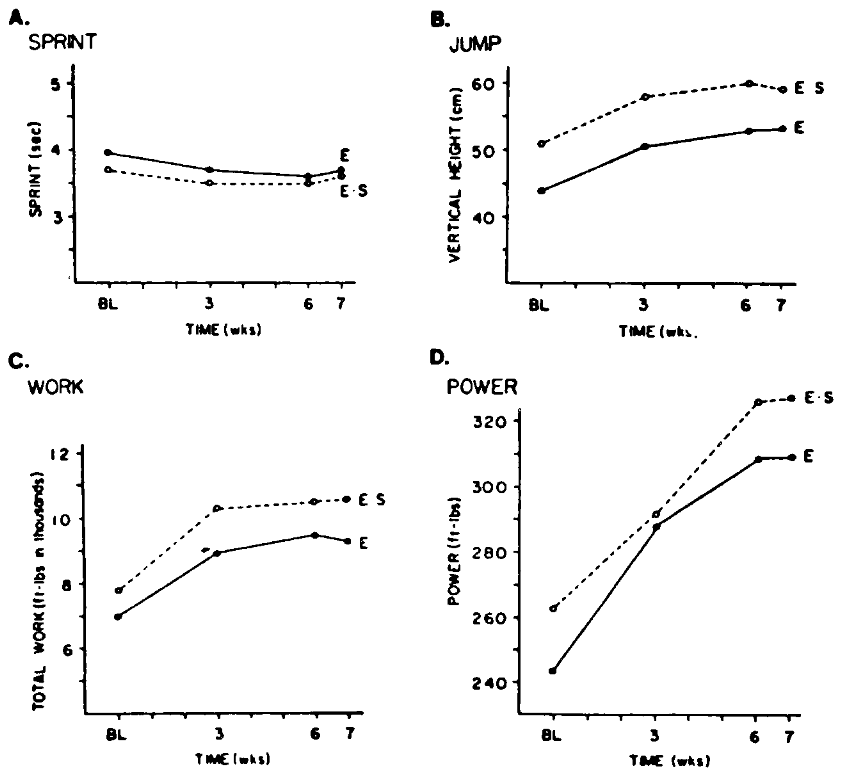

Figure 2. Parallel changes in sprint time (A), vertical displacement (B), work (C), and power production expressed as foot-pounds (D) based upon differences between groups from baseline to each test session. Times: 3, 6, and 7 weeks correspond to test sessions 2, 3, and 4, respectively.

examine quadricep fiber type composition among these subjects. Thus far, accumulating evidence[14,15] indicates little correlation between strength changes and percentage of muscle area occupied by different fiber types within the quadriceps femoris muscle mass.

The age factor among our subjects may be an important consideration to account for changes with training intervention. Larsson's study[11] found that isometric and dynamic strength increases through ages 20 to 29 and levels out through age 50, after which a decline occurs. As a result of random assignment, Group E/S was generally younger than Groups E and C. Whether initial or subsequent test measure improvements in Group E/S might be due to age differences cannot be clearly ascertained. This factor may be a consideration because the E/S-E group comparisons from baseline to Time 2 (12 training sessions, before application of electrical stimulation) showed significant improvements among variables FR75max, FR25avg, FR25max, and work for Group E/S (Table 2).

Group E/S produced significantly greater changes from baseline in variable FR25avg at all subsequent test times than did Group E. This test was set to measure force exerted under acceleration conditions from low (25 deg/sec) to high (75 deg/sec) speed. The principle for training in variable speed mode is that the resistance applied by the subject is greater under the conditions in which the subject is capable of exceeding the speed set up by the machine. Thus, the subject who is capable of exceeding the machine speed will generate more resistance than a subject who is slower and cannot attain the same velocities.

A key measurement relevant to performance was vertical jump. Both Groups E and E/S improved significantly compared to Group C. Electrical stimulation did not appear to contribute to these improvements.

A common observation within Group E/S was a complaint of fatigue during stimulation; yet at testing Time 3, in the absence of stimulation, and at followup (Time 4), Group E/S members would inevitably perform better than at the prestimulation test sessions (baseline, Time 1) and without subjective complaints of fatigue. The occurrence of decremental responses with stimulation or under conditions of prolonged isometric contractions has been attributed to central fatigue wherein motoneurons may become substantially depolarized to the point of reduced discharge.[1,7] Central fatigue may account for Group E/S members' feelings of decreasing strength during training with maximal stimulation. This should be examined in subsequent studies by quantifying changes in electromyographic activity during stimulation intervals under the different resistive training situations. On the other hand repeated electrical stimulation in the presence of resistive exercise may potentiate motoneuronal responses to subsequent voluntary efforts or cause adaptive responses within afferents or internuncial spinal neurons. In fact, enhanced motoneuronal activity has been reported during upper extremity strength training.[17]

From a statistical perspective the administration of electrical stimulation during dynamic resistive training did not produce any significant performance changes above those attributable to the resistive training alone. It must be remembered that this study represents only an initial attempt at examining electrical stimulation under voluntary efforts at different loads. Further study appears warranted, repeating these trials using different stimulation parameters and with a surging current that builds as each voluntary effort increases throughout a movement rather than provision of an instantaneous peak current. Equalizing age representation among group members, increasing the number of training sessions with stimulation among athletes with varying skill levels, or assigning group members based upon quantification of specific skills may produce even more substantial and prolonged improvement in performance.

ACKNOWLEDGMENTS

We thank Michael H. Kutner, PhD, Biometry Department, Emory University School of Medicine, Atlanta, Georgia, for his assistance with data analyses. The loan of a programmable dual channel muscle stimulator from EMPI, Inc., is gratefully appreciated. The work presented herein was supported by a grant from the United States Olympic Committee.

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COMMENTARY

William A. Grana, MD, *Oklahoma City, Oklahoma:* It is intriguing to think that electrical stimulation of muscles could improve the effect of resistive exercise training. Eventually we may have information that affirms or negates this concept. This study does neither, but it is very nicely done. The authors are to be commended for their testing methods. I am sorry that they did not take more care with the ages of the subjects so that the groups were more homogeneous. It is also unfortunate that there were not more subjects in each group, which would have lent more credibility to statistical analysis.

Even if this study had documented that electrical stimulation enhanced resistive exercise training, it would remain to be seen what those laboratory results mean for an athlete's performance and function. There is a big difference between the parameters measured in this study and on-the-field performance. There are so many more variables that we may find it much more difficult to confirm that electrical stimulation has any effect at all on athletic performance.

In addition, the people participating in this study knew who was being stimulated and who was not; therefore, there is enormous potential for placebo effect, which I feel is an enormous potential problem. The athlete's psychological benefit from receiving a treatment which the athlete knows the investigator feels may help him could certainly alter the results in these tests. I have yet to see an isokinetic testing device that could not be fooled.

My bias is that there is a limiting factor to the effects of electrical stimulation. It is determined by the unique physiology of muscle as an excitable tissue. The depolarization-repolarization process takes time and muscles must be used in phase with the electrical stimulation that is occurring; otherwise, electrical stimulation could perhaps interfere with the effects of resistive exercise training.

Obviously none of the things I have said are proven, but then the authors have not proven their thesis either. I think that this is an area where more work needs to be done using block "blinded" control and experimental groups.