Strength Changes in the Normal Quadriceps Femoris Muscle as a Result of Electrical Stimulation
R Keith Laughman, James W Youdas, Tom R Garrett and Edmund Y S Chao

The online version of this article, along with updated information and services, can be found online at:
http://ptjournal.apta.org/content/63/4/494

Collections
This article, along with others on similar topics, appears in the following collection(s):
Electrotherapy
Injuries and Conditions: Lower Extremity

E-Letters
To submit an e-Letter on this article, click here or click on "Submit a response" in the right-hand menu under "Responses" in the online version of this article.

E-mail alerts
Sign up here to receive free e-mail alerts
Strength Changes in the Normal Quadriceps Femoris Muscle as a Result of Electrical Stimulation

R. KEITH LAUHMAN,
JAMES W. YOUDAS,
TOM R. GARRETT,
and EDMUND Y. S. CHAO

The purpose of this study was to examine the effectiveness of an electronic muscle stimulator in strengthening normal quadriceps femoris muscle without the assistance of simultaneous isometric muscle contraction. The sample consisted of 58 subjects who were randomly divided into three independent groups. One group (n = 19) served as controls; one group (n = 20) underwent daily stimulation of the right quadriceps femoris muscle using a specified protocol; and one group (n = 19) underwent isometric strengthening of the quadriceps femoris muscle using a specified protocol. The mechanical force of isometric quadriceps femoris muscle contraction was recorded weekly for the three groups, and the initial and final values were subjected to an analysis of covariance. The electrical-stimulation and isometric-exercise groups had statistically significant increases in quadriceps femoris muscle torque when compared with the nonexercised controls (p < .001). The data supported the use of this electronic stimulator as an appropriate device for strengthening skeletal muscle without voluntary effort.

Key Words: Electric stimulation, Muscular strength, Quadriceps femoris muscle.

Rehabilitation specialists have expressed interest in the application of electrical current to the musculoskeletal system. As a result, there has been a proliferation of electrical devices for which claims of favorable results have been made. A controversy exists, however, as to whether electrical stimulation alone is capable of strengthening normal skeletal muscle. Johnson et al reported strength gains in patients with varied degrees of chondromalacia. Williams and Street and Johnson et al demonstrated increases in strength with the application of electrical stimulation. Conversely, studies by Nowakowska and Massey et al did not support the concept that electrical stimulation increases strength. Currier et al found no significant difference in strength gained by conventional isometric exercise and strength gained from isometric exercise combined with superimposed electrical stimulation.

The previous studies contained many differences in the type of stimulation device, the status of the subjects studied (healthy subjects vs patients), the type of exercise involved (dynamic vs static), and the various methods of documenting strength changes. Our study was designed to minimize these differences and to determine if electrical stimulation without voluntary effort could strengthen normal skeletal muscle.

The specific purpose of our research study was to evaluate the ability of a specific electronic muscle stimulator to increase strength in normal quadriceps femoris (QF) muscle within a five-week interval (25 sessions), without the combined effects of a voluntarily superimposed isometric muscle contraction of the QF muscle. The null hypothesis of no difference in the isometric strength of the right QF muscle before...
and after the five-week treatment period was tested among the three groups at the .05 level of significance.

**METHOD**

**Subjects**

The sample consisted of 58 volunteers, 28 men and 30 women, with no history of musculoskeletal disease. Their ages ranged from 21 to 39 years, with a mean of 23.5 years. Young healthy subjects were chosen to create a “worst case” situation, on the assumption that if a conditioned muscle could be strengthened, a deconditioned muscle would respond similarly, if not more favorably. Each volunteer was randomly assigned to one of three independent groups: a control group, an isometric-exercise group, or an electrical-stimulation group.

**Instrumentation**

The output of the electronic muscle stimulator,* as monitored on an oscilloscope,† consisted of a modulated sine wave with a frequency of 2,500 Hz. This wave form is periodically interrupted, creating 50 bursts of activity a second. Each pulse cycle or burst period is composed of 10 msec of sinusoidal output followed by a 10-msec silent period (Fig. 1). At a current intensity of 70 mA, the stimulator produced a peak-to-peak amplitude of 400 V. As a result, the use of this stimulation at our institution has been restricted to the lower extremities pending further research about upper body stimulation and its effect on the heart. The stimulator was designed to deliver 15 seconds of stimulation followed by a 50-second rest period. Because the current from the stimulator was surged, the subject did not receive the selected level of current intensity for the first 5 seconds. Therefore, the muscle received only 10 seconds of selected current intensity for each muscle contraction.

