Activation of human plantar flexor muscles increases after electromyostimulation training

NICOLA A. MAFFIULETTI, MANUELA PENSINI, AND ALAIN MARTIN
Groupe Analyse du Mouvement, Unité de Formation et de Recherche Sciences et Techniques des Activités Physiques et Sportives, Faculté des Sciences du Sport, Université de Bourgogne,
BP 27877-21078 Dijon Cedex, France

Received 27 August 2001; accepted in final form 5 November 2001

Maffiuletti, Nicola A., Manuela Pensini, and Alain Martin. Activation of human plantar flexor muscles increases after electromyostimulation training. J Appl Physiol 92: 1383–1392, 2002. First published November 9, 2001; 10.1152/japplphysiol.00884.2001.—Neuromuscular adaptations of the plantar flexor muscles were assessed before and subsequent to short-term electromyostimulation (EMS) training. Eight subjects underwent 16 sessions of isometric EMS training over 4 wk. Surface electromyographic (EMG) activity and torque obtained under maximal voluntary and electrically evoked contractions were analyzed to distinguish neural adaptations from contractile changes. After training, plantar flexor voluntary torque significantly increased under isometric conditions at the training angle (+8.1%, $P < 0.05$) and at the two eccentric velocities considered (+10.8 and +13.1%, $P < 0.05$). Torque gains were accompanied by higher normalized soleus EMG activity and, in the case of eccentric contractions, also by higher gastrocnemius EMG ($P < 0.05$). There was an 11.9% significant increase in both plantar flexor maximal voluntary activation ($P < 0.01$) and postactivation potentiation ($P < 0.05$), whereas contractile properties did not change after training. In the absence of a change in the control group, it was concluded that an increase in neural activation likely mediates the voluntary torque gains observed after short-term EMS training.

Address for reprint requests and other correspondence: N. A. Maffiuletti, Groupe Analyse du Mouvement, UFR STAPS, Faculté des Sciences du Sport, Université de Bourgogne, BP 27877-21078 Dijon Cedex, France (E-mail: Nicola.Maffiuletti@u-bourgogne.fr).

THE USE OF HIGH-FREQUENCY electromyostimulation (EMS) has previously been employed as a means to strengthen healthy human skeletal muscle (8, 10, 12, 26, 27, 34). Nevertheless, the physiological adaptations (muscular or neural) induced by this form of involuntary training and responsible for the increases in strength remain equivocal. The assessment of muscular adaptations to EMS has primarily been by direct observation in human (8) or rat muscles (18), whereas the neural adaptations have been inferred. Although very few studies have directly examined neural activity subsequent to EMS training, many studies on healthy human muscles have proposed that neural adaptations are largely responsible for the strength gains observed (10, 26, 27). This conclusion is based on the use of training periods that are too brief to induce muscular adaptations (see Refs. 31, 36). However, neural adaptations are possible because EMS results in excitation of intramuscular branches of the nerve and not the muscle fibers directly (23), which likely induces antidromic activation of the motoneurons. It could, therefore, be hypothesized that the strength gains observed subsequent to short-term EMS training are likely mediated by enhanced neural activation, rather than muscle activation.

To our knowledge, only one investigation has focused on the effects of EMS training on the surface electromyographic (EMG) activity of the agonist (i.e., stimulated) muscle in humans (10). Although the EMG activity of the biceps brachii significantly increased after 7 wk of elbow flexor EMS training (10), EMG values were not normalized to the compound action potential (M wave), and maximal voluntary activation was not assessed. Nonetheless, Colson et al. (10) observed changes in M-wave characteristics with a concomitant increase in the twitch time course, whereas Duchateau and Hainaut (12) reported no changes in single-twitch contractile properties but greater amplitude of the 100-Hz tetanus after 6 wk of adductor pollicis EMS training. These disparate findings may be due to the effect of EMS resistance training on the muscular contractile properties assessed with single and multiple stimuli, which has not been examined systematically.

The aim of the present investigation was to assess the effects of 4 wk of EMS training on neuromuscular properties of the plantar flexor (PF) muscles, with special emphasis on changes in neural activation. The EMG and mechanical responses obtained under maximal voluntary (isometric, concentric, and eccentric) and electrically evoked (single, paired, or tetanic stimuli) conditions were assessed to distinguish neural adaptations from contractile changes.

METHODS

Subjects

Eight healthy male individuals took part in this investigation and were tested before and after 4 wk of EMS training.

