The Effects of a Resistance Training Program on Average Motor Unit Firing Rates
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ABSTRACT
The purpose of this study was to examine the effects of an 8-week resistance training program on the relationship between average motor unit firing rates and recruitment threshold in the vastus lateralis. Eleven untrained men (mean ± SD age = 22.5 ± 4.2 years) volunteered to perform resistance training three times per week for 8 weeks. At the end of each week during the training, the subjects were tested for unilateral isometric strength of the dominant leg extensors. The subjects also performed a 6-second isometric muscle action at 80% of the maximum voluntary contraction while surface electromyographic (EMG) signals were detected from the vastus lateralis. The surface EMG signals were then decomposed into individual motor unit action potential trains, and the recruitment threshold and average firing rate for each motor unit were calculated. The results showed that despite increases in isometric strength, the resistance training program had no effect on the linear slope coefficient for the average motor unit firing rate versus recruitment threshold relationship. Thus, the resistance training did not bring the average motor unit firing rates of the high-threshold motor units up to a level comparable to those of the low-threshold motor units.

Key Words: Electrophysiology; Motor neuron; Exercise

INTRODUCTION
Increases in strength during a resistance training program are thought to be due to a combination of neural and hypertrophic factors (5). Generally speaking, the neural factors (e.g., increased motor unit recruitment, greater firing rates, enhanced synchronization, reduced co-activation of the antagonist muscle, etc.) are considered most important during approximately the first four weeks of the training program, while the increases in muscle size via increased contractile protein content are thought to dominate thereafter. A fairly common finding among early studies that examined the neural adaptations is the increased electromyographic (EMG) amplitude during a maximal muscle action (3,5). Since EMG amplitude is influenced both by the number of active motor units and their firing rates, it was difficult to determine the exact cause for the increases in EMG amplitude with resistance training. With improvements in the technology used to detect intramuscular EMG signals, however, several laboratories began using needle and/or fine wire techniques to examine the electrical activities of individual motor units. This allowed for examination of recruitment thresholds, peak and average motor unit firing rates, and motor unit synchronization, all of which could contribute to the neural adaptations associated with resistance training.

With the advent/beginning of the new techniques for examining the activities of individual motor units, several studies began investigating the mechanism(s) that could underlie the increases in EMG amplitude with resistance training. It quickly became apparent, however, that a general description of the neuromuscular adaptations to resistance training could not be made. For example, Kamen and Knight (4) reported increases in peak motor unit firing rates for the vastus lateralis during a maximal isometric muscle action after just one testing day/session. Once the subjects began the resistance training program, however, the peak motor unit firing rates decreased back to baseline levels. Furthermore, there were no changes in peak motor unit firing rates during submaximal muscle actions at 10% and 50% of the isometric maximum voluntary contraction (MVC). Thus, the responses during submaximal muscle actions were different from those during maximal muscle actions, which highlighted the importance of the experimental protocol when examining the activities of individual motor units (4). It is also important to acknowledge the technical difficulties that can occur with intramuscular EMG methods. For example, needle electrodes often cause severe pain during high force muscle actions, thereby limiting their use to submaximal muscle actions. In addition, fine wire EMG techniques run the risk of wire breakage inside the muscle during a contraction. Furthermore, with both needle and fine wire EMG methods, there is a relatively small pick-up area associated with the recording electrodes. Thus, intramuscular EMG techniques are capable of detecting the activities of just a few motor units (at most) during any given muscle action. For large limb muscles that can consist of several hundred motor units, it is possible that the activities of the motor units within the pick-up area of the recording...
electrodes are not reflective of the entire motor unit pool. Recently, however, De Luca et al. (2) developed a surface EMG technique that can be used to examine the activities of individual motor units. One of the most important advantages of this method when compared to intramuscular EMG is that it is much more comfortable for the subject and allows for examination of motor unit activities during both maximal and submaximal muscle actions. In addition, the pick-up area associated with surface EMG is typically much greater than that for intramuscular EMG, which allows many more motor units to be identified. Unfortunately, the increased pick-up area also results in more complex EMG signals, thereby increasing the difficulty associated with decomposition. The challenges associated with decomposition of surface EMG signals have been well documented (1). Fortunately, many of these challenges have been overcome, but no previous investigations have used the surface EMG decomposition technique to examine changes in motor unit firing rates during resistance training. Therefore, the purpose of this study was to examine the effects of an 8-week resistance training program on the relationship between average motor unit firing rates and recruitment threshold in the vastus lateralis using surface EMG.

METHODS
Subjects
Eleven untrained men (mean ± SD age = 22.5 ± 4.2 years; height = 183.3 ± 6.9 cm; body weight = 81.6 ± 13.8 kg) volunteered to participate in this investigation. The study was approved by the University Institutional Review Board for Human Subjects, and all subjects completed a health history questionnaire and signed a written informed consent document before testing. Each subject was also free from all neuromuscular and/or musculoskeletal disorders and had not performed resistance training for at least 6 months prior to the study.

