Mechanisms Underlying the Training Effects Associated with Neuromuscular Electrical Stimulation

Although neuromuscular electrical stimulation (NMES) can increase the ability of muscle to exert force, the means by which this is accomplished seem to be different from those associated with voluntary exercise. The aim of the study was to determine whether the recruitment order of motor units elicited by over-the-muscle electrical stimulation is different from that achieved with voluntary activation of muscle. This difference was tested by comparing muscle twitch responses that were elicited by Hoffmann reflexes (H-reflexes) and direct motor responses (M-responses) and by examining the effect of submotor NMES on the twitch force associated with H-reflexes. Because H-reflexes represent the summed activity of many motor units, in a manner that is consistent with volitional activation, variation in the time to peak twitch force indicates changes in the population of motor units that contribute to the response. The results demonstrated that the percutaneous application of submotor NMES to the limbs of human subjects causes a faster-contracting population of motor units to be activated during a test H-reflex. Consequently, it seems that the application of NMES preferentially activates faster-contracting motor units, perhaps those that are normally only active at high exercise intensities under voluntary conditions. [Trimble MH, Enoka RM. Mechanisms underlying the training effects associated with neuromuscular electrical stimulation. Phys Ther. 1991;71:273–282.

Key Words: Electromyography; Electrotherapy, electrical stimulation; Motor neurons; Neuromuscular facilitation.

Under appropriate conditions, neuromuscular electrical stimulation (NMES) can cause an increase in strength.1,2 There is, however, some uncertainty concerning the mechanisms by which NMES produces these changes.3,4 Are these changes strictly peripheral in nature or, like voluntary exercise, can they involve central processes? Although NMES represents an artificial means of activating muscle that bypasses the processes associated with volition, three lines of evidence suggest that it can induce strength-related neural adaptations: (1) a time course of strength gains that precedes changes in muscle size, (2) a lower requisite training intensity compared with that necessary for voluntary training, and (3) increased strength of the nonexercised contralateral limb that accompanies the strengthening of the test limb with NMES. These observations caused us to question the mechanisms by which NMES might elicit increases in strength.

Neuromuscular electrical stimulation elicits muscle force by initiating action potentials in intramuscular nerve.
branches. As with voluntary activation, one of the principal means of varying muscle force with NMES is by altering the number of active motor units. Under most conditions, tests of central nervous system function have indicated that motor units are recruited in a relatively fixed and unalterable order, which seems to depend on the size and biophysical properties of motor neurons and the distribution of synaptic input onto the motor neurons. The order of motor unit activation with NMES, however, depends on the combined effects of axon diameter and the distance between the axon and the active electrode.

These differences in the activation of muscle between voluntary control and NMES can be mimicked by two protocols that recruit different fractions of the motor unit pool; these protocols are the Hoffman reflex (H-reflex) and the direct motor response (M-response). H-reflexes involve activation of large-diameter afferent axons and recruit motor units in an order that goes from smallest to largest, as with volitional activation, and produce relatively slow twitch responses in muscle. In contrast, M-responses, for which a stimulus is delivered to the efferent nerve, selectively involve faster contracting motor units and produce faster twitch responses in muscle. Based on this distinction in the time course of the twitch response, it is possible to elicit H-reflexes and M-responses in conjunction with NMES in order to determine whether NMES affects the population of activated motor units.