The costs of publication of this article were defrayed in part by the payment of page charges. The article must therefore be hereby marked “advertisement” in accordance with 18 U.S.C. Section 1734 solely to indicate this fact.
(EMS group, age 20.4 ± 2.1 yr; height 186.4 ± 8.0 cm; weight 83.5 ± 9.6 kg; means ± SD). A control group of six subjects did not train and were tested before and after a 4-wk period to assess the reliability of the observations (C group, age 26.0 ± 5.1 yr; height 176.7 ± 4.8 cm; weight 69.5 ± 4.6 kg). For all of the subjects, the PF and dorsiflexor (DF) muscles of the right leg were tested. The subjects, all free from previous ankle injury, agreed to participate in the study on a voluntary basis and signed an informed consent before involvement in the investigation. Approval for the project was obtained from the University of Burgundy Committee on Human Research.

EMS Training Procedures

One week before the beginning of the stimulation period, the EMS group participated in one practice session to acquaint themselves with stimulation parameters. None of these subjects had previously engaged in systematic strength training or had experienced EMS. They completed sixteen 18-min sessions of isometric bilateral EMS over a 4-wk period, with four sessions per week. Forty-five isometric contractions were carried out during each training session. During the stimulation, subjects were seated on a calf machine (Multi-Form, La Roque D’Anthéron, France) with the ankle, knee, and hip joints flexed to −90°. A portable battery-powered stimulator (Compex Sport, Medicompex, Ecublens, Switzerland) discharged rectangular-wave pulsed currents (75 Hz) lasting 400 μs. Three 2-mm-thick, self-adhesive electrodes were placed over each leg. The two positive electrodes, each measuring 25 cm² (5 × 5 cm), which had membrane depolarizing properties, were placed over the superficial aspect of the soleus muscle, ~5 cm distal from where the two heads of the gastrocnemius join the Achilles tendon. The negative electrode, measuring 50 cm² (10 × 5 cm), was placed along the middorsal line of the leg, over both medial (MG) and lateral gastrocnemius (LG). Each 4-s contraction was followed by a pause lasting 20 s. Intensity (range 0–100 mA) was monitored on-line and was gradually increased to a level of maximally tolerated intensity, which varied between 30 and 90 mA, depending on differences among subjects in pain threshold. No subject reported serious discomfort. The individual level of isometric force developed during EMS was measured once a week with a myostatic-type dynamometer (Multifrm, UK). Each subject was initially familiarized with several testing sessions, subjects reported to the laboratory for percutaneous stimulation of the tibial nerve. Single and paired (doublet) stimuli and tetani were evoked at rest to investigate PF contractile properties and the associated compound action potentials (M waves, see EMG activity). Also, single stimuli were delivered before, during, and immediately after MVC to estimate maximal voluntary activation (i.e., twitch interpolation technique) and to quantify postactivation potentiation (PAP). During this session, subjects were examined under sitting conditions with the right knee and ankle flexed to ~90° of flexion. The foot was secured to a pedal equipped with strain gauges, which was developed by the local engineering school, to record the PF mechanical response. The posterior tibial nerve was stimulated by using a cathode ball electrode (0.5-cm diameter) pressed in the poplitea fossa. The anode was a large electrode (10 × 5 cm), placed on the anterior surface of the knee. The percutaneous electrical stimulus was a rectangular pulse (1-ms duration) delivered by a Digitimer stimulator (DS7, Hertfordshire, UK). Each subject was initially familiarized with several submaximal (range: 1–20 mA) electrical stimuli over a period of 10–15 min. The current was then progressively increased until maximal PF twitch torque and maximal soleus M-wave amplitude were achieved. This intensity was further increased by 10% (i.e., supramaximal) and then maintained for 1) four single twitches, each separated by 3 s, 2) four doublets (10-ms interval) separated by 5 s, and 3) two tetani (100 Hz; 250 ms). Two-minute rest periods were allowed between different stimuli and between tetani. Whatever the type of stimuli, mechanical traces were digitized on-line (sampling frequency: 2 kHz), averaged, and stored for analysis with...
commercially available software (Tida, Heka Elektronik, Lambrecht/Pfalz, Germany). The following variables were measured from the twitch traces associated with single and paired stimuli: peak torque (Pt), contraction time, half relaxation time, and maximum rate of tension development (RD) and relaxation (RR). Pt, RD, and RR were measured from the tetanic stimulation and were named P0, RD0, and RR0, respectively.

Subsequently, two maximal voluntary PF contractions were held for 3–4 s in the same isometric position, each separated by 5 min. Single stimuli were delivered 2 s before the MVC (control twitch), over the isometric plateau (superimposed twitch), and 5 s after the contraction (potentiated twitch) to assess the level of voluntary activation and the PAP. PF maximal voluntary activation was thus estimated according to the following formula (twitch interpolation technique) (2), i.e., %activation = (1 – superimposed twitch amplitude × potentiated twitch amplitude−1) × 100 (%). PF PAP was determined by computing the ratio between the amplitude of the potentiated twitch and the control twitch.

