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Comparison of the Effects of Electrical Stimulation and Exercise on Abdominal Musculature

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The purpose of this study was to test the effect of electrical stimulation and volitional exercise on abdominal muscle strength and endurance. Changes of voltage, current, and tissue resistance were analyzed to determine tissue conditioning to stimulation. Subjects were randomly assigned to a control, stimulation (S), volitional exercise, or exercise combined with stimulation (ES) groups. Maximal voluntary isometric contraction and endurance data were recorded. In the three experimental groups, the number of repetitions and time of sustained contraction were increased by a predetermined amount during 4 weeks of training. The S and ES groups were stimulated using a biphasic, symmetrical pulse waveform having 200 microsec phase duration and 50 pulses per second. The ES group demonstrated the largest significant increases in abdominal strength, while the S group was the second best mode. No significant change in endurance occurred among the groups. Voltage and current increased significantly whereas tissue resistance decreased. It was concluded that combined exercise and stimulation may prove to be the most effective method of improving abdominal strength.

Retardation of disuse atrophy or recovery of muscle strength following trauma or disease is a major goal of orthopaedic rehabilitation. Electrical stimulation has been found to retard atrophy of the quadriceps femoris muscle in patients recovering from knee ligament surgery[4, 17] and enhance strength gain in patients with chondromalacia patellae.[12] Eriksson and Haggmark[4] found that muscle re-education programs based on electrical stimulation superimposed on volitional isometric contractions minimized muscle atrophy and facilitated succinate dehydrogenase activity. The training protocol consisted of 360 daily repetitions of intermittent tetanic contractions of the quadriceps muscle. Each contraction lasted for 5 sec, followed by a rest period of 5 sec. The patients trained for 1 hour/day, 5 days a week, for a period of 4 weeks. A similar protocol consisting of 400 contractions spread over 16 hours/day for a 2-week period was used by Gould et al.[8, 9] and the results were in agreement with Eriksson's findings.

In muscles functioning at normal levels of strength, electrical stimulation has been shown to further enhance contractile strength. Currier and Mann[3] tested three experimental groups consisting of electrical stimulation alone, electrical stimulation superimposed on volitional exercise, and volitional isometric exercise and compared all three to a control group. The training protocol consisted of only 10 intermittent tetanic contractions of the quadriceps femoris muscle which lasted for 15 sec, followed by a 50-sec rest period. The subjects trained 3 days a week for a period of 5 weeks. All three experimental groups had gained significant strength compared to the control group; however, no significant differences were found between the experimental groups at the conclusion of training.[3]

Numerous other investigators used different protocols, and a wide range of electrical stimulation waveforms, phase durations, and pulse rates, as well as different contraction-relaxation ratios. Despite the variance, most studies performed on muscles functioning at normal levels of strength resulted in similar strength gains.[2, 5, 10, 11, 14, 16, 19, 20] Except for Currier and Mann's study[3] no other

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report was found which examined all three possible combinations of exercise and electrical stimulation, therefore making determination of the most effective therapeutic approach to muscle reeducation difficult to discern. Furthermore, most recent electrical stimulation studies have only examined the response of the quadriceps femoris muscle thereby limiting inferences to this muscle group. In particular, inference may not be extended to the abdominal musculature. These muscles cross multiple joints and function to move and stabilize the trunk with concomitant support to internal organs and breathing patterns. Furthermore, it has been postulated that the abdominal musculature should be considered disused and atrophied in most healthy subjects due to the sedentary western lifestyle.[13] Only one study was found where abdominal musculature responded favorably to electrical stimulation.[11] The investigators did not compare the electrical stimulation effects to a control group or any other mode of abdominal muscle strengthening. Recently, Aikman et al.[1] reported that electrical stimulation of the abdominals over 4 weeks of training did not result in strength gain compared to a control group.

Repetitive electrical stimulation over several weeks of training may not only alter the effectiveness of muscle contraction but also the response of noncontractile tissue. Several studies reported that subjects required more current output as training progressed.[3,5,10,14,20] No study could be found where quantification of the changes in electrical stimulation variables were documented.

The purpose of this investigation was to examine the effectiveness of electrical stimulation, volitional exercise, and electrical stimulation superimposed on volitional exercise on the abdominal musculature with respect to muscle strength and endurance. In addition, voltage, current, and tissue resistance were measured to determine if changes occurred in electrical variables during training.

METHODS

Eleven males and 21 females volunteered for the study, ranging in age from 20 to 40. None were involved in activities resulting in hip flexor or abdominal strengthening or conditioning. After signing a consent form, subjects were randomly assigned to one of four groups: a control group (C), a volitional exercise group (E), an electrical stimulation group (S), and a volitional exercise with concurrent electrical stimulation group (ES) (Table 1).