The purposes of the study were (1) to compare the time course of the twitch elicited by the H-reflex and the M-response and (2) to determine whether the population of motor units that is activated during an H-reflex is affected by the application of submotor NMES. The first aim was tested by comparing changes in the time to peak twitch force for H-reflexes that were elicited by over-the-nerve stimulation with twitches associated with M-responses that were evoked by over-the-muscle stimulation. The second aim was tested by examining the effect of submotor NMES on the twitch response elicited with an H-reflex. Because the H-reflex involves the activation of motor units in the order from smallest to largest, a change in the time course of the twitch response would suggest an effect of submotor NMES on the recruitment order of motor units. Based on the electrical stimulation literature, we hypothesized that the time to peak twitch force would be less for the M-responses compared with the H-reflexes. Furthermore, we hypothesized that the order of motor unit recruitment associated with an H-reflex would be altered during submotor NMES because of input to motor neurons from cutaneous afferents that have been activated by the artificial signal and that this effect would be apparent by a change in the time to peak force of the twitch response. Such a difference in the time course of the twitch would suggest that submotor NMES influences the recruitment order associated with volitional activation. These two observations (the time to peak force of the H-reflexes versus the M-responses and the effect of submotor NMES on the time to peak force of the H-reflexes) on the effects of over-the-muscle electrical stimulation on the time to peak force might explain some of the neural adaptations, such as those outlined in the first paragraph, that are associated with NMES.

**Method**

The study was based on measurements of force and, on some occasions, electromyographic (EMG) potentials that were associated with electrically evoked twitch responses. Two types of evoked twitches were used, the H-reflex and the direct M-response. The H-reflex was evoked by passing a graded current across a peripheral nerve that resulted in a twitch response (force) and an associated EMG potential in the test muscle. The H-reflex occurs as a result of excitation of the group 1a afferents and the subsequent activation of motor units in the natural sequence of smallest to largest. The M-response was evoked by passing a graded current between large electrodes placed over each test muscle. The M-response, which involved higher stimulus intensities than the H-reflex, was elicited by direct activation of the motor axons. The H-reflex and the M-response can be distinguished on the basis of the latency from the stimulus to the evoked response. Both the H-reflex and the M-response evoke EMG waveforms and a twitch response in the test muscle. In this study, the focus was on the amplitude and the time-dependent characteristics of the twitch response. Because the time course of the twitch response, such as the time to peak twitch force, represents the summated effect of the many motor units that are activated by the electrical stimulus, variation in the time to peak force indicates changes in the population of motor units contributing to the response. For a group of fast-contracting motor units, such as those activated during an M-response, the time to peak force should be less than that for a group of slow-contracting motor units, such as those activated during an H-reflex.

**Subjects**

Twenty-two subjects (15 male, 7 female) volunteered to participate in the study and gave their informed consent on an institutionally approved form. All subjects did not participate in all phases of the project. The subjects ranged in age from 19 to 53 years and had no history of neuromuscular disease. The two muscle groups tested in this study were the quadriceps femoris and the triceps surae. There was no attempt to determine differential activation of the muscles within each group.

**Stimulation and Recording Techniques**

The subjects were positioned on a bench, either in a supine position (for quadriceps femoris muscles) or in a prone position (for triceps surae muscles). In the supine position, the hip joint was placed in full extension, the knee joint was flexed by 20 to 30 degrees, and
both the left and right shanks (lower legs) extended beyond the bench so that the test leg could be aligned with a force transducer* via an inextensible strap to measure a knee-extensor force. In this position, the shin of the right leg rested against a strap so that when the quadriceps femoris muscles were stimulated, the leg exerted a force against the strap and the force was measured by the transducer. In the prone position, the hip and knee were placed in full extension and both feet hung over the end of the bench so that they could be connected to the force transducer in order to measure the plantar-flexor force. The ankle was fixed in a position close to neutral (between dorsiflexion and plantar flexion), the position in which the slack in the muscle-tendonous unit was removed. To measure the plantar-flexor force, the sole of the foot rested against a strap and, when the triceps surae musculature was stimulated, the foot pushed against the strap and the force was measured with the transducer. Although subject position varied slightly between experiments, the position of each subject was kept constant within each experiment.