EMG Activity

Silver chloride surface electrodes of 10-mm diameter, with an interelectrode (center-to-center) distance of 2 cm, were used to record the EMG activity of three PF muscles (soleus, MG, and LG) and one DF muscle [tibialis anterior (TA)] during voluntary torque assessment and the stimulation test. For the soleus, recording electrodes were placed along the middorsal line of the leg, ~5 cm distal from where the two heads of the gastrocnemius join the Achilles tendon. MG, LG, and TA EMG electrodes were fixed lengthwise over the middle of the muscle belly with the reference electrode placed on the opposite wrist. Low impedance (<2 kΩ) at the skin-electrode interface was obtained by abrading the skin with emery paper and cleaning with alcohol. EMG signals were amplified with a bandwidth frequency ranging from 1.5 Hz to 2 kHz (common mode rejection ratio = 90 dB; Z input = 100 MΩ; gain = 1,000) and subsequently stored for off-line analysis. For voluntary torque testing, the root mean square (RMS) myoelectric activity of soleus, MG, LG, and TA was calculated every 0.02 s over the period of interest. During isometric actions, the RMS EMG was measured over a 1-s period after the torque had reached a plateau, whereas, during isokinetic actions, signals were analyzed between −10 and +10° of the complete movement (i.e., ±10° around the constant angular torque). This interval was selected because RMS values for the three PF muscles were then normalized to the amplitude (peak to peak) of the respective M wave of the session (measured at 0°), to avoid any systematic influence of muscle length on EMG amplitude and to reduce the variability across sessions. For the TA, the level of coactivation was determined by normalizing the RMS values with respect to the TA RMS recorded at baseline during maximal DF at 0°. The normalized RMS-angle and RMS-angular velocity relations for soleus, MG, LG, and TA muscles were thus determined before and after the 4-wk period.

Statistical Analyses

Ordinary statistical methods including means and their SDs or SEs were calculated for each parameter. A repeated-measures ANOVA was used to assess the effect of EMS training (EMS group) and the reliability of the measures (C group) on dependent variables. Independent two-tailed t-tests were used to analyze differences between means of variables for the EMS and C groups. In each case, the level of significance was established at P ≤ 0.05.

RESULTS

Maximal Voluntary Torque and Associated EMG Activity

The isometric PF torque significantly increased after EMS training exclusively at the training position (Fig. 1A; P < 0.05), i.e., 0°, and, because of the great variability, the increase failed to reach a significant level at −20° (P = 0.1). Under isokinetic conditions (Fig. 1B), the eccentric PF torque significantly increased at the two angular velocities considered (P < 0.01 for −120°/s and P < 0.05 for −60°/s), whereas concentric torque values were not significantly different after training. When the DF torque is considered, the only significant change observed after the present training protocol was an increase at the isometric training angle (Table 1; P < 0.05).

During PF, the RMS-angle relation shifted upward after EMS training for the three agonist muscles (soleus, MG, and LG) but the RMS values significantly increased exclusively for the soleus at 0 and −20° (Fig. 2A; P < 0.05). During isokinetic PF, posttraining RMS EMG values were significantly higher for the soleus at the two eccentric velocities (Fig. 3A; P < 0.05), for the MG at −60°/s (Fig. 3B; P < 0.05), and for the LG at −120°/s (Fig. 3C; P < 0.05). No significant changes were observed under concentric conditions. The present EMS training did not modify the level of coactivation of

![Fig. 1. Torque-angle (A) and torque-angular velocity (B) relations obtained during maximal voluntary plantar flexion, before (Pre) and after (Post) 4 wk of electromyo-stimulation training of the plantar flexor muscles. All values are means ± SE from 8 experimental subjects. Posttraining torque values were significantly higher than pretraining values (ANOVA repeated measures) at *P < 0.05 and **P < 0.01.](https://jap.physiology.org/10.1152/jappl.00121.2017)
the TA during isometric (Fig. 2D) and isokinetic PF (Fig. 3D). Also, the RMS values when this muscle acted as an agonist (i.e., during DF) and the concomitant level of coactivation of the three PFs were unchanged after training (Table 2).

In the C group, isometric (Fig. 4A) and isokinetic (Fig. 4B) torque values during PF and DF (Table 1) and the associated RMS EMG (Figs. 5 and 6, Table 2) values were unchanged after the 4-wk period. Moreover, no significant difference was observed at baseline between EMS and C groups for these variables.

Electrical Stimulation Results

At baseline, independent two-tailed t-test showed no significant difference between the two experimental groups in M-wave amplitude and PF contractile properties, and EMS training did not modify any of these parameters (Table 3).