During initial screening, each subject assumed a supine position with the knees bent to 90° while the feet were in full contact with the floor but without external support. The subjects then performed a 5-sec voluntary abdominal curl followed by a 5-sec period of rest. This cycle was repeated for as long as the subject could lift the inferior angle of the scapula so that it was not in contact with the supporting surface. The cycles were counted and the number of repetitions (NR) was established. Subjects whose NR exceeded 30 were excluded from the study on the presumption of having strong abdominals. Qualifying subjects were oriented to the testing procedures. A 3-day practice period involving the specially constructed testing apparatus was required prior to initiation of training to diminish the effects of learning.

Baseline strength measurements were taken while each subject was tightly secured to the apparatus (Fig. 1). The force generated by maximal isometric abdominal contraction was measured using a 221A03 piazoelectric force transducer (PCB, Piezoelectronics Inc., Buffalo, NY) and recorded in millivolts using a digital electrometer model 615 (Kiethly Instruments, Cleveland, OH). The test consisted of three maximal voluntary isometric contractions (MVIC) and the three force readings were averaged to obtain a single force value for each subject.

Muscular endurance of the abdominals was determined using an electric goniometer affixed to the subject's trunk (Fig. 2). The subject's ability to maintain an abdominal curl at a constant angle was measured in units of time. The degree of angulation was read directly from an analogue to digital conversion unit. Lying supine with the knees flexed to 90° and the feet unsupported (hooklying position) the subject was asked to raise the head and trunk and maintain them, as high as possible, but not greater than 45° of trunk flexion. According to Flint,[6] the abdominals are most ac-

TABLE 1
Descriptive data of subjects

Grouping	Sex		Age		Initial NR* of Abdominal Curls
	M	F	M	F	
Group C	4	4	26.8	28.0	0
Group E	1	7	29.0	25.4	13.9
Group S	4	4	29.5	21.3	19.4
Group ES	2	6	25.5	23.5	13.6

* Number of repetitions.

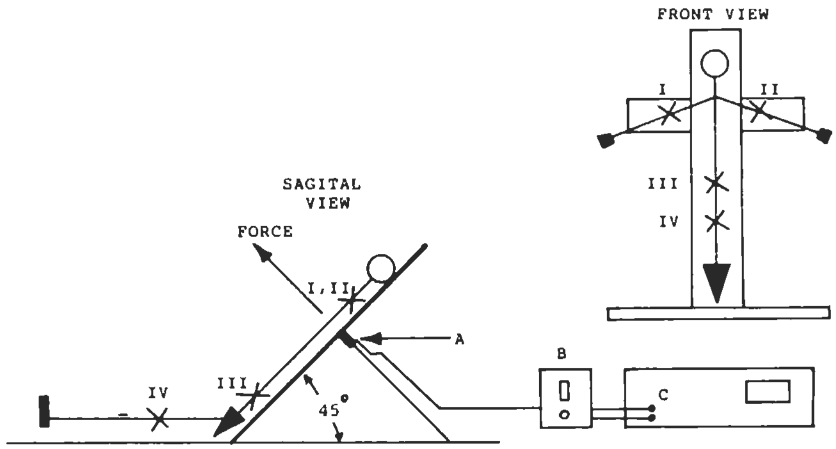

Fig. 1. *Testing apparatus. A, Piezoelectric force transducer; B, charge amplifier; C, digital electrometer. I–IV, subject to apparatus securing sites.*

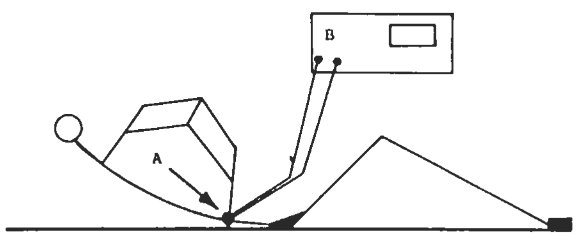

Fig. 2. *Measurement of curl-up. A, Potentiometer; B, analog to digital conversion and display system.*

tive within this range. Timing began when the subject attained the desired angle and terminated when the angle decreased more than 3°.

Subjects participated in their respective training regimes 3 times/week for 4 consecutive weeks. All subjects used the previously described position for training. Measurements of strength and endurance were taken at 1-week intervals for all groups.