The submaximal H-reflex and the M-response were elicited by rectangular, monophasic stimulus pulses that were delivered through stimulus-isolation and constant-current units.† For the quadriceps femoris musculature, the current pulses (width=0.5 ms) for the H-reflex were passed across the femoral nerve, with the cathode located in the popliteal fossa and the anode placed over the superior aspect of the patella. Because it is usually more difficult when passing current across a nerve to elicit an M-response without an H-reflex, M-responses were elicited by activating the intramuscular nerve branches with large carbon electrodes (100 cm² and 36 cm²) placed over the test muscles (pulse width=1–10 ms). The variation in current pulse width between conditions and subjects was necessary to improve our resolution for grading the stimulus intensity. H-reflexes and M-responses were elicited at several stimulus intensities at which the minimal intensity necessary to elicit a response was defined as the stimulus threshold and stimulus intensity was incremented in fixed steps (one-quarter turns); however, we did not determine the increase in current with each step increment in stimulus intensity.

The twitch responses evoked by the nerve stimulation were characterized by the measurement of EMG latency, time to peak force, and peak force. The surface EMG measurements were obtained either from the vastus lateralis and vastus medialis muscles or from the soleus and lateral gastrocnemius muscles using standardized bipolar electrode arrangements (silver-silver chloride, 8-mm diameter; interelectrode distance=3 cm; bandwidth=10 Hz–5 kHz).‡ The recording electrodes were positioned as follows: (1) vastus medialis muscle—one fifth of the distance from the medial margin of the knee to the anterior superior iliac spine, (2) vastus lateralis muscle—one third of the distance from the superior pole of the patella to the greater trochanter, (3) soleus muscle—approximately 4 cm above the point at which the two heads of the gastrocnemius muscle join the Achilles tendon, and (4) lateral gastrocnemius muscle—one third of the distance from the head of the fibula to the calcaneus. The EMG waveform could not be measured when the M-response was elicited by electrodes placed over the muscle or when NMES was used to stimulate the cutaneous afferents. In subsequent work (MH Trimble, unpublished observations) with over-the-muscle stimulation, a short-latency (2–4 ms) EMG wave was seen at stimulus intensities from threshold to supramaximum with no longer-latency waves observed. This finding indicates that the response was due to excitation of different branches and was not a reflex-mediated response. The EMG and force signals were displayed on oscilloscopes† and recorded on FM tape.†

In addition to these standard tests of the H-reflex and the M-response, H-reflexes were elicited before, during, and after a 3-minute conditioning period with submotor NMES. The NMES consisted of a sinusoidal high-frequency (3.3-kHz) current that was modulated to give bursts of stimuli at a rate of 50 per second.§ The stimulus was delivered through two large electrodes (either 100 cm² or 36 cm²) that were located over the belly of the test muscle. The stimulus intensity was arbitrary and subthreshold for a motor response (submotor), yet sufficient to elicit a tingling sensation that was presumably associated with cutaneous afferent feedback to the motor neuron pool.

**Protocol**

Once a subject was positioned on the bench with the leg connected to the force transducer and the EMG electrodes attached, one of the muscle groups of the subject was tested with one of three protocols: (1) H-reflex recruitment curve, (2) M-response recruitment curve, and (3) NMES. For the H-reflex recruitment curve protocol, the stimulus strength was varied over several increments to elicit H-reflexes that varied in amplitude.
but that elicited, at most, a minimal M-response. The M-response was kept small (low stimulus intensity) in order to limit the activation to slower-contracting motor units. Five responses were elicited at each stimulus strength. These data were intended to show how the H-reflex-elicited twitch responses (ie, time to peak force and peak force) varied as a function of stimulus strength. For the M-response recruitment curve protocol, the same protocol was used to elicit M-responses of varying magnitude and to indicate the association between the M-response-elicited twitch responses and stimulus strength. For the NMES protocol, 20 H-reflexes were elicited before, during, and after the 3 minutes of submotor NMES. For all three protocols, the H-reflexes and M-responses were elicited at a rate of one every 7 seconds.

