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STRENGTHENING OF HUMAN QUADRICEPS MUSCLES BY CUTANEOUS ELECTRICAL STIMULATION

Donald F. McMiken, Martin Todd-Smith and Colin Thompson

Department of Biological Sciences, Cumberland College of Health Sciences, Sydney, Australia

ABSTRACT. The effectiveness of cutaneous electrical stimulation as a muscle-strengthening technique was evaluated by comparison with an isometric regime. Sixteen normal healthy subjects were randomly assigned to either *an electrical* group or *an isometric* group. A pretest was given of maximum voluntary force in the quadriceps (extensor) muscles, measured with a cable tensiometer. Subjects then trained (isometrically or by electrical stimulation) four days per week for three weeks. Training by electrical stimulation was via a square-wave pulse (75 Hz and 0.1 ms) with the voltage determined by subject tolerance for ten, 10-sec induced contractions (with 50-sec rest intervals). Isometric training consisted of ten, 10-sec maximal contractions (with 50-sec rest intervals) at each session. Feedback of the generated force was standardised for both groups. Post-training measures were then administered using the same protocol as the pretest. Both groups demonstrated a marked improvement in quadriceps strength of 22 ± 5.3% for the *electrical* group and 25 ± 6.9% increase for the *isometric group* ($p < 0.02$). The change in strength was apparently *not* dependent on the magnitude of the stimulating voltage (5–10 V) nor on the tension induced. There was no significant difference in the strength gains achieved by the two regimes ($p > 0.05$). No pain, muscle lesions or other ill effects were observed with electrical stimulation. We conclude that cutaneous electrical stimulation is a viable strengthening technique. There are obvious practical applications of this technique to the rehabilitation of patients who are not able to maintain an effective voluntary contraction.

Key words: Electro-stimulation, electro-therapy, isometric training, muscle adaptation, muscle contraction and muscle strength

We designed an experiment to test the effectiveness of electrical stimulation as a muscle-strengthening technique; since it has potential application in both rehabilitation and sports-medicine. Electrical stimulation or "Faradism" has been used clinically for re-educating denervated muscle (1, 2). It has also been found effective for reinforcing treatment of atrophied muscle and in conditions like Chondromalacia Patellae (7, 12). Some attempts have been made to quantify the effect of electrical stimulation on the musculature of quadriplegics and other patients (5, 11) but data on normal subjects—free of pathological complications—were not available at the time of our investigation. Since then Currier et al. (3) have reported comparable results in healthy subjects for an isometric regime and an isometric *plus* electrical stimulation regime. We compared the effectiveness of electrical stimulation with a conventional clinical (isometric) muscle strengthening regime.

THEORETICAL CONSIDERATIONS

Direct cutaneous electrical stimulation is known to initiate muscle contraction in man as in other animals; presumably by a similar process of sarcolemma depolarization as in normal activation by a motor nerve. If muscle contraction on electrical activation is similar to the usual contractile process; then the cellular mechanisms of adaptation should be activated during stimulation producing an adaptation of increased muscle strength and endurance similar to normal voluntary muscular exercise.

The celluar processes of adaptation although having a central role in biology and medicine are not at all well known. Some recognized features of these adaptation mechanisms are; that structural changes do occur in all biological tissue in response to protracted and intense physiologic activity, and that these modifications are mediated via the synthesis of nucleic acids and proteins. The most comprehensive model of this process is that proposed by Meerson (10). Meerson proposes a single mechanism at the cellular level that produces—at least in the myocardium—the same structural adaptations of increased muscle mass, mitochondria and oxidative enzymes to any of the stresses imposed in his laboratory (physical load, hypothermia and hypoxia). An implication of these data is that a single stimulus triggers a set response of the genetic apparatus controlling the transcription of cellular proteins (possibly the intracellular ATP/ADP ratio amplified by ΔIMP concentrations.)

If Meerson's model is correct, then adaptation to repeated muscle contraction would be expected to be similar regardless of the method of initiating contraction; provided of course that the intensity and duration of the contractions were similar.

An additional component of human adaptation however is the central neural changes that occur in response to repeated muscular work. That such CNS inhibition of voluntary contraction exists is easily demonstrated by the fact that a variety of central stimulation augments maximal muscular performance in man (6). Therefore changes due to a volitional isometric regime would presumably include both CNS and cellular adaptations, while the involuntary stimulation of muscle should result in changes that are attributable to cellular adaptation alone. We proceeded to test the hypothesis that adaptation to electrical stimulation would be similar to or less than adaptation to voluntary contractions of the same intensity. We did this because of the potential usefulness of the technique for clinical applications, the lack of data on the normal response, and also because a preliminary investigation had indicated a greater response to electrical stimulation than isometric exercise! (personal communication from Pross and Bevan, Cumberland College).

