

Equal Effectiveness of Electrical and Volitional Strength Training for Quadriceps Femoris Muscles After Anterior Cruciate Ligament Surgery

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Summary: Neuromuscular electrical stimulation and voluntary muscle contraction are two exercise modes widely used in rehabilitation to strengthen skeletal muscle. Since there is debate as to which mode is most effective, we compared electrical stimulation with voluntary contraction performed at matched intensities following reconstructive surgery of the anterior cruciate ligament. Forty men and women, aged 15-44, were randomly assigned to either an electrical stimulation or a voluntary contraction group. None of the subjects had a previous history of neuromuscular injury. The subjects received treatment for 30 minutes a day, 5 days a week, for 4 weeks. Knee extension torque was monitored during treatment to try to match the absolute muscular tensions (quantified as "activity") achieved during therapy. To match the activity of the subjects in the electrical stimulation group, who were treated at the highest stimulation intensity they could tolerate, the subjects in the voluntary contraction group were paced at progressively increasing intensities corresponding to 15, 25, 35, and 45% of the injured limb's maximum voluntary torque during weeks 1, 2, 3, and 4, respectively. We found no significant difference between the groups in terms of maximum voluntary knee extension torque throughout the study period. In addition, 1 year after surgery, there was still no significant difference between groups with regard to knee extension torque ($p > 0.4$). These data suggest that neuromuscular electrical stimulation and voluntary muscle contraction treatments, when performed at the same intensity, are equally effective in strengthening skeletal muscle that has been weakened by surgical repair of the anterior cruciate ligament.

Neuromuscular electrical stimulation is widely used to delay or prevent the atrophy associated with disuse of the quadriceps femoris muscles. Several studies have demonstrated that, in normal individuals, electrical stimulation strengthens muscle with the same efficacy as either voluntary contraction by itself or the two therapies in conjunction (3,4,12,16) and that electrical stimulation results in significantly greater gains in strength than no electrical or voluntary contraction treatment at all. In patients with a reconstructed anterior cruciate ligament, the available evidence suggests that electrical stimulation is actually *more* effective than voluntary muscle contraction in strengthening quadriceps muscles (2,5,18,21). The difference in results between normal subjects and those with a reconstructed ligament may be due to actual differences in the intrinsic efficacies of the two treatment modalities or may result from patients' inability to activate their

muscles voluntarily soon after surgery. Since evidence exists that voluntary activation of muscle may recruit different muscle fiber populations than electrical stimulation (10,20), either possibility is plausible.

To interpret the results from the various studies, it is necessary to define the underlying elements involved in strengthening muscle fibers. Several lines of evidence support the concept that strength gains in skeletal muscles are a result of stress imposed on the muscle fibers. In basic science research, hypertrophy of muscle fiber has been shown to occur when a muscle is surgically overloaded and required to generate higher forces than normally required for animal locomotion (15). Indeed, even *immobilization* of a muscle can cause fiber hypertrophy as long as significant tension is imposed upon it (17,19). Another example of the importance of muscle tension on muscle strength was recently presented by Kernell et al., who investigated the effect of various patterns of electrical stimulation on the peroneus longus muscle in cats (11). They found that the stimulation pattern that caused the greatest increase in strength was the one that produced the most muscle tension. In clinical settings, the studies that have shown significant strengthening ef-

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TABLE 1. Characteristics of subjects

	Age (yrs)	Height (cm)	Weight (kg)	Tibial length (cm)
Neuromuscular electrical stimulation	28.0 ± 8.2	176.5 ± 9.1	74.9 ± 11.5	37.1 ± 2.4
Voluntary contraction	27.3 ± 8.5	174.5 ± 7.4	76.2 ± 12.7	36.1 ± 1.7

Values represent mean ± SD (n = 20 per group).

facts of neuromuscular electrical stimulation have been those in which muscles were activated to a relatively high proportion (e.g., more than 50%) of the highest level of voluntary contraction attained by the subject. An outstanding example of such a case was presented by Delitto et al., who demonstrated significant strength gains in a competitive power lifter when muscle tensions during treatment actually exceeded the individual's maximum voluntary contraction (7).