**Data Analysis**

The dependent variables in this design were time to peak force and peak force of the twitch responses associated with the H-reflexes and the M-responses (Fig. 1). The reliability of the twitches for each type of response in the two test muscles was assessed by determining Pearson Product-Moment Correlation Coefficients (r) between stimulus intensity and twitch response parameters across trials; correlation coefficients close to 1.00 for each subject would suggest a reliable association between stimulus intensity and twitch response. The subjects' EMG activity was assessed qualitatively in order to determine the relative contributions of the H-reflexes and the M-response to the twitch force during the recruitment protocols and to determine whether the stimulus remained relatively constant before and after the NMES protocol. A one-factor analysis of variance (ANOVA) for repeated measures was performed on each dependent variable in each of the three protocols. For the H-reflex and M-response recruitment protocols, stimulus intensity was the independent variable. This analysis was designed to determine whether time to peak force and peak force changed as stimulus intensity was varied. When the ANOVA detected a significant effect, a trend analysis was conducted to determine the extent to which the association between time to peak force or peak force and stimulus intensity was linear. For the ANOVA, stimulus intensity was normalized with respect to the threshold intensity and then grouped by step increments (one-quarter turn on the constant current stimulating unit) of stimulus intensity. Thus, in Figures 2 and 3, the values on the abscissa represent five current steps on the stimulator. In the submotor NMES protocol, the two force parameters (ie, time to peak force and peak force) were examined before, during, and after the application of NMES. Tables 1 and 2 contain the means and standard errors of the time to peak force and the peak force for the subjects. The alpha level of acceptance was set at .05 for all protocols.

**Results**

The data consist of baseline values for twitch responses associated with H-reflexes and M-responses and the effect of submotor NMES on the H-reflex-elicited twitch responses. The trial-to-trial reliability coefficients (r values) across subjects for the peak twitch force and the time to peak force associated with the H-reflexes and the M-responses ranged from .90 to .99.

**H-Reflex Recruitment Curve**

The H-reflex-elicited twitches in the two muscle groups were similar in peak force and time to peak force. In
the quadriceps femoris musculature, peak force for all subjects ranged from 19 to 195 N ($\bar{X} \pm SE = 88.9 \pm 36.8$) and time to peak force varied from 65 to 100 milliseconds ($74.2 \pm 7.4$), whereas for the triceps surae musculature, the ranges of peak force and time to peak force were 17 to 83 N ($47.2 \pm 21.9$) and 56 to 102 milliseconds ($80.6 \pm 12.3$), respectively. Peak force for the H-reflex occurred prior to the appearance of an M-response, which is known to cause the H-reflex force to diminish. The magnitude of the peak twitch force increased and the time to peak twitch force decreased as the H-reflex stimulus intensity increased. These changes were apparent in both the superimposed twitch responses (Fig. 1) and in the values averaged across subjects (Figs. 2, 3) for the two test muscles. The data were derived from 11 subjects for the quadriceps femoris musculature and 14 subjects for the triceps surae musculature. The ANOVAs indicated that both the time to peak force and peak force varied significantly ($P < .05$) across stimulus intensity. As with the H-reflexes, trend analyses revealed a dominant linear association (94%–96% of the variance) between the force measurements and stimulus intensity. The Pearson product-moment correlation coefficients were nearly perfect ($r = -.85$ to $- .99$), indicating that time to peak force decreased as peak force increased.

**M-Response Recruitment Curve**

As with the H-reflexes, the magnitude of the peak twitch force increased with the M-response stimulus intensity (Fig. 3). In contrast to the H-reflexes, however, the time to peak twitch force increased with stimulus strength (Figs. 1, 2). The ANOVAs, based on 11 subjects for the quadriceps femoris musculature and 14 subjects for the triceps surae musculature, indicated that time to peak force and peak force varied significantly ($P < .05$) across stimulus intensity. As with the H-reflexes, trend analyses revealed a dominant linear association (94%–96% of the variance) between the force measurements and stimulus intensity. The Pearson product-moment correlation coefficients were nearly perfect ($r = -.85$ to $- .99$), indicating that time to peak force decreased as peak force increased.