Training protocols of the experimental groups were performed in the following manner: The E group was trained to sustain the abdominal curl position. The first week consisted of a 5-sec curl-up followed by a 5-sec relaxation period and each subject repeated his/her own NR plus 10%. For each of the remaining weeks the contract/relax duration increased to 7.5, 10, and 12.5 sec, respectively. A 20% increase in the NR was added for each consecutive week. The sequence of increasing the contraction/relaxation times and the number of repetitions is summarized in Table 2.

The S group received electrical stimulation to the abdominal musculature using conductive rubber electrodes shaped to contour the entire abdominal area. Stimulation consisted of cyclic periods of 5 sec ON, and 5 OFF. The training protocol for the S group was identical to that of the E and ES groups as summarized in Table 2.

TABLE 2

Training protocols for experimental groups

Week	Contract	Relax	Repetitions
1	5 sec	5 sec	$NR + 0.1\ NR = R_1$
2	7.5 sec	7.5 sec	$R_1 + 0.2\ R_1 = R_2$
3	10 sec	10 sec	$R_2 + 0.2\ R_2 = R_3$
4	12.5 sec	12.5 sec	$R_3 + 0.2\ R_3 = R$

The ES group protocol consisted of exercise with concurrent stimulation. While receiving maximally tolerated motor excitation the subjects performed a voluntary maximal curl up for 5 sec with a 5-sec rest period interjected between each repetition for the first week. The protocol for the remaining weeks was the same as for the E and the S groups.

An intellect VMS prototype (Chattanooga Corp. Chattanooga, TN) stimulator was used for the S and ES groups. Subjects received stimulation with a biphasic symmetrical pulse waveform having 200 μsec phase duration and pulse rate of 50 pps. Peak of total circuit voltage and peak voltage across a 2-ohm resistor were measured from an oscilloscope as illustrated in Figure 3. Using Ohm's law, peak current and tissue resistance were calculated from these measurements.

Abdominals' force and endurance were calculated as a percentage of change per week for each subject. This was determined by dividing each successive week's test by the initial week's test. Percent changes were analyzed using a two-factor analysis of variance (ANOVA): factor A being the groups with all four groups as treatment levels, and factor B being weeks with all training weeks as treatment levels.

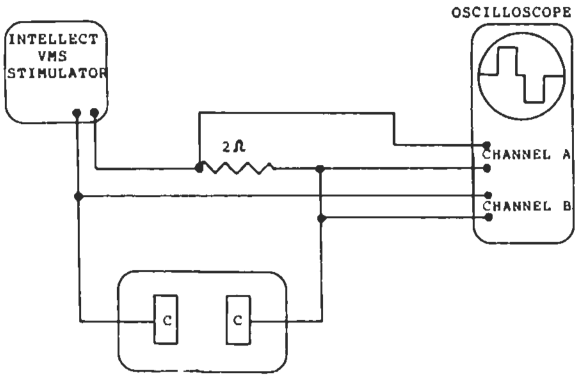

Fig. 3. *Schematic illustration of electrical measurements. A, Voltage across a 2-ohm resistor; B, total voltage across the electrodes; C, surface electrodes.*

TABLE 3

Summary of ANOVA test on percent increase of maximal isometric strength

Source	df	MS	F*
Weeks	3	11706.69	3.44
Error	28	3398.28	
Groups	3	1153.99	6.73
Groups × weeks	9	770.59	4.49
Error	84	171.48	

* Significant at $\alpha = 0.05$ level.

TABLE 4

Newman-Keuls post hoc analysis of mean tension for all groups

Groups	q-Statistic*
Group E vs group C	5.59
Group E vs group S	14.93
Group E vs group ES	17.91
Group C vs group S	9.33
Group C vs group ES	12.32
Group S vs group ES	2.98

* Significant at $\alpha = 0.05$.

Peak voltage, peak current, and tissue resistance measurements taken from the S and ES groups were submitted to a one-factor ANOVA with the treatment levels being the 4 weeks of training.

RESULTS

Analysis of variance corrected for repeated measures on weeks of training resulted in significant changes in abdominal strength (Table 3). Newman-Keuls post hoc analysis demonstrated that the ES group gained significant strength over all other groups. The S group was significantly stronger than the E and C groups. Surprisingly, the C group had gained significantly greater strength than the E group (Table 4). The mean percentage increases relative to pretraining strength for C, E, S, and ES groups were 19.0, 6.1, 40.6, and 47.4%, respectively (Fig. 4). Change in abdominal endurance occurred in all the groups. The percent increase from baseline for the C, E, S, and ES groups averaged 112.0, 52.5, 127.7, and 143.9%, respectively. But due to considerable variance these differences were statistically insignificant.