Unfortunately, since most clinical studies have not actually recorded the level of muscle tension during treatment, it is difficult to quantify the relationship between "treatment tension" and strength gain precisely. However, in the several studies that have reported the level of the subjects' maximum voluntary contraction achieved during treatment, improvements in strength were positively correlated with high treatment tension (12,13). Even if the treatment levels for neuromuscular electrical stimulation could be increased to those obtained during voluntary muscle contraction, it is not clear that electrical stimulation-based exercise would be as effective as voluntary exercise, because the population of muscle fibers recruited by the therapy could be modality-dependent. For example, a voluntary muscle contraction of 50% of the subject's maximum voluntary contraction may result from activation of 70% of the quadriceps femoris muscle fibers to 70% of their maximum tension, whereas an electrically induced contraction of 50% of the maximum voluntary contraction may result from activation of 50% of the quadriceps femoris muscle fibers to 100% of their maximum tension. Such a difference could occur if muscle fibers were selectively activated by fiber type (8) or position within the muscle (1). If tension and strengthening of the muscle fibers are related, the two different treatment modalities would clearly produce differential strength gains, which would have important clinical implications, as outlined previously (8).

Therefore, to determine the intrinsic efficacy of treatments based on both voluntary muscle contraction and electrical stimulation, this study compared the two therapies under conditions in which the muscle tensions in both treatment groups were matched.

METHODS

Selection of Subjects

Forty men and women, 15-44 years of age, were recruited for the study (Table 1). The requirements for entrance into the study

were surgical reconstruction of the anterior cruciate ligament within the previous 2-6 weeks and the ability to position the knee in 90° of flexion. None of the subjects had a previous operation on the knee, and the anterior cruciate ligament was the only ligament involved in each leg studied. All surgical procedures were identical and performed by one of two surgeons. Each subject was familiarized with the testing protocol, which was approved by the Committee on the Use of Human Subjects in Research of the University of California at San Diego.

Treatment

The subjects were randomly assigned to either the neuromuscular electrical stimulation or the voluntary muscle contraction group. They were positioned in an elevated chair and the distal tibia was secured to a force transducer with a Velcro strap. Both groups were paced using a PDP-11/73+ microcomputer (Digital Equipment, Maynard, MA, U.S.A.) connected to the force transducer and a video terminal, which provided visual and audio feedback to the subject as previously described (14). Each contraction was recorded by the computer so the entire tension treatment history of each subject could be calculated.

The maximum voluntary contraction of the injured leg was measured for each subject prior to each treatment session. Subjects in both groups were treated in the same clinic by the same therapist. On the basis of pilot studies (n = 6) of the magnitude of torque induced by neuromuscular electrical stimulation that could be elicited at this postoperative treatment time, the voluntary contraction group was paced to match the electrical stimulation group by exercising at progressively increasing torque levels over the 4-week treatment period: 15% of the injured leg's maximum voluntary contraction for that session the first week, 25% the second week, 35% the third week, and 45% the fourth week. The output of the extension torque transducer was provided to each subject performing voluntary contraction, along with the target torque level. When exercising, they contracted their muscles to match this target torque level for the same activation/relaxation times experienced by the electrical stimulation group (see below). The initiation of each contraction was signaled by the computer with audio feedback so that each contractile record could be acquired and quantified. In this way, the voluntary muscle contraction group "exercised" at a predetermined tension level that we attempted to match to that of the neuromuscular electrical stimulation group. Subjects in the electrical stimulation group, however, were "exercised" at the highest intensity they could tolerate. Prior to each treatment session, these subjects were given several minutes to experience the cyclic activation/relaxation cycle in order to determine a stimulation intensity that they could tolerate for 30 minutes. This peak stimulation intensity was kept constant throughout the 30-minute treatment period. Each contraction cycle (stimulated or voluntary) consisted of 10 seconds of muscle contraction followed by 20 seconds of rest. Contractions induced by electrical stimulation were ramped on and off over a 2-second period for the comfort of the patient; the ramping also simulated the slow activation and relaxation of the torque records from the voluntary contraction group. All subjects were treated for 30 minutes a day, 5 days a week, for 4 weeks, and every subject attended every session. During the 4-week experimental treatment period, subjects were allowed to participate in a therapist-monitored home exercise program.