Finally, the present training protocol resulted in a significant increase in PF activation level (Fig. 7A; \( P < 0.01 \)) and in PAP (Fig. 7B; \( P < 0.05 \)), both by 11.9%, whereas no significant changes were observed for the C group.

DISCUSSION

The major findings of this study were that, after 4 wk of EMS training, PF contractile properties did not change, whereas isometric and eccentric voluntary torque increased. The increase in strength was accompanied by 1) significantly higher EMG activity of the agonist (i.e., stimulated) muscles and no changes in antagonist coactivation, 2) enhanced maximal voluntary activation, and 3) augmented PAP. In the absence of a change in the C group, these results suggest that increases in neural activation are likely to mediate the voluntary torque gains observed after 4 wk of EMS training.

Table 1. Torque-angle and torque-angular velocity relations obtained during maximal voluntary dorsiflexion, before and after the 4-wk intervention period, for EMS and C groups

<table>
<thead>
<tr>
<th>Ankle angle, °</th>
<th>EMS</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>After</td>
<td>Before</td>
</tr>
<tr>
<td>−20</td>
<td>19.3±3.9</td>
<td>19.5±4.0</td>
</tr>
<tr>
<td>0</td>
<td>41.6±7.1</td>
<td>44.5±7.1*</td>
</tr>
<tr>
<td>+30</td>
<td>47.4±6.3</td>
<td>48.9±5.6</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Angular velocity, °/s</th>
<th>EMS</th>
<th>C</th>
</tr>
</thead>
<tbody>
<tr>
<td>−120</td>
<td>44.2±8.8</td>
<td>45.4±12.4</td>
</tr>
<tr>
<td>−60</td>
<td>41.6±9.1</td>
<td>43.8±11.9</td>
</tr>
<tr>
<td>60</td>
<td>22.0±2.8</td>
<td>22.4±3.7</td>
</tr>
<tr>
<td>120</td>
<td>13.9±2.2</td>
<td>16.5±3.5</td>
</tr>
<tr>
<td>240</td>
<td>5.3±3.5</td>
<td>5.9±4.0</td>
</tr>
</tbody>
</table>

Values are means ± SD. EMS, electromyostimulation group (n = 8); C, control group (n = 6). *Posttraining torque values were significantly higher than pretraining values at \( P < 0.05 \).

Fig. 2. Normalized root mean square (RMS) electromyographic (EMG)-angle relations for respective muscles obtained during maximal voluntary plantar flexion, before and after 4 wk of electromyostimulation training of the plantar flexor muscles. A: soleus; B: medial gastrocnemius (MG); C: lateral gastrocnemius (LG); D: tibialis anterior (TA). RMS EMG values for soleus, MG, and LG were normalized to the respective M-wave amplitude of the session. TA RMS values were normalized with respect to the RMS value obtained during maximal voluntary dorsiflexion (DF) at 0° before the 4-wk period. All values are means ± SE from 8 experimental subjects. *Posttraining RMS values were significantly higher than pretraining values (ANOVA repeated measures) at \( P < 0.05 \).
Changes in activation were studied with two different techniques in the present investigation. The RMS EMG values obtained during voluntary contractions were normalized to the respective M wave, and maximal voluntary activation was assessed with the twitch interpolation technique. To our knowledge, these methods have not been utilized in previous EMS studies. However, one prior study recorded the surface EMG activity of muscles that had been submitted to EMS training (10), and, after 7 wk of stimulation to agonist biceps brachii, EMG increased for isometric and eccentric conditions, but no significant change in the antagonist triceps brachii activity was observed. Although EMG activity was not normalized to the M wave in this previous study, EMG results from the present study, which were normalized to the M wave, demonstrated a similar increase. In addition to agonist EMG activity, the level of voluntary activation and the response of three PF muscles and one DF muscle were assessed in the present experiment. Indeed, muscles other than the one directly stimulated might be affected by EMS training because of current diffusion. In line with Colson et al. (10), the EMG activity from the antagonist TA (i.e., the level of coactivation) was not affected by the present isometric EMS training. However, voluntary isometric training has been reported to involve a reduction in the coactivation level (9). This result enabled us to exclude one potential site of adaptation in the central nervous system, i.e., a reduced neural drive to the antagonist muscle, accounting for the greater torque observed after EMS training. Indeed, the net torque around a joint will increase because of removal of the negative torque contributed by the antagonist muscle, but this was not the case with this particular EMS protocol.

