Hypertrophy, Resistance Training, and the Nature of Skeletal Muscle Activation

Christine L. Ruther¹, Catherine L. Golden³, Robert T. Harris¹, and Gary A. Dudley²*

¹The Biometrics Corp. and ²National Aeronautics and Space Administration, Kennedy Space Center, Florida 32899; ³Dept. of Exercise and Sport Science, University of Florida, Gainesville, Florida 32611; ⁴Dept. of Biological Sciences, Ohio University, Athens, Ohio 45701.

Reference Data

ABSTRACT

This study compared hypertrophy of the left quadriceps femoris (QF) after sedentary subjects trained 2 days a week for 9 weeks using electrical stimulation or voluntary effort. Each day, 3 to 5 sets of 10 lengthening and shortening actions were performed. Maximal effort was used for voluntary training. Electrical stimulation evoked tetanic force in 50% or more of the QF. Muscle cross-sectional area, determined by MR imaging, showed a group × time × leg interaction (p < 0.05). This reflected a 10% increase for the left QF with electrical stimulation as compared to the 4% increase after voluntary training. The right, untrained QF did not change in size (p > 0.05) after either intervention. Voluntary and electrical stimulation trainees, respectively, showed 25 and 56% increases (p < 0.05) in training torque. The results suggest that voluntary effort limits hypertrophy early in resistance training, as done in this study.

Key Words: electromyostimulation, strength training, neuromuscular

Introduction

The results of numerous studies have been interpreted to suggest that the increase in strength early in resistance training cannot be fully accounted for by an increase in skeletal muscle size (15, 21, 23, 25, 29, 31, 34, 35). The relative increase in strength was found to be greater than the relative increase in skeletal muscle size, or increases in strength and skeletal muscle size were not clearly related. Accordingly, it has been put forth that increases in strength early in resistance training reflect mainly neural adaptations, although this is not universally accepted (4, 5, 9, 15, 17, 18, 24, 31, 34).

It seems reasonable that neural adaptations would occur when sedentary individuals start resistance training. Numerous investigators have suggested that activation of skeletal muscle is not complete when untrained individuals perform maximal voluntary efforts (4, 11, 33, 36, 37). It seemed to us that this inhibition of activation early in resistance training might limit loading, and thereby compromise hypertrophy.

The interest of the present study was to address this issue. We compared the hypertrophic response of the left quadriceps femoris muscle group (QF) after 9 weeks of resistance training when muscle actions were evoked by maximal voluntary effort versus surface electrical stimulation that elicited tetanic force of 50% or more of the QF. The right QF was not trained and served as an internal control. Skeletal muscle cross-sectional area (CSA) was measured by magnetic resonance imaging. We hypothesized that hypertrophy would be greater with electrical stimulation than with voluntary training if some neural inhibitory mechanisms limit activation during voluntary effort.

We found a significant group × time × leg interaction concerning QF average CSA. This was due to a 10% increase for the left QF of the electrical stimulation trainees as compared to a 4% increase with voluntary training. It is suggested, therefore, that inhibition of activation during voluntary effort early in resistance training, as performed in this study, limits hypertrophy.

Methods

General Design
Sixteen subjects were recruited for this study. They were familiarized with surface electrical stimulation of the quadriceps femoris muscle group (QF) and the resistance training protocol. All 16 were willing to participate and subsequently performed 9 weeks of resistance training. Magnetic resonance (MR) images of the thighs were taken both before and after training to assess skeletal muscle cross-sectional area (CSA). Torque developed during training was recorded to assess loading and improvement in performance.

Subjects
Sixteen healthy adults (13 men and 3 women) not accustomed to lower body resistance training were recruited from the contractor work force at the Kennedy...
Space Center. Their age, height, and weight were \( 33 \pm 3 \) yrs, \( 176 \pm 2 \) cm, and \( 82 \pm 4 \) kg. All were exposed to surface electrical stimulation of the left QF and the resistance training protocol on two or three occasions so we could select subjects who could tolerate the level of electrical stimulation to be used in this study. Eight (6 men and 2 women) felt comfortable with it and were assigned to the electrical stimulation group. The other 8 performed voluntary training. Familiarization was kept to a minimum to avoid training adaptations. Before any testing or training, each subject gave informed written consent to participate; the study was approved by the Human Research Review Board at the Kennedy Space Center.