The electrical stimulator was a custom-built, computer-controlled device (14), which used an asymmetrical, bipolar charge-balanced signal with a maximum amplitude of 100 mA. Stimulation frequency was set to 50 Hz and stimulation pulse width was 250 microseconds. In practice, a nominal current output of 30 mA was used.

To quantify the total tension induced by neuromuscular electrical stimulation and voluntary muscle contraction treatment, an activity parameter was defined. This was calculated as

$$\text{Activity (Nm} \cdot \text{min)} \equiv \sum_{n=1}^{n=60} \int_{t=0 \text{ min}}^{t=0.17 \text{ min}} \tau(t) \cdot dt$$

where n = number of contractions during the 30-minute treatment period, $\tau(t)$ = knee extension torque (in Nm) at time t , and t = time during the 10-second (0.17 minute) activation period (either electrical or voluntary muscle activation). The accuracy of the digital integration algorithm was 0.04%. The integration and summation are illustrated in Fig. 1. First, the raw contractile record was digitally integrated (Fig. 1A), yielding the torque impulse. Then, the impulses for each of the 60 isometric contractions over the 30-minute treatment period were summed, yielding the total activity for that treatment session (Fig. 1B). Quantifying the activity allowed us to match the treatment intensities of the voluntary contraction and electrical stimulation groups.

Subsequently, knee extension torque was measured in the clinic at 6, 8, 12, 24, and 52 weeks following surgery using a similar strength-measuring device consisting of a chair with a force transducer. This measurement was performed with the hip and knee joints flexed to 90° and with motivation identical to that offered during the treatment sessions. The knee joint angle of 90° resulted in approximately 85% of the maximum torque occurring at a knee flexion angle of 60°. We used 90° in order to simplify the line of force application to the transducer.

Statistical Analysis

All data were screened for normality using the Shapiro and Wilk test to justify the use of parametric statistics. The maximum voluntary contraction levels of each group were compared for initial and final conditions using two-way analysis of covariance (ANCOVA) with repeated measures. ANCOVA was used with total treatment activity as the covariate to account for observed differences in treatment activity (see below). Linear regression was used to determine whether maximum voluntary contraction changed significantly during the 4-week treatment period. The significance level (α) was set to 0.05 for all tests, and the statistical power (β) was calculated as approximately 70% for the parameters of maximum voluntary contraction and activity (based on the observed values for maximum voluntary contraction σ and activity σ