Electrical parameters of voltage, current, and resistance from the two electrical stimulation groups (S and ES) were compared. The ANOVA test revealed significant changes in each of the three parameters over the 4-week training period. Mean values for the amount of peak current subjects tolerated progressively rose over the 4 weeks of training (Fig. 5). Post hoc analysis revealed significant gains for weeks 2 through 4 when compared to the first week and again during the fourth week when compared to the second and third weeks (Table 5). Mean values of tissue resistance exhibited a decreasing trend for all weeks except during the second week where slight increases in resistance were noted (Fig. 5). Post hoc analysis showed a significant decrease during the last week as compared to weeks 1 through 3 (Table 6). Mean values for peak voltage exhibited increases during all weeks except for the last week which displayed a slight decrease (Fig. 5). The post hoc analysis demonstrated significant voltage gains for weeks 2 through 4 when compared to the first week (Table 7).

DISCUSSION

The effects of volitional exercise (E), electrically induced exercise (S), and the combined form of exercise (ES) on abdominal strength and endurance have never been compared in available literature. Thus, interpretation of the aforementioned results must be done with great care. The present findings single out the exercise plus stimulation training (ES) as the best form for strength improvement, followed by electrical simulation alone. These findings differ somewhat from Currier and Mann's[3] reporting where no difference existed between the two forms of training using normal quadriceps femoris muscle. The discrepancy may be related to the observation that the adult abdominal musculature are atrophied in otherwise normal subjects.[13] Once disuse atrophy is present in skeletal muscles the combination of exercise and electrical stimulation have been reported to be more effective than exercise

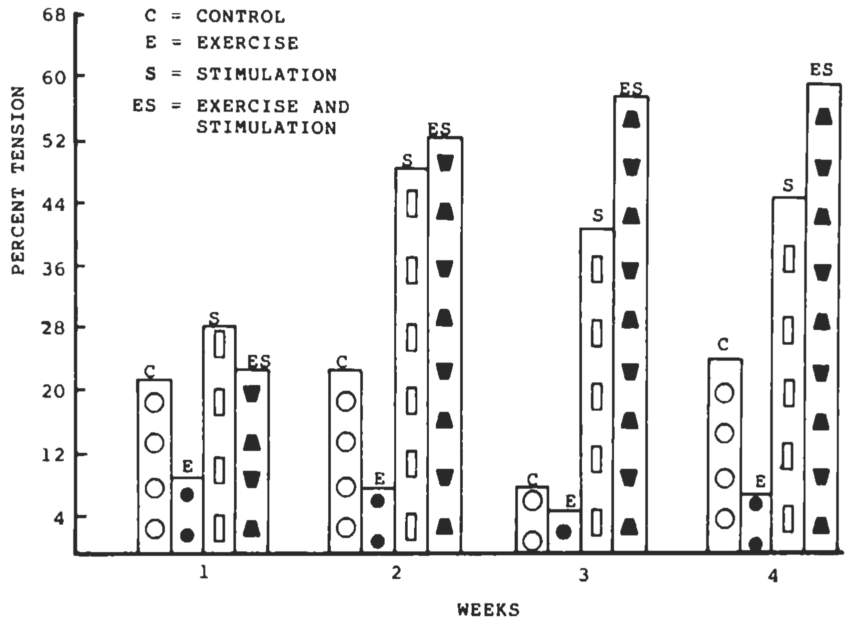

Fig. 4. *Percent mean increases of MVIC over pretraining MVIC.*

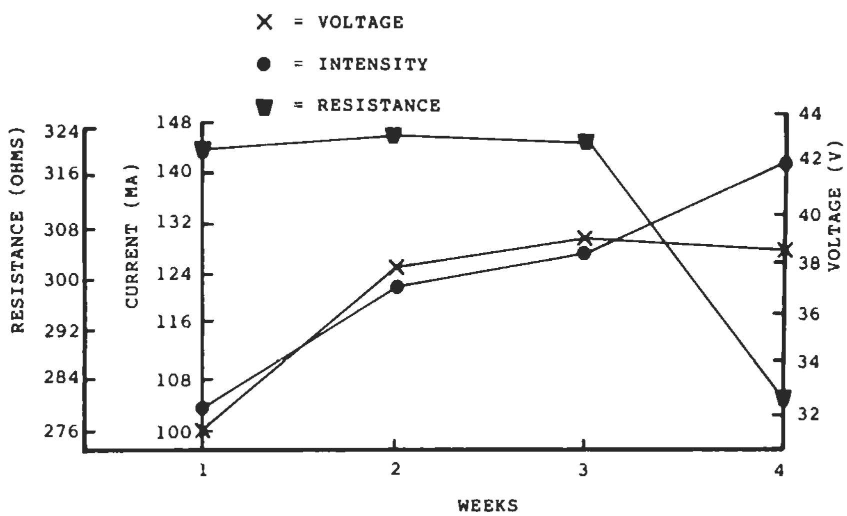

Fig. 5. *Mean changes of electrical parameters during training.*

TABLE 5

Newman-Keuls post hoc analysis of current combined for groups S and ES for all weeks