**Procedure**

Treatment protocol for both experimental groups was fixed by the on-off cycle of the stimulator. The electrical-stimulation group received 15 seconds of electrical stimulation to the right QF muscle, 10 seconds of which was at the selected level, followed by a 50-second rest interval. The isometric-exercise group performed a 10-second voluntary maximal isometric contraction of the right QF muscle, followed by a rest interval of 50 seconds. The right QF muscle of both experimental groups was exercised 10 times once a day, five days a week for five weeks. The control subjects did not undergo QF muscle exercising but did participate in the weekly strength evaluations. All subjects were requested to avoid changing their normal activities during the study.

On Monday of each week, QF muscle strength for all three groups was measured with a torque cell‡ while the subjects sat with their hips and right knees positioned at 60 degrees from full extension (Fig. 2).

---

* Electro-Stim 180, MicroMed Instruments, Montreal, Quebec, Canada H4P 1Z8.
† Model 5111 Single Beam Oscilloscope, Tektronix, Beaverton, OR 97005.
‡ Reaction Torque Sensor, Model 2110, Lebow Associates, Troy, MI 48084.
The torque transducer converted the mechanical force of muscle contraction into an electrical signal, which was displayed on a digital meter. The largest torque value (in kilogram-centimeters) for three QF muscle contractions was used for the statistical analysis. The subjects were not informed of their daily or weekly torque values until the study was completed. During the daily exercise sessions and the weekly evaluations, the performances of the subjects were not influenced by the investigators in any manner.

During the daily electrical-stimulation and isometric-exercise sessions, the subjects were positioned as described earlier. The pelvis was stabilized by a belt 5 cm wide across the anterosuperior iliac spines of the pelvis. The exercised leg was prevented from extending onto the femur by a padded wooden bar or load cell placed anterior to the tibia and superior to the ankle joint. The leg was held firmly against the load cell or bar by a Velcro strap, which kept the knee joint from flexing during the rest period. The unexercised leg was allowed to hang unconstrained over the edge of the table. The reliability of this exercise position has been confirmed by previous investigators.7, 8

The experimental groups had their isometric exercise or stimulation efforts monitored on alternate days. The force produced at the distal tibia was recorded by a load cell and displayed on a polygraph (Grass Model 7**). The torque was calculated by multiplying the load by the distance between the medial joint line of the knee and the shaft of the load cell.

Each subject in the electrical-stimulation group had two Burdick electrodes†† 13 cm in diameter secured to the right thigh. The electrodes were covered with a generous amount of ultrasound transmission gel (Aquasonic 100‡‡). The proximal electrode was placed inferior to the inguinal ligament over the upper margins of the rectus femoris and vastus lateralis muscles to cover the diverging motor branches of the femoral nerve. The distal electrode was secured on the thigh over the distal margin of the vastus medialis muscle, 5 to 7 cm (2-2.75 in) superior and medial to the superior pole of the patella.

The subjects in the electrical-stimulation group were instructed to refrain from assisting with the right QF muscle contraction produced by the stimulator. Although this was difficult to monitor, the force curves themselves were smooth, without abrupt changes in slope, which would be expected from increased torque secondary to voluntary effort (Fig. 3). This smooth curve indicated that the subject was not superimposing an active contraction of the QF muscle along with the tetanic contraction produced by the electrical stimulator.

Analysis

In addition to the weekly means being calculated, the initial and final values of the QF muscle torque for each individual were plotted in scatter diagrams. Each scatter diagram showed the torque values for two groups and their respective linear regression lines. The linear regression lines were compared statistically by analysis of covariance, in which the differences between the final QF muscle torque for the two groups were adjusted for differences in the initial torque values.9

RESULTS

On the average, the control group's strength increased by 2 percent, the isometric-exercise group increased by 18 percent, and the electrical-stimulation group by 22 percent (Tab. 1). Similar trends, but of a lesser magnitude, were observed in the data from the unexercised extremity (Fig. 4). The average weekly torque values of the right QF muscle for the electrical-stimulation group are shown in Table 2.