**Table 1. Effect of Submotor Neuromuscular Electrical Stimulation (NMES) on Twitch Force Elicited by H-Reflexes in Quadriceps Femoris Musculature**

<table>
<thead>
<tr>
<th>Condition</th>
<th>Before NMES</th>
<th>During NMES</th>
<th>After NMES</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Subject</strong></td>
<td>$\bar{X}$</td>
<td>SE</td>
<td>$\bar{X}$</td>
</tr>
<tr>
<td><strong>Time to peak force (ms)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>78.21</td>
<td>0.79</td>
<td>71.40</td>
</tr>
<tr>
<td>2</td>
<td>80.25</td>
<td>0.35</td>
<td>74.60</td>
</tr>
<tr>
<td>3</td>
<td>86.40</td>
<td>0.37</td>
<td>77.83</td>
</tr>
<tr>
<td>4a</td>
<td>71.77</td>
<td>0.34</td>
<td>62.55</td>
</tr>
<tr>
<td>4b</td>
<td>72.99</td>
<td>0.45</td>
<td>64.90</td>
</tr>
<tr>
<td>5a</td>
<td>75.30</td>
<td>0.45</td>
<td>65.69</td>
</tr>
<tr>
<td>5b</td>
<td>73.61</td>
<td>0.39</td>
<td>64.40</td>
</tr>
<tr>
<td><strong>Peak force (N)</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>79.36</td>
<td>1.04</td>
<td>80.10</td>
</tr>
<tr>
<td>2</td>
<td>137.79</td>
<td>0.79</td>
<td>121.67</td>
</tr>
<tr>
<td>3</td>
<td>215.56</td>
<td>4.35</td>
<td>236.55</td>
</tr>
<tr>
<td>4a</td>
<td>91.48</td>
<td>1.42</td>
<td>88.33</td>
</tr>
<tr>
<td>4b</td>
<td>83.88</td>
<td>1.22</td>
<td>75.53</td>
</tr>
<tr>
<td>5a</td>
<td>94.57</td>
<td>0.37</td>
<td>93.80</td>
</tr>
<tr>
<td>5b</td>
<td>80.90</td>
<td>0.78</td>
<td>79.90</td>
</tr>
</tbody>
</table>

*Subjects 4 and 5 were each tested on two occasions (hence 4a and 4b, 5a and 5b).*
Table 2. Effect of Submotor Neuromuscular Electrical Stimulation (NMES) on Twitch Force Elicited by H-Reflexes in Triceps Surae Musculature

<table>
<thead>
<tr>
<th>Subject</th>
<th>Before NMES</th>
<th>During NMES</th>
<th>After NMES</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X</td>
<td>SE</td>
<td>X</td>
</tr>
<tr>
<td>Time to peak force (ms)</td>
<td>94.30</td>
<td>0.54</td>
<td>83.20</td>
</tr>
<tr>
<td>2</td>
<td>89.10</td>
<td>0.29</td>
<td>78.40</td>
</tr>
<tr>
<td>Peak force (N)</td>
<td>32.44</td>
<td>0.48</td>
<td>30.47</td>
</tr>
<tr>
<td>2</td>
<td>74.28</td>
<td>0.11</td>
<td>74.60</td>
</tr>
</tbody>
</table>

Correlation between peak force and time to peak force ranged from .89 to .99 for the M-responses of the quadriceps femoris musculature and from .51 to .99 for the triceps surae musculature, indicating that increases in time to peak force accompanied increases in peak force.