The normalized RMS EMG values enabled assessment of each individual muscle composing the triceps surae (the main PF) to be assessed in response to training, whereas the twitch interpolation technique provided an estimation of the compound level of voluntary activation of the muscles innervated by the tibial nerve. In the present experiment, EMS training resulted in a significant increase in the normalized EMG activity during isometric and eccentric actions and not during concentric contractions, particularly for the soleus muscle, which, in turn, indicates a “specific” increase of the neural drive (1, 21, 22; see also herein). Maximal voluntary activation significantly increased by 11.9% after training, thus revealing that EMS training increased the overall activity of the agonist muscles. This enhanced voluntary activity could be accounted for by an increase in motor unit recruitment or discharge rate (30), both mediated by changes in descending cortical outflow. Although the present methodology does not permit determination of the relative contribution of motor unit recruitment vs. discharge rate to activation increases and to the enhanced strength, there are at least three lines of evidence that

Fig. 3. Normalized RMS EMG-angular velocity relations for respective muscles obtained during maximal voluntary plantar flexion, before and after 4 wk of electromyostimulation training of the plantar flexor muscles. A: soleus; B: MG; C: LG; D: TA. All values are means ± SE from 8 experimental subjects. *Posttraining RMS values were significantly higher than pretraining values (ANOVA repeated measures) at P < 0.05.
ELECTROSTIMULATION TRAINING-INDUCED ADAPTATIONS

Table 2. Normalized RMS EMG-angle and RMS EMG-angular velocity relations for respective muscles obtained during maximal voluntary dorsiflexion, before and after the 4-wk intervention period, for EMS and C groups

<table>
<thead>
<tr>
<th></th>
<th>EMS</th>
<th>Before</th>
<th>After</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tibialis anterior</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>–20°</td>
<td>0.937 ± 0.105</td>
<td></td>
<td>0.986 ± 0.205</td>
</tr>
<tr>
<td>0°</td>
<td>1.000 ± 0.000</td>
<td>1.084 ± 0.170</td>
<td></td>
</tr>
<tr>
<td>+30°</td>
<td>1.024 ± 0.093</td>
<td>1.059 ± 0.063</td>
<td></td>
</tr>
<tr>
<td>–120°/s</td>
<td>1.018 ± 0.129</td>
<td>1.050 ± 0.119</td>
<td></td>
</tr>
<tr>
<td>60°/s</td>
<td>0.843 ± 0.093</td>
<td>0.959 ± 0.079</td>
<td></td>
</tr>
<tr>
<td>120°/s</td>
<td>0.950 ± 0.053</td>
<td>1.044 ± 0.138</td>
<td></td>
</tr>
<tr>
<td>240°/s</td>
<td>1.030 ± 0.157</td>
<td>0.997 ± 0.127</td>
<td></td>
</tr>
<tr>
<td>Soleus</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>–20°</td>
<td>0.005 ± 0.002</td>
<td></td>
<td>0.005 ± 0.002</td>
</tr>
<tr>
<td>0°</td>
<td>0.006 ± 0.001</td>
<td>0.006 ± 0.002</td>
<td></td>
</tr>
<tr>
<td>–120°/s</td>
<td>0.005 ± 0.002</td>
<td>0.005 ± 0.002</td>
<td></td>
</tr>
<tr>
<td>60°/s</td>
<td>0.005 ± 0.002</td>
<td>0.005 ± 0.002</td>
<td></td>
</tr>
<tr>
<td>120°/s</td>
<td>0.005 ± 0.001</td>
<td>0.006 ± 0.002</td>
<td></td>
</tr>
<tr>
<td>240°/s</td>
<td>0.006 ± 0.002</td>
<td>0.006 ± 0.002</td>
<td></td>
</tr>
<tr>
<td>Medial gastrocnemius</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>–20°</td>
<td>0.006 ± 0.002</td>
<td></td>
<td>0.007 ± 0.002</td>
</tr>
<tr>
<td>0°</td>
<td>0.006 ± 0.002</td>
<td>0.006 ± 0.002</td>
<td></td>
</tr>
<tr>
<td>–120°/s</td>
<td>0.008 ± 0.004</td>
<td>0.007 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>60°/s</td>
<td>0.007 ± 0.003</td>
<td>0.008 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>120°/s</td>
<td>0.007 ± 0.003</td>
<td>0.008 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>240°/s</td>
<td>0.008 ± 0.003</td>
<td>0.008 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>Lateral gastrocnemius</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>–20°</td>
<td>0.008 ± 0.003</td>
<td></td>
<td>0.008 ± 0.003</td>
</tr>
<tr>
<td>0°</td>
<td>0.009 ± 0.003</td>
<td>0.009 ± 0.004</td>
<td></td>
</tr>
<tr>
<td>–120°/s</td>
<td>0.009 ± 0.003</td>
<td>0.009 ± 0.004</td>
<td></td>
</tr>
<tr>
<td>60°/s</td>
<td>0.009 ± 0.003</td>
<td>0.009 ± 0.004</td>
<td></td>
</tr>
<tr>
<td>120°/s</td>
<td>0.009 ± 0.003</td>
<td>0.010 ± 0.003</td>
<td></td>
</tr>
<tr>
<td>240°/s</td>
<td>0.010 ± 0.003</td>
<td>0.011 ± 0.004</td>
<td></td>
</tr>
</tbody>
</table>