**Resistance Training**

The left QF was subjected to 9 weeks of resistance training. The right QF was not trained and served as an internal control. Twice each week, 3 to 5 sets of 10 coupled lengthening and shortening isovelocity (1.31 rad/s) actions were executed with 3 min of rest between sets. Three sets were performed for Weeks 1 through 3, then 4 sets for Weeks 4 through 6, and 5 sets for Weeks 7 through 9. All training and testing was done on a KIN/COM isovelocity loading dynamometer (Chattecx, Chattanooga, TN) with subjects seated as described previously (11). Muscle actions traversed a 1.31 rad arc between 0.17 and 1.48 rad below horizontal. Lengthening actions started at 0.17 rad below horizontal and shortening actions started at 1.57 rad. Torque between 0.44 and 1.32 rad was integrated for each action of the first 3 sets executed each training day, and was subsequently averaged per week so that the magnitude of the training stimulus and performance could be examined.

**Muscle Activation**

Voluntary training was performed using maximal effort. A computer controlled transcutaneous electrical stimulation system was used for surface electrical stimulation (12). Voltage was delivered across the skin through two self-adhesive, carbonized rubber electrodes (Tenzcare, 3M, St. Paul, MN) applied to the skin overlying the QF. The electrodes (76 x 114 mm) were centered distally and proximally over the vastus medialis and vastus lateralis muscles, respectively. Each involuntary muscle action was evoked by a 1-s train of 500 \( \mu \)s sinusoidal pulses delivered at 50 Hz.

Stimulation current was adjusted so that isometric torque was approximately 70% of maximal voluntary at the start of training, and was subsequently used to evoke each shortening and lengthening action. Current was held constant during each training session for a given subject. Over the course of training, current was progressively increased to provide an ever increasing training stimulus. By the end of training, stimulation evoked an isometric torque that was approximately 80% of pretraining maximal voluntary.

**Magnetic Resonance Imaging**

Proton MR images of both thighs were obtained pre- and postraining using a 1.5 Tesla superconducting magnet (General Electric, Milwaukee). Transaxial slices 1 cm thick and spaced 0.5 cm apart were taken from the knee joint to the head of the femur. Ink marks on the thigh aligned with the cross-hairs of the imager and a foot brace allowed for similar positioning of the subjects over repeat scans. MR images (TR/TE, 600/20, 4 NEX, 256 x 256 matrix resolution) were collected within a 40-cm rectangular field of view of the whole body coil. Data were transferred to a Macintosh computer for determination of skeletal muscle CSA using a modified version of the public domain NIH Image software package as done previously (34).

The QF and hamstring muscle groups, the individual vasti muscles, and the rectus femoris muscle borders were traced by an individual who was blind to their source, and the CSA of each user-defined region of interest was subsequently calculated. The coefficient of variation for these measures in our hands averages 2 to 3%. Average CSA for each skeletal muscle group or muscle of interest was determined by averaging values over 9 contiguous slices from the mid thigh. This region of the thigh was chosen because it represents the maximal CSA of each of the QF muscles (32).

**Statistics**

Multivariate analyses of variance with repeated measures were run with the SAS statistical package to analyze data. CSA data for the QF were compared to examine the major effect of training on skeletal muscle size. When a significant three-way interaction was found (group x time x leg), individual skeletal muscle CSA data were further analyzed to determine which muscles were responsible for the hypertrophy (muscle x time x leg). Performance data were compared using a group x time x muscle action model. When significant interaction or main effects were found, means were compared using a Duncan's multiple range test. The level of significance was set at \( p < 0.05 \).

**Results**

The 8 stimulation trainees tolerated the intervention quite well. Overall, integrated torque, averaged over the first 3 training sets for the 2 sessions each week, was less \( (p < 0.05) \) for electrical stimulation than for voluntary training. This was due mainly to lower \( (p < 0.05) \) values for shortening actions, especially at the start of training. Average integrated torque increased \( (p < 0.05) \) 25 and 24% for shortening and lengthening actions, respectively, over the course of training with voluntary effort. The corresponding increases \( (p < 0.05) \) with electrical stimulation training were 53 and 60%, respectively.

There was a group x time x leg interaction \( (p < 0.05) \) for the overall model examining changes in QF average CSA with training (Table 1). This was due to
Table 1

<table>
<thead>
<tr>
<th>Torque*</th>
<th>Elec. stim. (n = 8)</th>
<th>Voluntary (n = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Week 1</td>
<td>Week 9</td>
</tr>
<tr>
<td>Shorten</td>
<td>86 ± 6</td>
<td>133 ± 11</td>
</tr>
<tr>
<td>Lengthen</td>
<td>162 ± 10</td>
<td>258 ± 18</td>
</tr>
</tbody>
</table>

Note. Values are mean ± SE in Nm.
*Increase, p < 0.05, in integrated training torque for each type of muscle action for each group; overall torque less for elec. stim. than for voluntary group, p < 0.05.