Resistance Training
All subjects were required to perform a supervised resistance training program for eight weeks. During this program, the subjects came to the laboratory three times per week and performed the bench press, leg press, and leg extension exercises. For each exercise, the subjects performed three sets of 10-12 repetitions with approximately 80% of their one repetition maximum (1-RM), and the weight was increased when the subject could perform 12 repetitions for all three sets. Thus, the weights used for each exercise increased as the subjects got stronger during the eight week training program. In addition, the subjects were provided with at least two minutes of rest between each set during their training program to ensure that they did not fatigue to the point where their strength levels were reduced. All training sessions were supervised by a certified strength and conditioning specialist (CSCS).

Isometric Testing
At the end of each week during the training program, the subjects were tested for maximal unilateral isometric strength of the dominant (based on kicking preference) leg extensors in a custom-built chair (Cybex, Ronkonkoma, New York) designed for isometric testing of the leg extensors. Specifically, the subjects were required to perform two, 4-sec maximal muscle actions of the leg extensors separated by 1-min of rest at a joint angle of 120° between the thigh and the leg. A tension/compression load cell (model SSM-AJ-500, Interface, Scottsdale, AZ) was attached to an ankle cuff to allow for measurement of force production. In addition, during each maximal muscle action, a surface EMG signal was detected from the biceps femoris and used for biofeedback. Specifically, during each muscle action, the subjects were instructed to produce as much leg extension force as possible without generating an EMG signal from the biceps femoris. This technique ensured that the leg extension force that was being produced was free from any co-contraction force from the leg flexor muscles. After determination of the isometric maximum voluntary contraction (MVC), the subjects performed a trapezoid isometric muscle action of the leg extensors. Specifically, the subjects were required to linearly increase isometric leg extension force from 5% to 80% MVC over a period of four seconds. They then held the force constant at 80% MVC for six seconds, followed by a linear decrease in force from 80% to 5% MVC in four seconds. The subjects were provided with a visual template and feedback of their force production through the load cell during the trapezoid isometric muscle action, and trials were repeated if the actual force production varied more than 5% from the template. The visual template is developed with the software provided by the Surface EMG Decomposition System (Delsys, Inc., Boston, MA).

EMG Signal Detection and Processing
Four separate bipolar surface EMG signals were detected from the vastus lateralis during the trapezoid isometric muscle action with a surface array EMG sensor (Delsys, Inc., Boston, MA) that consists of 5 gold pin electrodes (Figure 1). Prior to detecting any EMG signals, the skin over the belly of the vastus lateralis was shaved and cleansed with rubbing alcohol. The surface EMG decomposition sensor was then placed over the belly of the vastus lateralis and fixed with adhesive tape. The reference
Table 1. Leg extension and bench press one-repetition maximum (1-RM) strength for each subject before (Pre) and after (Post) the training program.

<table>
<thead>
<tr>
<th>Subject Number</th>
<th>Leg Press 1-RM (kg)</th>
<th>Bench Press 1-RM (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre</td>
<td>Post</td>
</tr>
<tr>
<td>1</td>
<td>244.9</td>
<td>399.2</td>
</tr>
<tr>
<td>2</td>
<td>244.9</td>
<td>471.7</td>
</tr>
<tr>
<td>3</td>
<td>267.6</td>
<td>408.2</td>
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<td>4</td>
<td>308.5</td>
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</tr>
<tr>
<td>5</td>
<td>226.8</td>
<td>390.1</td>
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<td>6</td>
<td>204.1</td>
<td>367.4</td>
</tr>
<tr>
<td>7</td>
<td>226.8</td>
<td>430.9</td>
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<tr>
<td>8</td>
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<td>349.3</td>
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<tr>
<td>9</td>
<td>204.1</td>
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<tr>
<td>10</td>
<td>267.6</td>
<td>326.6</td>
</tr>
<tr>
<td>11</td>
<td>149.7</td>
<td>276.7</td>
</tr>
<tr>
<td>Mean ± SD</td>
<td>233.8 ± 41.3</td>
<td>380.6 ± 70.5</td>
</tr>
</tbody>
</table>