Values are means ± SD. EMS group, n = 8; C group, n = 6. Tibialis anterior root mean square (RMS) values were normalized with respect to the RMS value obtained during maximal voluntary dorsiflexion at 0° before the 4-wk period. RMS electromyographic (EMG) values for soleus, medial gastrocnemius and lateral gastrocnemius were normalized to the respective M-wave amplitude of the session.

substantiate a significant role for altered recruitment rather than discharge rate. First, Miller et al. (28) have recently claimed that single electrical impulses delivered during MVC detect an inability to recruit motor units, whereas pulse train stimulation is required to detect suboptimal synchronization and frequency modulation of already recruited motor units. The first method was adopted in the present study; thus our results can be interpreted as an increased recruitment of motor units. Second, although Van Cutsem et al. (39)

Fig. 4. Torque-angle (A) and torque-angular velocity (B) relations obtained during maximal voluntary plantar flexion, before and after the 4-wk period for the control group. All values are means ± SE from 6 subjects.
have reported an increase in discharge rate of the TA motor units after 12 wk of voluntary ballistic training, it is still not clear if this mechanism contributes directly to increased force production (35). Indeed, greater MVC force can be produced without the need to drive motor units at excessively high discharge rates (33). Third, improved motor unit recruitment can be considered as an early response to resistance training, explaining rapid increases in voluntary force production (33), such as those observed in the present study. Future investigations of EMS training will need to determine the relative contribution of motor unit recruitment and discharge rate to voluntary torque gains, but also other motor unit properties (e.g., synchronization), to better comprehend the neural adaptations associated with this form of training.

Although the neural mechanism, which is altered subsequent to EMS training, cannot be directly elucidated from this experiment, supraspinal centers, interneurons that project to the motoneurons innervating the triceps surae muscles, and, as previously discussed, α-motoneurons could be proposed as the site of adaptation, accounting for the increased descending outflow. Although EMS likely induces antidromic activation of the motoneurons, adaptations at the spinal cord level are unlikely, because we observed no significant changes for the soleus reflex response evoked at rest (H reflex) after the present EMS training (unpublished observations). These observations suggest that adaptation in motoneuron excitability and in afferent neurons or interneurons did not play a major role in the increased activation that we found after training. Consequently, the mechanism most likely accounting for our results could be an increased volitional drive from the supraspinal centers that causes greater activation of the muscles that assist the prime movers.

Although incomplete activation of the PF muscles has previously been reported (6, 17, 24), the maximal voluntary activation values estimated here might appear low (EMS group ~82%, C group ~80%). However, similar values have been reported in many recent investigations that have focused on the knee extensor muscles (3, 7, 19). Furthermore, the precision of the twitch interpolation technique has been questioned (5), and the actual position of the research community is still equivocal (see Ref. 4). As a consequence, the present activation level results cannot be interpreted alone but in conjunction with the normalized EMG activity recorded during voluntary contractions. As a matter of fact, the results obtained in the C group before and after the 4-wk period clearly confirm the reliability of the present twitch interpolation data.

Because it is likely that EMS results in a reversal of the recruitment order of motor units, and it may even preferentially activate the largest motor units first (13, 16, 20), another intriguing observation of this type of training is the possible preferential adaptation of the type II motor units (10, 12, 26). This assumption is supported by the increase in voluntary eccentric torque that has been observed after EMS training (10, 26, 34).

**Fig. 5.** Normalized RMS EMG-angle relations for respective muscles obtained during maximal voluntary plantar flexion, before and after the 4-wk period for the control group. A: soleus; B: MG; C: LG; D: TA. All values are means ± SE from 6 subjects.
and by a concomitant increase of the agonist EMG activity (10). Results from the present study extend these findings and confirm that neural activity, which increases after EMS training, could be ascribed to adaptations in the largest motor units. This assumption is further supported by the significant EMG increase that was observed for the two gastrocnemii during eccentric PF and not during isometric and concentric contractions (Figs. 2 and 3) after EMS training. Indeed, it has been reported that high-threshold motor units of the LG (and probably of the MG) are selectively activated during eccentric contractions (32), although this is not a general finding (see Ref. 14). This is, therefore, not surprising to observe significant torque increases under isometric and eccentric conditions without concomitant concentric torque increases.