PROCEDURES

Subjects

Eighteen student volunteers were involved in this study. Their ages ranged from 19–27 years with a mean of 21.3 years. These subjects included 15 women and three men and they were randomly allocated to either the *electrical* or *isometric* groups. Two of the men were actually assigned to the *electrical* group and the other performed *isometric* exercise. During the experiment two female subjects informed us of muscular pain during *isometric* contractions and were consequently discharged from the experiments. A third subject was also discharged due to an error in procedure. This attrition left eight subjects in the *electrical* group and seven subjects in the *isometric* group for analysis.

Experimental design

All subjects were tested for a maximum voluntary isometric contraction of the left quadriceps to the experiment. They were then trained daily in either the electrical stimulation or isometric regime for three weeks (however because of time constraints on the students they averaged about 10 training sessions each). They were then retested for a maximally voluntary contraction as before; the resulting changes were compared between groups.

Methods and Material

The test apparatus was a wooden bench constructed so that the lower leg could be extended at an angle of about 30° against resistance of a cable attached at the ankle. This cable incorporated a pulley system on an adjustable track which allowed the direction of resistance to be altered so that it was always at right angles to the lower leg. The force of static contraction was recorded using cable tensiometers (Pacific Scientific Co.). These tensiometers were calibrated before, during and after the experiments and remained accurate throughout. The same apparatus was used for training and subjects were able to monitor their progress by a system of mirrors which enabled them to read the cable tension during the contraction.

Electrode placement was made after careful skin preparation, using large, flat, plate electrodes (130×60 mm distal & 120×40 mm proximal) placed on folded, moistened limb pads and secured by straps to the leg. The proximal electrode was placed over the femoral triangle of the quadriceps and the distal electrode was over the motor point of medialis.

Testing and training procdures were strictly controlled and standardized for both groups. Both groups were tested on the same apparatus and with the leg at 30° flexion from the straight knee. The maximum voluntary contraction was taken as the mean of three trials (10 s contractions separated by a 50 s rest period). A warm up preceeded each testing or training session and involved a standardized routine of ten full knee bends and one minute of "running-on-the-spot".

Training of the electrical stimulation group consisted of daily sessions of ten, 10 s contractions induced by clinical stimulator (Stewart Faradic Unit model GF01) using a faradic current of 75 HZ at 0.1 ms. Electrical application was in accord with the clinical practice of physical therapy. The high frequency ensured that the contractions were tetanic and we had previously noticed that this frequency was effective and illicited little pain or discomfort. (There were 50 s rest periods between each set of contractions.) Prior to these sessions each subject's quadriceps was prepared for electrical stimulation by washing the general area over the motor points of the rectus femoris and medialis; then applying a hot, wet towel to the skin for five minutes to reduce skin resistance. During the electrially induced contractions the stimulator was positioned so that the subjects were *not* able to observe the measured voltage. The voltage was controlled entirely by the operator to maintain a contraction not exceeding 80% of the maximum voluntary cable tension for each subject. A voltage limit of 10 V was observed however for safety purposes in respect of the possibility of damage to the motor nerves or connective-tissue rupture if Golgi-tendon inhibition was grossly overridden. Subjects were only informed of the voltage by the operators if asked directly, in order to maintain the integrity of the situation and allay the subjects' fear if they were feeling discomfort. Also an additional safety device was a "cut-out" switch which was controlled by the subject and interrupted electrical stimulation if pain was experienced. A period of ajustment was necessary at the beginning of each training session. This involved slowly increasing the voltage of stimulation until a contraction approaching 80% maximum was illicited.

Table I. *Quadriceps force before and after the training regimes*[a]

	Electrical group		Isometric group	
	Before	After	Before	After
	368	471	407	495
	667	834	520	476
	329	383	231	299
	363	402	309	417
	231	373	309	432
	432	481	333	476
	338	338	221	319
	368	490	–	–
$\bar{X}$	386.7	471.3	332.7	416.1
s	126.5	156.7	103.8	78.3

[a] Units are newtons of torque.