Weeks	Calculated q-statistic
Week 1 vs week 2	5.07*
Week 1 vs week 3	6.16*
Week 1 vs week 4	9.50*
Week 2 vs week 3	1.08
Week 2 vs week 4	4.42*
Week 3 vs week 4	3.34*

* Significant at $\alpha = 0.01$.

TABLE 6

Newman-Keuls post hoc analysis of resistance combining groups S and ES for all weeks

Weeks	Calculated q-statistic
Week 4 vs week 3	4.03*
Week 4 vs week 1	4.04*
Week 4 vs week 2	4.25*
Week 3 vs week 1	0.014
Week 3 vs week 2	0.222
Week 1 vs week 2	0.208

* Significant at $\alpha = 0.01$.

TABLE 7

Newman-Keuls post hoc analysis of voltage combining groups S and ES for all weeks

Weeks	Calculated q-statistic
Week 1 vs week 2	5.69*
Week 1 vs week 3	5.58*
Week 1 vs week 4	5.47
Week 4 vs week 3	0.213
Week 4 vs week 3	1.11
Week 2 vs week 3	0.898

* Significant at $\alpha = 0.01$.

alone.[4,12,17,18] These results concur with the present findings.

The least amount of strength improvement was recorded in the E group even in comparison to the C group which did not exercise at all. These findings could not be readily explained and are somewhat disturbing. Retrospectively it was noted that the E group included seven females, three of which had their testing during the menstrual period and may have not exerted maximal effort due to discomfort. Having a sample size of only eight subjects may have adversely affected the mean strength of the volitional exercise group. The ES group was also comprised of high female/male ratio, yet testing three of them during menstrual period did not seem to affect their abdominal contraction force. Conceivably, the electrical stimulation helped to minimize the dysmenorrhea.[15]

Increase strength of the C group reached 19% after 4 weeks of testing. This was in sharp contrast to studies of the normal quadriceps, where with one exception[20] only 1–2% increase has been reported.[2,3,7,16] The novel testing, the learning effect associated with it, and the complexity of the abdominal musculature may all have contributed to the high gains of the C group. If the 19% are subtracted from the percent increase of the S and ES groups, the increase strength of these two experimental groups become 21.6 and 28.4%, respectively. These values are in good agreement with present literature.[3,14,16,19,20]

Abdominal endurance increased in all four groups but substantial variability proved those changes to be statistically insignificant. In contrast, lehl et al.[11] reported significant improvement of abdominal endurance. The disagreement can be explained by at least two observations. First, lehl and coworkers did not compare the experimental group with a control. Second, endurance was determined by lehl et al. through torque decrement as recorded by dynamometry, while in the present study it was determined by the time of sustained contraction. The substantial variability observed among the subjects, could be attributed in part to the testing procedure. Several subjects noted fatigue of the neck musculature and may have terminated the testing prematurely. Fluctuations in electric goniometer read-outs were created by movement of the thorax making the decision to terminate the test somewhat difficult.

Increased current and voltage indicated subject conditioning as well as accommodation to stimulation over time. Other investigators have qualitatively reported similar observations.[3,5,10,14,20] This study was the first to quantify them. Tissue resistance decreased significantly, possibly indicating improvements in tissue conductivity. Such improvement could be attributed to an increase in interestitial fluid over the training period. Furthermore, alteration in the concentration of subcutaneous fat may have occurred, and subsequently contributed to decreased resistance to current flow. There may be other reasons associated with the electrical attributes, which could explain this phenomenon. Whereas the resulting changes seem to be consistent with Ohm's law, it is not possible within the constraints of this study to ascertain the exact cause of the aforementioned changes in tissue conductivity. Further investigation is indicated to accurately assess the source of these changes.

CONCLUSION

The combined use of electrical stimulation and volitional exercise was determined to be the most effective mode for isometric strength gain of the abdominal musculature. Stimulation alone was better than exercise alone or no exercise. No significant gain in endurance was recorded among the groups after 4 weeks of training. Electrical stimulation was found to decrease tissue resistance indicating improvement of tissue conductivity over time. Further studies are needed to delineate the most effective protocols of stimulation to increase strength and endurance in the abdominal musculature. Additional investigations are also necessary to elucidate the source of the changes in tissue conductivity.

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