It has recently been shown that a correlation exists between postactivation twitch potentiation (i.e., the increased force of a twitch after a MVC) and muscle fiber type (19), with type II fibers conferring greater potentiation (29). Although the exact peripheral mechanism by which training increases PAP is not fully understood (19), phosphorylation of myosin light chains during the MVC, which renders actin-myosin more sensitive to Ca$^{2+}$ in a subsequent twitch (37), has been suggested as a possible mechanism. Furthermore, the observation of greater PAP in type II fibers is likely related to a greater capacity of the myosin light chains to be phosphorylated in these fibers in response to high-frequency activation. Only a few longitudinal strength-training studies have tested for changes in PAP, and to date there has been no attempt to investigate the effects of EMS training on PAP. If EMS preferentially activates the largest motor units, one could expect PAP increases after EMS training. Interestingly, in the present investigation, PAP significantly increased by 11.9% after training, whereas no changes were observed in the C group.

In the present training protocol, PF twitch and doublet and tetanus contractile properties evoked at rest (i.e., not potentiated) were not modified. These evoked contractions provide an indication of changes in muscle properties and enable psychological factors and alterations in the central recruitment pattern to be excluded. In this study, both electrical (M-wave) and mechanical (contractile) properties were not affected by training, and thus one can argue that 4 wk of EMS have no significant effect on peripheral components of the triceps surae neuromuscular system. In addition, an increase in surface EMG activity in the absence of M-wave modification supports results from prior studies (39) that neural adaptations mediate the increase in voluntary torque subsequent to EMS training. Our results for twitch contractile properties and the related surface action potentials from the PF muscles are similar to prior reports for the adductor pollicis (12). How-

Fig. 6. Normalized RMS EMG-angular velocity relations for respective muscles obtained during maximal voluntary plantar flexion, before and after the 4-wk period for the control group. A: soleus; B: MG; C: LG; D: TA. All values are means ± SE from 6 subjects.
and RR: Pt, RD, and RR measured from the tetanic stimulation, respectively. The interspike interval for paired stimulation was 10 ms, and the duration of the 100-Hz tetanus was 250 ms.

Table 3. M-wave amplitude and plantar flexor contractile properties associated with single-twitch, paired (doublet), and tetanic stimulation, before and after the 4-wk intervention period, for EMS and C groups

<table>
<thead>
<tr>
<th></th>
<th>EMS Before</th>
<th>EMS After</th>
<th>C Before</th>
<th>C After</th>
</tr>
</thead>
<tbody>
<tr>
<td>M-wave amplitude, mV</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Soleus</td>
<td>9.46 ± 2.77</td>
<td>8.99 ± 1.93</td>
<td>10.93 ± 2.76</td>
<td>10.34 ± 2.99</td>
</tr>
<tr>
<td>MG</td>
<td>6.60 ± 2.56</td>
<td>5.86 ± 2.39</td>
<td>7.80 ± 3.92</td>
<td>7.42 ± 4.04</td>
</tr>
<tr>
<td>LG</td>
<td>5.51 ± 3.42</td>
<td>5.06 ± 2.84</td>
<td>4.72 ± 1.31</td>
<td>6.47 ± 2.61</td>
</tr>
<tr>
<td>Twitch properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt, N•m</td>
<td>20.99 ± 4.29</td>
<td>19.89 ± 4.19</td>
<td>17.48 ± 3.63</td>
<td>16.28 ± 5.51</td>
</tr>
<tr>
<td>CT, ms</td>
<td>128.38 ± 11.96</td>
<td>128.53 ± 7.88</td>
<td>136.02 ± 9.22</td>
<td>135.11 ± 9.59</td>
</tr>
<tr>
<td>HRT, ms</td>
<td>90.28 ± 16.68</td>
<td>93.81 ± 17.34</td>
<td>94.43 ± 10.85</td>
<td>98.64 ± 8.39</td>
</tr>
<tr>
<td>RD, N•m•ms⁻¹</td>
<td>0.300 ± 0.053</td>
<td>0.285 ± 0.065</td>
<td>0.244 ± 0.060</td>
<td>0.242 ± 0.086</td>
</tr>
<tr>
<td>RR, N•m•ms⁻¹</td>
<td>0.185 ± 0.038</td>
<td>0.167 ± 0.042</td>
<td>0.141 ± 0.042</td>
<td>0.134 ± 0.052</td>
</tr>
<tr>
<td>Doublet properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt, N•m</td>
<td>41.20 ± 7.76</td>
<td>38.93 ± 9.04</td>
<td>35.72 ± 8.30</td>
<td>33.43 ± 10.49</td>
</tr>
<tr>
<td>CT, ms</td>
<td>145.93 ± 11.88</td>
<td>144.94 ± 11.58</td>
<td>150.35 ± 9.27</td>
<td>150.39 ± 9.91</td>
</tr>
<tr>
<td>HRT, ms</td>
<td>108.21 ± 17.39</td>
<td>109.88 ± 11.18</td>
<td>104.34 ± 5.43</td>
<td>106.56 ± 10.98</td>
</tr>
<tr>
<td>RD, N•m•ms⁻¹</td>
<td>0.540 ± 0.092</td>
<td>0.510 ± 0.123</td>
<td>0.460 ± 0.122</td>
<td>0.446 ± 0.148</td>
</tr>
<tr>
<td>RR, N•m•ms⁻¹</td>
<td>0.339 ± 0.055</td>
<td>0.296 ± 0.068</td>
<td>0.286 ± 0.077</td>
<td>0.253 ± 0.083</td>
</tr>
<tr>
<td>Tetanus properties</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pt₀, N•m</td>
<td>94.70 ± 31.83</td>
<td>102.59 ± 25.52</td>
<td>96.54 ± 21.71</td>
<td>92.36 ± 31.93</td>
</tr>
<tr>
<td>RD₀, N•m•ms⁻¹</td>
<td>0.714 ± 0.242</td>
<td>0.814 ± 0.282</td>
<td>0.794 ± 0.188</td>
<td>0.877 ± 0.220</td>
</tr>
<tr>
<td>RR₀, N•m•ms⁻¹</td>
<td>0.718 ± 0.220</td>
<td>0.849 ± 0.126</td>
<td>0.703 ± 0.213</td>
<td>0.614 ± 0.297</td>
</tr>
</tbody>
</table>