Table 2
Average CSA of Muscle Groups Before and After Resistance Training W/Surface Electr. Stimul. vs. Voluntary Effort

<table>
<thead>
<tr>
<th>Muscle</th>
<th>Elec. stim. (n = 8)</th>
<th>Voluntary (n = 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
</tr>
<tr>
<td>Quadriceps femorisa</td>
<td>L 75.5</td>
<td>83.1</td>
</tr>
<tr>
<td></td>
<td>±5.2</td>
<td>±5.5</td>
</tr>
<tr>
<td></td>
<td>R 76.5</td>
<td>77.7</td>
</tr>
<tr>
<td>Rectus femorisb</td>
<td>L 8.1</td>
<td>9.4</td>
</tr>
<tr>
<td></td>
<td>±0.9</td>
<td>±1.1</td>
</tr>
<tr>
<td></td>
<td>R 8.7</td>
<td>9.1</td>
</tr>
<tr>
<td>Vastus interm.3</td>
<td>L 25.2</td>
<td>27.4</td>
</tr>
<tr>
<td></td>
<td>±1.6</td>
<td>±1.7</td>
</tr>
<tr>
<td></td>
<td>R 25.7</td>
<td>26.2</td>
</tr>
<tr>
<td>Vastus laterals3c</td>
<td>L 26.7</td>
<td>30.2</td>
</tr>
<tr>
<td></td>
<td>±2.2</td>
<td>±2.2</td>
</tr>
<tr>
<td></td>
<td>R 24.5</td>
<td>25.3</td>
</tr>
<tr>
<td>Vastus medialisb</td>
<td>L 13.4</td>
<td>14.5</td>
</tr>
<tr>
<td></td>
<td>±1.2</td>
<td>±1.2</td>
</tr>
<tr>
<td></td>
<td>R 15.5</td>
<td>15.8</td>
</tr>
<tr>
<td>Hamstrings</td>
<td>L 21.1</td>
<td>21.9</td>
</tr>
<tr>
<td></td>
<td>±1.8</td>
<td>±2.1</td>
</tr>
<tr>
<td></td>
<td>R 19.5</td>
<td>20.3</td>
</tr>
<tr>
<td></td>
<td>±1.7</td>
<td>±2.0</td>
</tr>
</tbody>
</table>

Note. Values are mean ± SE in cm².
*aSignificant group x time x leg interaction, p < 0.05, due to increase in size of left, trained QF for elec. stim; btime x side effect for elec. stim, p < 0.05; cLarger increase other than QF muscles, p < 0.05.

of the four QF muscles (Table 2). Of these, the vastus lateralis muscle showed the greater growth (p < 0.05). Neither intervention influenced average CSA of the hamstring muscle group nor of skeletal muscle of the contralateral, untrained thigh.

Discussion

The interest of the present study was to determine whether hypertrophy early during the course of resistance training, performed by previously sedentary individuals, was limited by voluntary effort. Numerous studies have reported that some neural inhibitory mechanisms limit force during maximal voluntary efforts performed by untrained individuals, and that adaptations early in resistance training occur mainly in motor control (4, 5, 9, 11, 15, 17, 18, 24, 31, 32, 34, 36, 37). In light of these observations, it seemed to us that inhibition of activation of skeletal muscle early in resistance training might compromise loading, and thereby hypertrophy. We therefore tested the hypothesis that hypertrophy would be greater during the early course of resistance training when lengthening and shortening actions of the quadriceps femoris muscle group (QF) were evoked by surface electrical stimulation versus maximal voluntary effort.

A successful test of our hypothesis required that electrical stimulation evoke marked force development by a large portion of the QF. To this end, we used a 1-s train of 500 µs sinusoidal pulses delivered at 50 Hz to evoke each lengthening and shortening action. This pulse duration, pulse frequency, and training duration were chosen because, when combined, they result in tetanic force (7, 10, 22). The level of electrical stimulation was also set to evoke an isometric torque equal to 70 to 80% of pretraining maximal voluntary. This was done because we have shown that such force development, evoked by surface electrical stimulation, arises from activating 50 to 60% of the average CSA of the QF (1). We then employed a training protocol common to those generally used in resistance exercise. Multiple sets of 10 coupled lengthening and shortening actions were performed 2 days each week.

The most significant result of the present study was that hypertrophy was greater with electrical stimulation than with voluntary resistance training. It could be argued that this was due to less than optimal effort by our voluntary trainees. They were treated no differently, however, than subjects in our previous resistance training studies (10, 20). They also showed a marked increase in performance and a modest increase in skeletal muscle size. Comparable results have been reported by others after short-term resistance training (19, 28). These observations, taken together, attest to the validity of the resistance training program in this study.