Isometric training also consisted of a daily routine of ten, 10 s near maximal contractions (also with a 50 s rest period between sessions). Control of the training effort was necessary for this study and therefore we provided equal feed-back to each group by way of the mirror system which enable the subject to read cable tension. And to standardize the degree of effort *no* verbal encouragement was given to either group. The total number of training sessions for each group was finally 9.5±0.9 for the *electrical* group and 9.7±0.8 for the isometric group.

RESULTS

Results of our experiments are contained in Table I. The change in the force of muscle contraction induced by training regimes was an increase of 22% for the *electrical* group ($t=4.1$, $p<0.01$) and 25% for the *isometric* group ($t=3.6$, $p<0.02$). There was no significant difference between the changes affected by the two regimes ($p>0.05$).

We also calculated the subject's improvement in strength due to training, as a function of their initial level of strength. This relationship was *not* statistically significany ($r=-0.13$, $p>0.05$).

DISCUSSION

A positive aspect of this investigation is that repeated cutaneous electrical stimulation was effective in inducing muscle adaptation in man. This regime was comparable in effectiveness to a common clinical technique of isometric exercise and that there were no undesirable side effects associated with the use of electrical stimulation on normal men and women. Our results confirm—with normal subjects—previous reports that electrical stimulation is clinically effective in muscular rehabilitation.

The quantitative increase in muscle strength varies of course with the biological function of the subject and with the protocol of stimulation and the number of times it is applied. By way of comparison our results for electrical stimulation are listed with those from other sources in Table II. Of these sources Godfrey et al. (5) used a total of twelve sessions on a daily basis. Johnson et al. (1977) applied nineteen sessions with a periodicity from one to four days and Kots (8) used a regime similar to ours. Godfrey et al. (5) however observed a superiority of electrical stimulation—in terms of muscular adaption—to normal voluntary contraction using an isokinetic "Cybex" apparatus. The reason for this nonconformity of Godfrey's data is not obvious. Johnson et al. (7) found too that their weaker subjects initially, tended to have the greatest strength increments with training. We observed that our weakest subject did in fact improve the most (74%), but the relationship for the entire group was not significant.

A physiological interpretation of our results involves considerable speculation but our data are consistent with our initial hypothesis that according to Meerson's model of adaptation, repeated muscular contractions, however induced, will trigger the cellular mechanisms of adaptation. In normally innervated muscle the recruitment sequence of fibres appears to be slow-twitch (type I) at low EPSP thresholds and with increased tension being required the fast-twitch (type IIA & B) are recruited —voluntarily via the motor cortex, or reflexly—at higher EPSP thresholds. The motor-unit activation also alternates asynchronously which minimizes metabolic fatigue in the fibres while the muscle as a

Table II. *Comparison of the quantitative effects of electrical stimulation*

Source	Percent change in strength	Mean number of sessions
This study	22	9.5
Currier et al. (1979)	21	10
Kots (1971)	15–20	20
Godfrey et al. (1979)	62–95	12
Johnson et al. (1977)	25–200	19

whole maintains tension. Such concepts of motor-unit recruitment have recently been verified in intact man (9).

We speculate that cutaneous electrical stimulation overrides this normal sequence of recruitment to some extent and tends to activate the fibres collectively while interrupting normal alternation of fibres. We also surmise that the observed adaptations were primarily at the cellular level and did *not* depend on volitional stimuli as Currier et al. (3) have postulated; because the changes were similar in each regime. (Although we have no histochemical evidence for this.)

The therapeutic value of electrically-stimulated muscle contractions appears to lie in the fact that voluntary exertion of the patient is not required; therefore the results of treatment are not so closely bound to his motivation or tolerance for exertion. On the other hand the possible dangers of the technique include neural, vascular and metabolic lesions in the underlying tissue (2, 13). There is also the potential of direct trauma to muscle and connective tissue as a result of too much tension being developed when golgi-tendon inhibition is overridden (4). Other dangers of the technique include the possibility of burns resulting from contact of the electrodes with the skin or open abrasions. However in our study the subjects suffered no ill effects beyond mild muscle fatigue which disappeared after several sessions.

In conclusion cutaneous electrical stimulation appears to be a viable muscle-strengthening technique for patients who are poorly motivated or who find it difficult to achieve a near maximal contraction. In this respect it appears to be as effective as an isometric regime.

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Address for offprints:

Dr D. F. McMiken
Sveriges Lantbruksuniversitet
Faculty of Veterinary Medicine
Department of Medicine I
S-750 07 Uppsala Sweden