electrode was placed over the patella. All analog EMG signals were low-pass (fourth-order Butterworth; 24 dB/octave slope; 9,500 Hz cutoff) and high-pass (second-order Butterworth; 12 dB/octave slope; 100 Hz cutoff) filtered prior to sampling at a rate of 20,000 samples/second. The digitized EMG signals were then digitally bandpass filtered with an eighth-order Butterworth filter (24 dB/octave on both the high- and low-pass slopes; cutoff frequencies of 250 and 2,000 Hz). The four separate filtered EMG signals then served as the input to the Precision Decomposition III (PD III) algorithm (EMGWorks 4.0, Delsys, Inc., Boston, MA) (2). However, prior to decomposition, baseline noise levels were monitored by the investigator to ensure that the EMG signals were not excessively contaminated. After acquisition, the EMG signals were decomposed with the PD III technique, which was designed specifically for decomposing surface EMG signals into their constituent motor unit action potential trains. These trains were then used to calculate the recruitment threshold and average firing rate of each motor unit. Specifically, as shown in Figure 2, each motor unit that was detected by the PD III algorithm begins firing at a specific location on the force curve. This location is defined as the recruitment threshold for that motor unit. The earlier recruited motor units are defined as low-threshold, while the later recruited motor units are high-threshold. In addition, once all motor units have been recruited and the relative force production has plateaued at the desired level, each motor unit is firing at a rate that remains relatively constant, but fluctuates around an average value (Figure 2). This average value is defined as the average firing rate for that particular motor unit. Once the recruitment thresholds and average firing rates for all active motor units have been calculated, a plot of their relationship can be created with average firing rate on the y-axis and recruitment threshold on the x-axis. All data analyses were performed by the first author.

### Statistical Analyses

The relationship between average firing rate and recruitment threshold was examined using linear regression analyses. The resulting mean linear slope coefficients were then compared statistically across weeks one through eight using a one-way repeated measures analysis of variance (ANOVA). A one-way repeated measures ANOVA was also used to determine if there were significant mean differences among the unilateral isometric leg extension strength values across weeks one through eight. When appropriate, follow-up analyses included Bonferroni post hoc comparisons. In addition, the mean bench press and leg press 1-RM strength values before (Pre) and after (Post) the 8-week resistance training program were compared using two separate paired-samples t-tests. An alpha level of 0.05 was used for all statistical analyses.

### RESULTS

The mean ± SD number of motor units decomposed during the submaximal isometric muscle actions at 80% MVC was 28.1 ± 0.6 motor units. In addition, the mean ± SEM accuracy of the decomposition for each motor unit was 88.3 ± 0.1%. Table 1 shows the bench press and leg press 1-RM strength values for each subject during the Pre- and
Post-training testing. The resistance training resulted in significant increases in both bench press and leg press 1-RM strength. Figure 4 demonstrates the mean ± SD unilateral isometric leg extension strength values across the 8-week resistance training program. The resistance training resulted in an initial decrease in isometric strength during the first two weeks of training, followed by a linear increase during the remaining six weeks (see Figure 4 for pairwise differences in strength). Figure 5 shows the mean ± SD linear slope coefficients for the relationship between average motor unit firing rate and recruitment threshold across the 8-week resistance training program. There were no significant mean differences among the linear slope coefficients from weeks one through eight. Figure 3 shows an example of the relationship between average motor unit firing rate and recruitment threshold for one subject during the Pre- and Post-training testing.

DISCUSSION

The results from the present study indicated that an intensive 8-week resistance training program did not affect the relationship between average motor unit firing rate and recruitment threshold for the vastus lateralis. Specifically, the average firing rates of the high-threshold motor units were always lower than those of the low-threshold motor units (Figure 2), and the linear slope of the relationship between average firing rate and recruitment threshold did not change with resistance training (Figure 5). Thus, the resistance training program did not bring the average firing rates of the high-threshold motor units up to levels that are comparable to those of the low-threshold motor units. Another important finding was that the resistance training caused an initial decrease in unilateral isometric leg extension strength during the first two weeks of training, followed by a linear increase throughout the remaining six weeks. The initial decrease in strength was most likely due to soreness from the resistance training, since all subjects were untrained, and the resistance training program was relatively demanding. In fact, all of the subjects reported that they had experienced muscle soreness during the first two weeks of the training. For the most part, however, this soreness was reduced after the second week of training, and the strength levels of the subjects began increasing during the isometric strength test and on all training exercises.

Several previous studies have investigated the neuromuscular adaptations associated with resistance training. For example, Van Cutsem et al. (9) reported that 12 weeks of dynamic resistance training of the dorsiflexors increased the occurrence of brief motor unit interspike intervals (i.e., doublets) in the tibialis anterior at the onset of ballistic contractions, as well as increases in the maximal firing frequencies of the individual motor units. The dynamic training was purposefully done in an explosive manner (10 sets of 10 repetitions with 30-40% of the maximum strength) in an attempt to improve the maximal rate of force development, as well as muscle strength. Pucci et al. (7), however, reported that a 3-week isometric resistance training program (3 sets of 10 maximal muscle actions performed 3 times per week) of the leg extensors improved maximal force, as well as maximal EMG amplitude and M-wave amplitude for the vastus lateralis. There were no changes, however, in average motor unit firing rates, and a small increase in voluntary activation, as assessed by the twitch interpolation technique. Thus, it was concluded that mechanisms other than increased motor unit firing rates (e.g., improved motor unit recruitment and synchronization) were responsible for the increased force production from resistance training (7). In addition, Patten et al. (6) found that maximal motor unit firing rates for the abductor digiti minimi in both young and elderly subjects did not change during a 6-week resistance training program. Interestingly, however, two baseline testing visits (i.e., before training) showed that maximal motor unit firing rates increased after the initial testing session, and then decreased thereafter for both the young and elderly subjects. Thus, it was concluded that resistance training-induced adaptations in motor unit firing rates may be very complex and influenced by the interaction between optimal force production and