---

** Grass Instruments Co, 101 Old Colony Ave, Quincy, MA 02169.
†† Burdick Corp, Milton, WI 53563.
Final strength of the electrical-stimulation group was significantly ($F = 21.0; df = 1, 36; p < .001$) higher than that of the control group, even after adjustment was made for initial strength differences (Fig. 5). Final strength of the isometric-exercise group was significantly ($F = 18.8; df = 1, 35; p < .001$) higher than that of the control group (Fig. 6). No significant difference was noted between the electrical-stimulation and isometric-exercise groups (Fig. 7).

The force monitored during the daily exercise sessions for the two groups revealed that the exercise group on the average worked at 78 percent of the maximal isometric QF muscle torque during the seventh contraction, whereas the subjects in the electrical-stimulation group averaged 33 percent of the voluntary maximum.

The subjects in the electrical-stimulation group tolerated progressively increasing amounts of current intensity during the study (Tab. 2). No one in this group complained of patellofemoral joint discomfort during or after their daily sessions. No subject described the current as painful, but most subjects preferred to adapt to the current’s “pins and needles” sensation by increasing the daily treatment intensities gradually.

### DISCUSSION

The literature on rehabilitation has not been in agreement on whether transcutaneous electrical stimulation when used alone is an appropriate technique for strengthening skeletal muscle. Currier and associates reported that significant strength gains in skeletal muscle are achieved only through voluntary muscle contraction.6 The data from the present preliminary investigation do not support their conclusions. Data from this study indicate that 25 training sessions with the described electronic muscle stimulator to the right QF muscle, without a simultaneous voluntary contraction, produce a statistically significant increase in the muscle’s isometric torque when compared with the results in nonexercised controls.

---

**Table 1**

**Right Quadriceps Femoris Muscle Torque Developed Before and After a Five-Week Training Period**

<table>
<thead>
<tr>
<th>Group</th>
<th>Control ($n = 19$)</th>
<th>Exercise ($n = 19$)</th>
<th>Stimulation ($n = 20$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X \pm s$ (kg-cm)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Before</td>
<td>1,524.7 ± 438.0</td>
<td>1,588.4 ± 593.7</td>
<td>1,464.2 ± 429.0</td>
</tr>
<tr>
<td>After</td>
<td>1,555.0 ± 437.1</td>
<td>1,874.4 ± 592.8</td>
<td>1,786.5 ± 399.6</td>
</tr>
<tr>
<td>Change (kg-cm)</td>
<td>30.3</td>
<td>286.0</td>
<td>322.3</td>
</tr>
<tr>
<td>%</td>
<td>2.0</td>
<td>18.0</td>
<td>22.0</td>
</tr>
<tr>
<td>Range (kg-cm)</td>
<td>851-2,283</td>
<td>673-2,468</td>
<td>766-2,265</td>
</tr>
<tr>
<td>Before</td>
<td>969-2,311</td>
<td>945-2,786</td>
<td>1,124-2,455</td>
</tr>
</tbody>
</table>

Fig. 4. Percentage of strength increase observed for all three groups for the exercised and the unexercised leg.
TABLE 2
Current Intensity Tolerated by the Electrical-Stimulation Group and the Weekly Quadriceps Femoris Muscle Torque Values During the Five-Week Training Period

<table>
<thead>
<tr>
<th>Week</th>
<th>Intensity (mA)</th>
<th>Strength (kg-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X  s Range</td>
<td>X  s Range</td>
</tr>
<tr>
<td>1</td>
<td>34.3 9.7 19-72</td>
<td>1,504 400 623-2,120</td>
</tr>
<tr>
<td>2</td>
<td>45.4 13.5 28-90</td>
<td>1,595 444 598-2,163</td>
</tr>
<tr>
<td>3</td>
<td>50.8 14.1 25-88</td>
<td>1,674 425 888-2,320</td>
</tr>
<tr>
<td>4</td>
<td>55.9 13.0 34-88</td>
<td>1,750 406 910-2,533</td>
</tr>
<tr>
<td>5</td>
<td>59.6 13.0 37-88</td>
<td>1,786 400 1,124-2,455</td>
</tr>
</tbody>
</table>

stimulation group was 22 percent. Because the isometric-exercise and electrical-stimulation groups also underwent the same weekly evaluations in addition to their daily training sessions and because only the relative changes between groups were examined, the evaluation process itself did not introduce an additional uncontrolled variable.