It is also possible that the measure of skeletal muscle size used in this study was in error. This is highly unlikely, as magnetic resonance (MR) imaging provides unparalleled visualization of skeletal muscle.
morphology (14). Therefore, that the results of the present study appear to support our contention that inhibition of activation during maximal voluntary effort limits loading early in resistance training as employed in this study, and thereby hypertrophy.

We believe this reflects a conservative approach of the neuromuscular system to maintain performance on an acute and long-term basis while utilizing energy efficiently. For an acute episode of voluntary exercise, it has been put forth for some time that skeletal muscle is activated in an asynchronous manner to optimize performance while minimizing metabolic demand (6, 27). When the same exercise protocol is evoked by artificial activation, however, the same muscle fibers are activated repeatedly. This exaggerates metabolic demand, and fatigue ensues. This is why we and others have reported that fatigue is substantially greater for a given bout of exercise when muscle actions are evoked by electrical stimulation as opposed to voluntary effort (1, 26).

Thus, electrical stimulation on the one hand imposes marked mechanical stress on a given amount of muscle tissue that evokes hypertrophy, but on the other hand it seriously compromises the ability to maintain force in an acute sense. The neural strategy for voluntary activation, by contrast, is designed to minimize mechanical stress, and thereby metabolic demand, such that performance can be maintained.

On a long-term basis, several neural adaptations have been cited as explaining marked increases in performance early in resistance training with modest hypertrophy. Enhanced recruitment of high-threshold motor units and alterations in synchronization have both been suggested (9, 18, 25, 30, 31, 32, 34). Regardless of the neural mechanism responsible, neuromuscular performance has been improved without owing solely to the costly metabolic event of adding skeletal muscle tissue. Hypertrophy ensues as training continues because skeletal muscle is exposed to ever increasing loads as performance improves (34). The conservative approach to enhancing performance early in resistance training, therefore, seems to be to take advantage of the greater plasticity of the motor control system compared to the skeletal muscle system.

Electrical stimulation training evoked approximately a 10% increase in QF size in this study. This result is in accord with those reported by some investigators (2, 3, 8, 16) but not others. This may reflect the greater difficulty of detecting moderate increases in muscle size using the needle biopsy technique (13) as compared to MR imaging as done in this study (14). It may also be that biopsy samples were not always taken from regions of the muscle that had been trained through electrical stimulation. We have previously shown that electrical stimulation does not activate a uniform mass of muscle within a given location of the QF among subjects (1). Such growth of skeletal muscle within particular regions of the QF would not be missed with MR imaging.

The 10% increase in QF average CSA found in this study may not seem impressive. However, only about 50% of the average CSA of the QF was being activated by electrical stimulation. This is based on the previous observation that surface electrical stimulation of the QF at a current that evokes a torque equal to approximately 75% of maximal voluntary isometric activates 54% of the QF average CSA (1). In this study current was set to evoke a torque equal to 70 to 80% of maximal voluntary isometric. This being the case, a 10% increase in size of the whole QF probably reflected a 20% increase in size of the half of the muscle that was stimulated.

Electrical stimulation did not evoke an increase in average CSA of the hamstring muscle group of the trained thigh, nor of any muscle of the contralateral, untrained thigh in this study. This lack of hypertrophy of the hamstring muscle group shows that stimulation was localized to the anterior thigh compartment (1). The lack of hypertrophy in the contralateral limb suggests that the crossover effect of electrical stimulation for strength reported by some but not others is not due to an increase in muscle size (15).

In summary, the results of the present study showed that surface electrical stimulation evokes greater hypertrophy than voluntary effort early in resistance training as employed in this study. This should not be viewed as a negative consequence of voluntary effort, but instead as a conservative strategy of the neuromuscular system to enhance performance. Enhanced performance early in resistance training occurs more by taking advantage of the plasticity of voluntary motor control than by the costly metabolic event of net contractile protein accumulation.

**Practical Applications**

The results might be interpreted to mean that electrical stimulation could be used as an adjunct to resistance training for power/strength athletes. We would suggest, however, that this is not the case. Most athletes are well conditioned, not sedentary like the subjects in this study. Power/strength athletes have already enjoyed major neural adaptations to resistance exercise, and can thus impose marked mechanical stress on skeletal muscle. Our results do suggest that researchers examining the effect of different factors on hypertrophy should thoroughly acclimate their subjects to resistance exercise before beginning the investigation.

**References**


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*Present address for Gary A. Dudley: Dept. of Exercise Science, University of Georgia, Athens, GA 30602.