**Submotor Neuromuscular Electrical Stimulation**

The overlapping EMG records shown in Figure 4, which include 20 responses before and 20 responses after submotor NMES, indicated that it was possible to elicit stable submaximal (50%-75%) H-reflexes in both the quadriceps femoris and triceps surae muscle groups. Prior to application of the submotor NMES, the twitch responses for the quadriceps femoris musculature (n=7) and the triceps surae musculature (n=2) had time to peak forces (mean±SE of the group data) of 77.2±2.0 and 91.6±3.7 milliseconds, respectively, and peak forces of 111.9±18.8 and 53.3±29.5 N, respectively (Tab. 1, 2). Most of the variability could probably be accounted for by between-subject differences such as muscle-fiber length and characteristics, elastic properties of non-contractile tissue, and the degree of subject fixation to the apparatus. The 3-minute conditioning period of submotor NMES over the bellies of the test muscles did not alter the peak twitch force, but it did significantly shorten the time to peak twitch force during NMES (P<.05). Time to peak force decreased by an average of 8 milliseconds in the quadriceps femoris musculature and by an average of 11 milliseconds in the triceps surae musculature during submotor NMES. These values represented an 11% (average) decrease in contraction time during the submotor NMES and can be contrasted to the 2% variability in time to peak force when comparing the before and after NMES conditions. Although the peak force varied 4%, on average, during the three conditions, the magnitude and direction of this variance was not associated with superimposition of the NMES, as indicated by the ANOVA. This decrease in time to peak force was interpreted as the activation of a faster-contracting population of motor units during submotor NMES. Furthermore, because the values before and after submotor NMES were not significantly different, the decrease in the time to peak twitch force represented a transient effect.

**Figure 4.** Superimposed electromyographic (EMG) waveforms that were elicited by H-reflexes. Each trace contains 20 responses before and 20 responses after submotor neuromuscular electrical stimulation. The upper trace is from the vastus medialis muscle of one subject, and the lower trace is from the lateral gastrocnemius muscle of another subject. These overlapping EMG records indicate stable H-reflexes.
**Discussion**

The objective of this study was to determine whether the recruitment order of motor units elicited by over-the-muscle electrical stimulation was different from that achieved with voluntary activation in human subjects. One unique feature of the study was that, rather than assess recruitment order on the basis of a pair-wise comparison of motor units, we examined the effect on populations of motor units. Along with previous literature, the results indicate two ways in which electrical stimulation can alter the recruitment order of motor units in human subjects.

First, as has been shown in animal models but not convincingly in humans, graded electrical stimulation elicits M-responses of progressively increasing time to peak force and peak force. This association suggests that as the stimulus intensity was increased in our study, motor units with a slower contraction time were progressively recruited, which resulted in a lengthening in the time to peak force of the M-response. In contrast, an increase in the stimulus strength for the H-reflexes resulted in a decrease in the time to peak force. These findings are consistent with the recruitment of progressively faster-contracting motor units, as occurs under the condition of voluntary activation. Thus, direct activation of the motor axons by electrical stimulation, as does occurs with NMES, produces a recruitment order of motor units that is different from the order used during voluntary exercise.

Second, activation of cutaneous afferents has been shown to alter the recruitment threshold of motor units participating in voluntary and reflex muscle contractions in both humans and animals. The results of our study extend these observations by indicating that NMES at an intensity below the motor threshold can alter the population of motor units that is activated during the H-reflex. Because the H-reflex is a labile response that is readily influenced by movement of the stimulating electrode, remote muscle activity (ie, Jendrassik effects), and variations in spinal cord excitability, the appearance of overlapping EMG responses is regarded as evidence that the H-reflex stimulus remained constant before and after the NMES. Furthermore, even minor variations in the responses would have been accentuated by the bipolar measurement of EMG activity that was used in this study. The consistent EMG response before and after the submotor NMES suggests that the current passed across the peripheral nerve of each test muscle remained relatively constant during the NMES. The activation of a different population of motor units during the submotor NMES was apparent by the change in the time to peak force for the twitches elicited by the H-reflex before, during, and after the submotor NMES. The decrease in the time to peak force during submotor NMES was interpreted as the activation of a faster-contracting population of motor units. Thus, cutaneous afferent input, which occurs with NMES, can alter the population of motor units that is activated by voluntary and reflex means.