Strength change observed for the untrained left QF muscle provides additional support for the cross-education effect of muscle strengthening. Interestingly, it has recently been suggested that the mechanism for cross education consists of neural factors (motor learning) that increase the maximal level of muscle activation at various levels of the nervous system. Cross education also was observed in the subjects in the electrical-stimulation group, even though they exerted no voluntary effort.

Fig. 6. Comparison of control (n = 19; only 18 points shown on the graph owing to the overlap of two subjects' data) and isometric-exercise subjects (n = 19). Data reveal a significant (p < .001) difference between the two groups.

The weekly data demonstrated that on the average the strength values of the stimulation subjects and their tolerance of the current intensity increased rapidly during weeks 1 through 3, with a slight leveling

Fig. 7. Comparison of the isometric-exercise (n = 19) and electrical-stimulation (n = 20) subjects. No significant difference was found between the two groups.
off between weeks 4 and 5. No correlation was found between the current intensities of individual subjects and the strengthening results.

Percentage increase of right isometric QF muscle torque between weeks 1 and 6 indicated that the electrical-stimulation group had a larger strength gain than the isometric-exercise group (Fig. 4). This appears to be paradoxical, however, because the daily exercise output of the isometric-exercise group was considerably greater in terms of peak torque than that of the electrical-stimulation group.

The lower exercise torque observed in the electrical-stimulation group could have resulted from either a reduced QF muscle contraction or a cocontraction of the subject’s right hamstring muscle. Liberson has stated, however, that the electrical stimulation of the agonist produces a simultaneous inhibition of the antagonist, indicating that the hamstring muscles would not be active during the stimulation of the QF muscle and therefore could not be responsible for the observed reduced exercise torque. If Liberson’s data are correct, our study indicates that the subjects in the electrical-stimulation group strengthened their right QF muscles while experiencing less joint compressive forces than the subjects in the isometric-exercise group. The implication is that the patient with degenerative joint disease or total knee arthroplasty could have less compressive force across the knee joint during QF muscle strengthening by using an appropriate muscle stimulator in place of isometric exercise. Additional research is necessary to clarify this relationship and to identify the optimal treatment regimen (current intensity, treatment duration, and treatment frequency).

CLINICAL IMPLICATIONS

Eriksson and Häggmark have reported that under clinically controlled conditions, transcutaneous electrical stimulation retards the biochemical and histologic changes that accompany disuse atrophy of the human QF muscle after major reconstructive knee surgery. With an appropriate muscle stimulator, transcutaneous electrical stimulation can significantly increase the strength of normal skeletal muscle and, in athletes, may reduce the rehabilitation time currently required after knee surgery. A tetanic muscle contraction produced by a device with the electrical characteristics similar to those of the Electro-Stim 180 may improve a patient’s postoperative knee function by isometrically strengthening the weak muscle group or by providing a passive, intermittent stretch to the shortened soft tissues of the joint. This therapeutic effect may be achieved while subjecting the joint and surrounding soft tissues to stresses of lesser magnitude than those developed through isometric contractions.

CONCLUSIONS

The present study indicates that under proper conditions, a specific transcutaneous electrical stimulator can produce a statistically significant change in the strength of skeletal muscle. The Electro-Stim 180 produced this increased torque within a clinically practical time period consisting of treatments lasting 10 to 15 minutes once a day for five weeks. If electrical stimulation is to be accepted, the claims made for the various devices must be reliably verified, and the medical community must be made aware of the differences in muscle stimulators.

REFERENCES

Strength Changes in the Normal Quadriceps Femoris Muscle as a Result of Electrical Stimulation
R Keith Laughman, James W Youdas, Tom R Garrett and Edmund Y S Chao