Values are means ± SD; EMS group, n = 8; C group, n = 6. MG, medial gastrocnemius; LG, lateral gastrocnemius; Pt, peak torque; CT, contraction time; HRT, half relaxation time; RD, maximum rate of tension development; RR, maximum rate of tension relaxation; Pt₀, RD₀, and RR₀: Pt, RD, and RR measured from the tetanic stimulation, respectively. The interspike interval for paired stimulation was 10 ms, and the duration of the 100-Hz tetanus was 250 ms.

ever, Duchateau and Hainaut (12) observed an increase in maximal tetanic (100 Hz) tension after training, which allowed these authors to conclude that intracellular processes were altered subsequent to EMS training and that muscle contractile kinetics were not altered.

In the present experiment, a slight increase in tetanus contractile properties was observed, and perhaps these changes did not achieve significance because the duration of EMS training in the present study was only 4 wk, whereas Duchateau and Hainaut (12) stimulated for 6 wk. It is well known that several weeks of training are necessary to observe changes at the muscle level (e.g., hypertrophy), whereas neural adaptations likely account for torque gains that occur after the first few weeks of strength training (13, 36). In support of this assumption, Eriksson et al. (15) showed that, in the quadriceps femoris, muscle enzyme activities and fiber size of mitochondrial properties did not change after 15 EMS training sessions spread over 4–5 wk. Finally, in our experimental conditions, the observation that, after training, PF MVC significantly increased whereas electrically evoked contractions did not change supports the viewpoint that adaptations at the muscle level after 4 wk of EMS are unlikely.

In accordance with Behm et al. (5), it is not surprising to observe a great disparity between the PF MVC and the maximal tetanic tension. It must, therefore, be considered that, when voluntary vs. evoked PF contractions are compared, muscles other than the soleus and gastrocnemii (e.g., peroneus longus and brevis) likely contribute to voluntary ankle joint torque but not to the evoked torque (6). Moreover, the contribution from the gastrocnemii to the voluntary ankle torque measured with the knee flexed at 90° was reduced because of shortened muscle length (11), consequently resulting in a recruitment alteration (25).

We conclude that the increases in voluntary torque after 4 wk of EMS training were largely due to an increase in activation of the agonist (i.e., stimulated) muscles. The most obvious change in the function of the nervous system is an increase in the quantity of the neural drive to muscle from the supraspinal centers.

Fig. 7. Plantar flexor maximal voluntary activation (A) and postactivation potentiation (B) for EMS and control (C) group, before and after the 4-wk period. All values are means ± SE from 8 subjects (EMS group) and 6 subjects (C group). Posttraining values were significantly higher than pretraining values (ANOVA repeated measures) at *P < 0.05 and **P < 0.01.
Also, preferential adaptation of the type II motor units could be conjectured to explain the increases in PAP and in gastrocnemius EMG observed after short-term EMS training.

The authors are especially indebted to Drs. Roger M. Enoka and Jennifer M. Jakobi from the Neural Control of Movement Laboratory (Department of Kinesiology and Applied Physiology, University of Colorado at Boulder) for critical reading of the paper, and to all of the members of the laboratory for friendly support during data analysis and redaction. We gratefully acknowledge the cooperation of all of our subjects and the excellent technical assistance of Yves Ballay. We also thank Gilles Cometti for providing the Complex stimulators.

REFERENCES