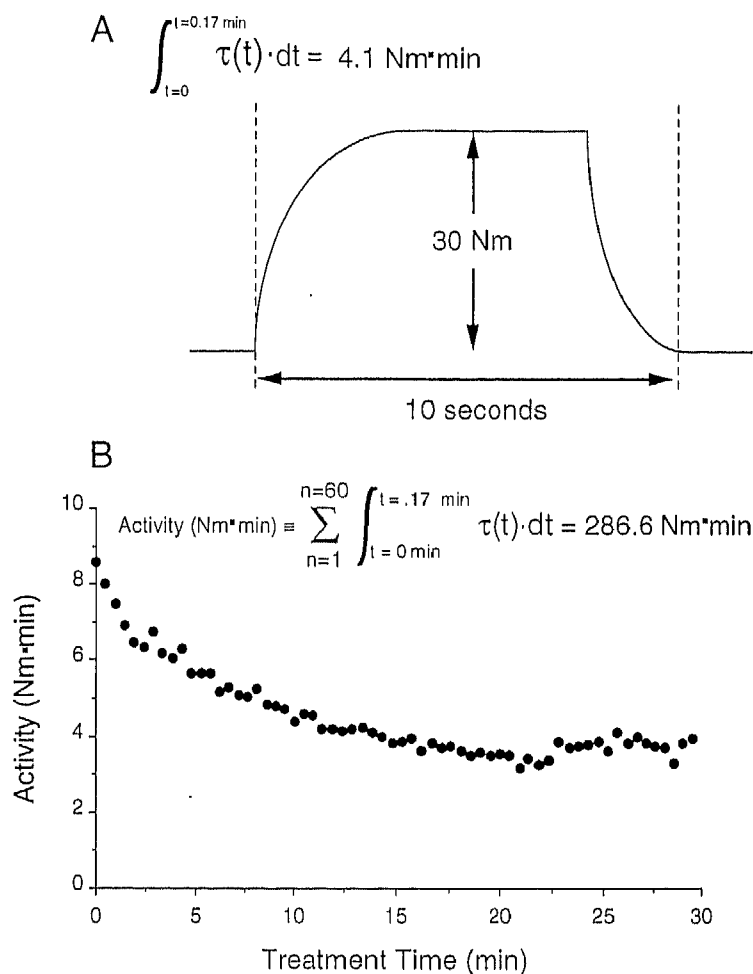


FIG. 1. A: Schematic representation of digital integration method for determination of the integrated torque for a single contraction. In this example, the peak torque of 30 Nm, which is ramped on over 2 seconds (0.033 minute), maintained for 6 seconds (0.10 minute), and ramped off over 2 seconds (0.033 minute), yields an integrated torque impulse of about 4.1 Nm·min. **B:** Summation of integrated torque values over the 30-minute treatment session. Each point represents the integrated torque for one contraction. These data are summed to yield the total activity for that treatment session. (Data are from one subject.)

of 32.6 Nm and 8,900 Nm-min, respectively). The values are presented in the text as mean \pm SEM unless otherwise noted.

RESULTS

No significant differences were found between the subjects' physical characteristics ($p > 0.1$) (Table 1). Coincidentally, 16 men and 4 women were assigned to each group. Subjects from both groups significantly increased the amount of treatment activity achieved during the 4-week training period ($p > 0.001$) (Fig. 2A). However, despite our attempt to match the activity levels of the two groups, the voluntary contraction group performed at a significantly greater level than the electrical stimulation group ($p < 0.05$). Thus, if anything, the study was biased toward the voluntary contraction group, since their ending activity (332.1 Nm-min) was approximately 30% greater than that of the electrical stimulation group (252.0 Nm-min) (Fig.

2B). (Obviously, our pilot experiments suggested too high a target level for the subjects performing voluntary muscle contraction.) This result suggested the use of ANCOVA (with total treatment activity as the covariate) to test whether levels of maximum voluntary contraction changed significantly during the 4-week study as a function of treatment group. In this way, maximum voluntary contraction was compared between groups as a function of time after correction for differences in total treatment activity. It should be noted that identical statistical significance was obtained using one-way analysis of variance to analyze maximum voluntary contraction.

Subjectively, the subjects in the voluntary muscle contraction group found the first week of exercise at 15% of their maximum voluntary contraction easy to perform but had more difficulty achieving the target torque over the succeeding 3 weeks; this suggests that