Figure 1. The surface electromyographic (EMG) decomposition sensor (left) next to a United States dime (right).
Figure 2. Average motor unit firing rate plots for one subject after five weeks of resistance training. The solid black line shows the leg extension force production, and the remaining curves demonstrate average firing rates across time for each of the 39 motor units that were decomposed during this particular muscle action.

Figure 3. Average motor unit firing rates versus recruitment threshold for the vastus lateralis. Data shown are from one subject before (Pre; solid diamonds and solid regression line) and after (Post; open squares and dashed regression line) the 8-week resistance training program. Notice that the linear slopes for these two relationships were very similar, thus indicating that the resistance training program did not improve the ability to activate high-threshold motor units at greater rates.
Figure 4. Mean ± SD unilateral isometric leg extension strength values across the 8-week resistance training program. The results from the one-way repeated measures analysis of variance are shown below the graph.

Week 1 < Weeks 7, 8
Week 2 < Weeks 6-8
Week 4 < Weeks 7, 8
Week 5 < Week 8
Week 6 < Week 8

Figure 5. Mean ± SD linear slope coefficients for the average firing rate versus recruitment threshold relationship for the vastus lateralis across the 8-week resistance training program.

The results from the one-way repeated measures analysis of variance showed that there were no significant mean differences among the linear slope coefficients during the training program.
injury prevention (6). Kamen and Knight (4) also reported significant increases in maximal motor unit firing rates for the vastus lateralis after just one testing session. It was hypothesized that for untrained subjects, just the act of performing a maximal muscle action may be sufficient for eliciting neural adaptations in the form of increased motor unit firing rates (4). Rich and Cafarelli (8), however, found that an 8-week isometric resistance training program for the leg extensors had no effect on average motor unit firing rates for the vastus lateralis during a submaximal isometric muscle action at 50% MVC. There were, however, significant increases in isometric strength, electrically-stimulated twitch amplitude, and the maximal rate of force production. Thus, it was suggested that the control properties of the nervous system were not affected by the 8-week resistance training program, despite significant changes in the contractile properties of the muscle (8).

The results from these studies (4,6-9), in conjunction with those from the present investigation, clearly illustrate the importance of the experimental design when examining neuromuscular adaptations to resistance training. For example, the type of muscle action being performed (i.e., maximal versus submaximal) when firing rates are assessed can influence their responses to resistance training (7). In addition, most previous studies that have examined changes in motor unit firing rates with resistance training have used indwelling EMG electrodes that are capable of detecting the action potential trains from only a few motor units during any given muscle action. Thus, for large muscles that consist of several hundred motor units, the responses of a few individual motor units may not be representative of the entire muscle. Furthermore, the type of resistance training that is performed (i.e., dynamic versus isometric), as well as the intensity, frequency, and duration of the training cycle are all important factors that could affect the neuromuscular adaptations to resistance training. There is also evidence to suggest that adaptations to motor unit firing rates may change during the course of a training program such that initial increases may be followed by decreases as the training progresses (4). Thus, the results from the present study should be interpreted within the context of the training program used, and not misconstrued to be applicable to all forms of resistance training.

It is also important to acknowledge the limitations of the experimental design used in the present study. Our finding of a stable relationship between average motor unit firing rate and recruitment threshold during resistance training does not necessarily mean that there were no changes in average motor unit firing rates. Rather, it simply means that the relationship between average motor unit firing rate and recruitment threshold was unaffected by resistance training. Within the context of the present study, this relationship provided a very simple tool for assessing motor unit firing rate changes. Future research is needed, however, to determine if there are other methods for examining longitudinal firing rate changes with resistance training.

In summary, the results from this investigation showed that there were no consistent changes in the linear slope of the average motor unit firing rate versus recruitment threshold relationship for the vastus lateralis during an 8-week resistance training program. These findings, however, are applicable only to the training program and testing procedures used in this investigation. Thus, future studies should manipulate the training stimulus to identify the motor unit firing rate responses to various training programs, in addition to examining the cross-education effect to an untrained limb.

REFERENCES


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