The literature suggests that electrical stimulation of nerve or muscle can alter either the recruitment order of motor units or the population of motor units that is activated by a stimulus. It seems that these changes are the consequence of differences in efferent axon excitability and differential feedback effects from cutaneous afferents. With regard to efferent axon excitability, the largest efferent axons are the most excitable to electrical stimulation, whereas among the motor neuron pool, the motor neurons with the smallest somas are generally considered to be the most excitable to synaptic excitatory input. Most inputs to a motor neuron pool tend to activate motor neurons in the order of smallest to largest. However, it appears possible to preferentially activate groups of faster-contracting motor units, either with feedback from cutaneous afferents or from other sources. The results of our study indicate that over-the-muscle electrical stimulation elicits an M-response that has a relatively fast (compared with the H-reflex) contraction time and that submotor NMES can alter the population of motor units that is activated during an H-reflex. These two observations probably represent the mechanisms by which NMES-induced therapeutic effects may differ from those associated with voluntary activation.

**Clinical Implications**

One of the most surprising observations in the NMES literature is the report that it is possible to induce increases in strength with minimal training intensities, much less than the intensities needed for voluntary training. This difference in the requisite training intensity is probably due to different motor units that may have been activated under the two training conditions. Perhaps NMES induces strength increases in higher threshold motor units that can normally be trained only at high intensities in voluntary conditions. Consistent with this rationale, some reports in the literature have indicated that the strengthening of hypotrophic muscle is more easily achieved with NMES than with voluntary exercise. Complete activation of hypotrophic muscle may not be possible voluntarily, especially following a decrease in motor neuron excitability. Neuromuscular electrical stimulation, however, may bypass these deficiencies and cause an increase in motor neuron excitability, both by direct activation of larger motor units and by the facilitatory effect of cutaneous afferent feedback on large motor neurons.

**Conclusion**

The percutaneous application of electrical stimulation to the limbs of human subjects, as compared with voluntary activation, can alter the recruitment order of motor units and the motor unit population that is activated by a given stimulus. These alterations seem to depend on two distinct mechanisms, one involving direct activation of large efferent axons and the other depending on the feedback effects of cutaneous afferents. The results obtained in this study indicate that...
over-the-muscle electrical stimulation activates faster-contracting motor units and that submotor NMES provides cutaneous feedback that alters the population of motor units activated during an H-reflex. By these means, it appears possible to preferentially activate faster-contracting motor units, perhaps those that are normally only active at high exercise intensities under voluntary conditions. This selectivity can be a useful adjunct to various rehabilitation interventions. One example would include situations in which strong muscle contractions would be detrimental to an injured extremity. Neuromuscular electrical stimulation, either in conjunction with or in alternation with voluntary exercise, may provide a more effective means of training high threshold motor units.

Acknowledgments

We gratefully acknowledge the technical assistance of Peter Worden, the statistical advice of Dr Timothy G Lohman, and the comments of Dr S Jayne Garland and Dr Carl G Kukulka.

References


Commentary

Objective assessment of the effects of neuromuscular electrical stimulation (NMES) is greatly dependent on the ability to predict what underlying structures are excited by the stimulus. In animal studies, invasive techniques allow direct access to peripheral nerves and nerve roots, which greatly facilitates the control of both stimulation and recording protocols. In the clinic, the ease of application of percutaneous stimulation replaces invasive procedures and, in so doing, introduces additional complicating factors to the controlled delivery of stimuli (eg, variable thickness of subcutaneous tissues, nonuniform distribution of the electrical field associated with the stimulus). A direct consequence of these complications is a loss of predictability of resultant neuron activity generated by the stimulus, further detracting from a quantitative assessment of NMES effects. Through a unique application of time-honored electrophysiological measurement techniques and basic neuromuscular principles, Trimble and Enoka have provided important basic information concerning the probable recruitment order of motor neurons during NMES. Such information is critical to our understanding of the neuronal activation schemes associated with NMES and should assist us in appreciating what happens from a neurophysiologic perspective, when an electrical stimulus is applied to a patient.