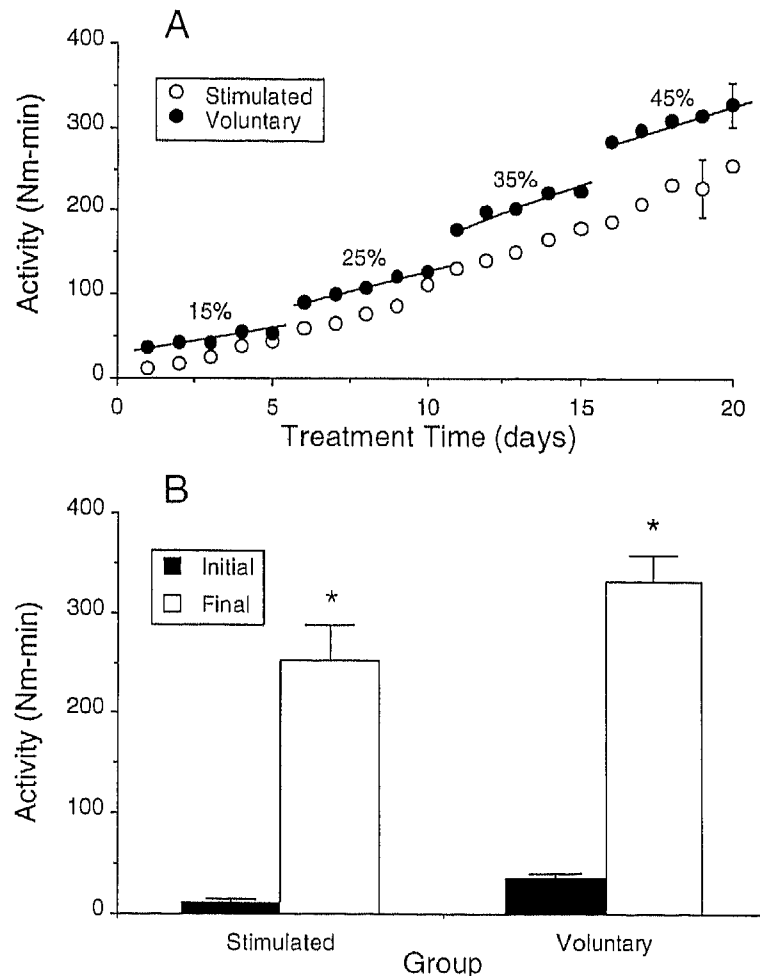


FIG. 2. A: Knee extension activity versus treatment time. Voluntary contractions were elicited over the 4-week period at 15, 25, 35, and 45% of the injured leg's maximum voluntary contraction, as measured at the start of each session. Step increases in activity for the voluntary contraction group result from the change in contraction level on successive Mondays. For clarity, the error bars show the SEM for the last two stimulation periods only, but there was no systematic variation in the SEM over the entire experimental treatment time. **B:** Change in activity from the initial treatment session to the final treatment session. The asterisk denotes a significant increase in activity from the initial treatment day to the final treatment day. Note that the activity for the voluntary group was significantly greater than that for the stimulated group.

TABLE 2. Analysis of covariance of maximum voluntary contraction

Source	Degrees of freedom	Sum of squares	Mean square	F value	P value
Treatment group	1	39.868	39.868	0.066	0.7990
Activity covariate	1	14,462.093	14,462.093	23.861	0.0001
Time	1	7,576.399	7,576.399	24.594	0.0001
Time \times group interaction	37	7.440	7.440	0.024	0.8773

the target activity level was within the range that would be used in an unpaced study. In addition, the subjects in the voluntary contraction group reported that great mental concentration was required to pace their exercise at precisely the correct time interval and torque level.

The values for maximum voluntary contraction increased significantly ($p < 0.001$) for both groups over the 4-week treatment period (Fig. 3A and Table 2). However, the magnitude of the increase was not significantly different between groups ($p > 0.7$) when total treatment activity was used as the covariate, and there was no significant interaction effect between

treatment group and time ($p > 0.8$). (Identical results were obtained by using either initial or final treatment activity as the covariate in the analysis or by performing one-way ANCOVA on the change in maximum voluntary contraction during the treatment time, using activity as the covariate.) Although at the beginning of the study the average maximum voluntary contraction for both groups was only 27.1 ± 2.8 Nm, this increased to 93.5 ± 5.2 Nm after 4 weeks of treatment (Fig. 3B). At this point, the treated leg still had only about 30% of the strength of the unaffected leg. At time points up to 1 year, there was still no significant difference in strength between groups ($p > 0.4$) (Fig.

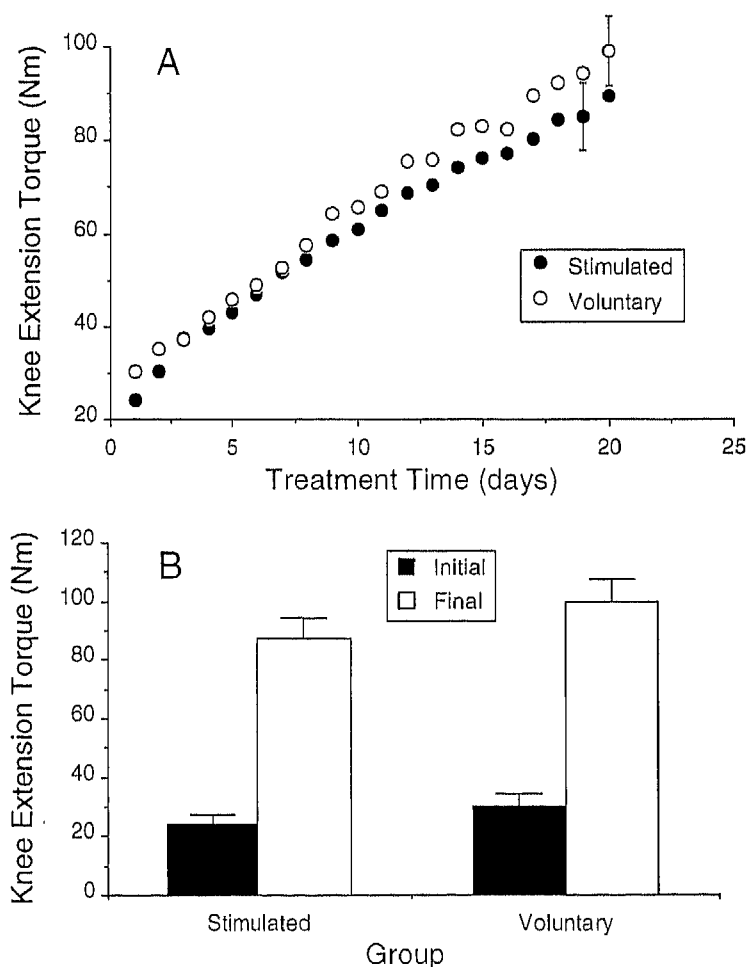


FIG. 3. A: Maximum knee extension torque versus time. For clarity, the error bars show the SEM for the last two stimulation periods only. **B:** Change in maximum knee extension torque from the initial treatment session to the final treatment session. There was no significant difference between groups in improvement in maximum voluntary contraction ($p > 0.7$).

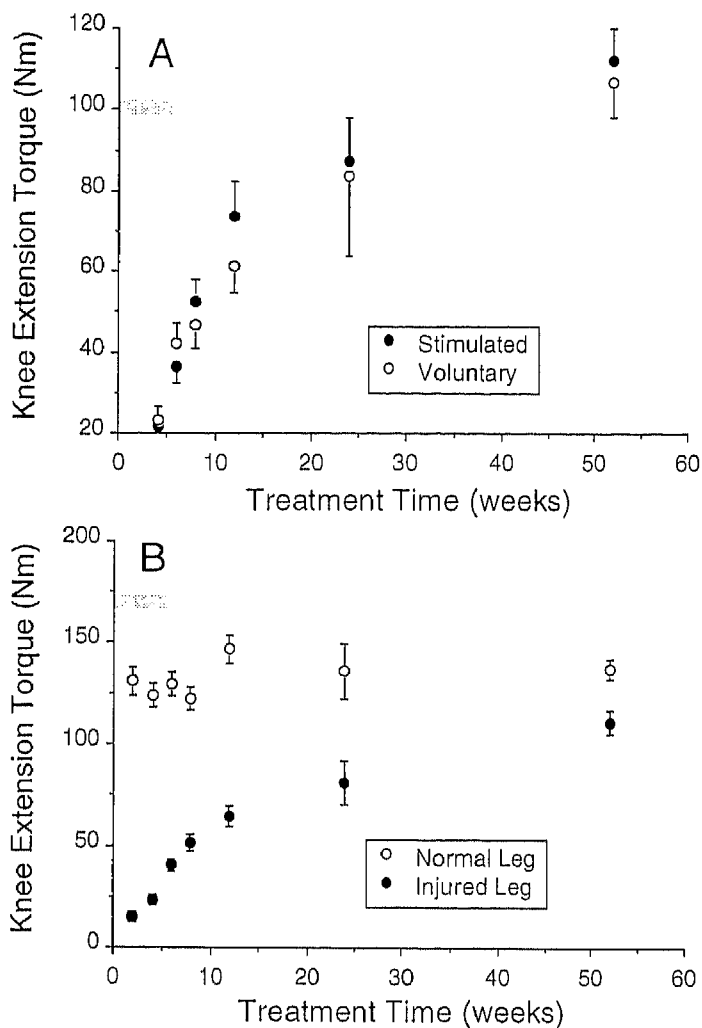


FIG. 4. A: Long-term maximum knee extension torque versus time. **B:** The difference between the strength of the injured legs and the contralateral control legs during the study. After 1 year, the extension strength of the injured knees was approximately 80% that of the contralateral knees. The shaded bar represents the 4-week experimental treatment period.

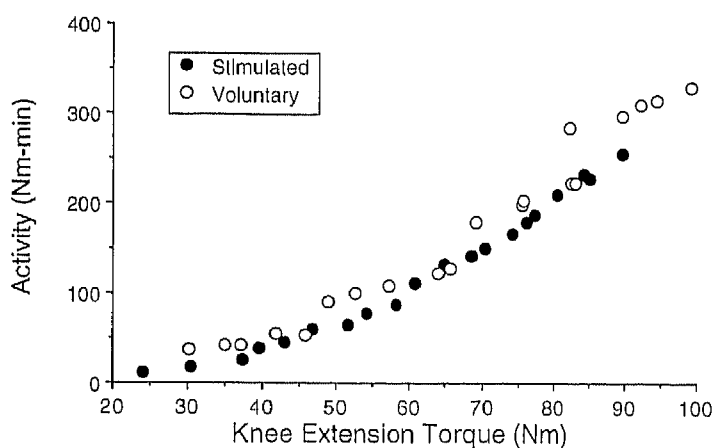


FIG. 5. Relationship between treatment activity and maximum voluntary contraction. Since the two are highly correlated ($r^2 = 0.71$; $p < 0.01$), it is possible that increased treatment activity leads to increased knee extensor strength.

4A). At the end of 1 year, the strength of the injured leg was about 80% of the strength of the contralateral leg (Fig. 4B).

The muscle treatment activity and the maximum

voluntary contraction attained by the subjects were significantly correlated ($p < 0.05$) for both groups; this suggests the possibility of a causal relationship (Fig. 5). The relationship between the two variables was not

significantly different for the two treatment groups (note the overlap of symbols in Fig. 5); therefore, it is probable that there were similar underlying mechanisms for the activity-induced change in strength. The simplest interpretation of this result is that greater activity during treatment results in a greater maximum voluntary contraction. However, the voluntary muscle contraction group, with its greater activity, did not always achieve greater maximum voluntary contractions (Fig. 5).

DISCUSSION

The main result of this study is that identical strength gains were achieved with neuromuscular electrical stimulation and voluntary muscle contraction therapy when treatment activity was matched between groups. When treatment is performed at the levels used in this study, therapeutic programs based on electrical stimulation and voluntary muscle contraction should be equally effective in strengthening skeletal muscles.

In this study, significant differences in strength between groups were not observed even after 1 year postoperatively. The data demonstrate that both types of therapy have equivalent long-term effects. Our results differ from those obtained by Snyder-Mackler et al. (18), who showed that 3 weeks of intense electrical stimulation therapy resulted in strength of about 70% of that of the unaffected leg only 2 months after surgery. Delitto et al. (6) also demonstrated a significantly greater effect of electrical stimulation when compared with voluntary exercise, but this was probably due to the much higher intensity of the electrical stimulation treatment that they used during rehabilitation. Comparisons between their study and the present study should be made with caution since our purpose was to match treatment intensities and quantify the intrinsic strengthening efficacy of the two methods, whereas Delitto et al. (6) were interested in quantifying the absolute efficacy of the two methods as used in the clinic. Our basic science findings in no way challenge their results.

It is difficult to reconcile the numerous studies that have reported differential effectiveness of electrical stimulation training. If we extrapolate directly from the training literature, then we expect that as treatment torque increases, so do strength gains. This, of course, assumes that both therapies utilize the same mechanism to strengthen muscles, which may not be a valid assumption. For example, Duchateau and Hainaut (9) presented data for normal adult men that suggested that stimulation training and voluntary exercise training had different effects on various fiber types. This conclusion was based on their observation that muscle endurance increased with voluntary exercise training but not with electrical stimulation train-

ing. Trimble and Enoka (20) demonstrated altered muscular recruitment patterns and rightly pointed out that this would have significant therapeutic consequences for electrical stimulation therapy as detailed by Delitto and Snyder-Mackler (8). An even more surprising result was presented by Laughman et al. (12), who demonstrated equivalent strength gains for the two therapies in spite of the fact that electrical stimulation therapy was performed at about 30% of maximum voluntary contraction while voluntary exercise training was performed at about 80% of maximum voluntary contraction levels. Future studies with carefully controlled treatment tensions are required to resolve these discrepancies.

Finally, we should point out the limitations of using maximum voluntary contraction as a dependent parameter. Although we have presented arguments related to muscle properties, any changes in the neural drive to the muscles will also alter the torque generated. This factor affects our study only to the extent that neural drive is altered differentially by voluntary muscle contraction compared with neuromuscular electrical stimulation.

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