Electromyostimulation Training Effects on Neural Drive and Muscle Architecture

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ABSTRACT

GONDIN, J., M., GUETTE, Y. BALLAY, and A. MARTIN. Electromyostimulation Training Effects on Neural Drive and Muscle Architecture. *Med. Sci. Sports Exerc.*, Vol. 37, No. 8, pp. 1291–1299, 2005. **Purpose:** The purpose of the study was to investigate the effect of 4 and 8 wk of electromyostimulation (EMS) training on both muscular and neural adaptations of the knee extensor muscles. **Methods:** Twenty males were divided into the electrostimulated group (EG, $N = 12$) and the control group (CG, $N = 8$). The training program consisted of 32 sessions of isometric EMS over an 8-wk period. All subjects were tested at baseline (B) and retested after 4 (WK4) and 8 (WK8) wk of EMS training. The EMG activity and muscle activation obtained under maximal voluntary contractions (MVC) was used to assess neural adaptations. Torque and EMG responses obtained under electrically evoked contractions, muscle anatomical cross-sectional area (ACSA), and vastus lateralis (VL) pennation angle, both measured by ultrasonography imaging, were examined to analyze muscular changes. **Results:** At WK8, knee extensor MVC significantly increased by 27% ($P < 0.001$) and was accompanied by an increase in muscle activation (+6%, $P < 0.01$), quadriceps muscle ACSA (+6%, $P < 0.001$), and VL pennation angle (+14%, $P < 0.001$). A significant increase in normalized EMG activity of both VL and vastus medialis (VM) muscles (+69 and +39%, respectively, $P < 0.001$) but not of rectus femoris (RF) muscle was also found at WK8. The ACSA of the VL, VM, and vastus intermedius muscles significantly increased at WK8 (5–8%, $P < 0.001$) but not at WK4, whereas no changes occurred in the RF muscle. **Conclusion:** We concluded that the voluntary torque gains obtained after EMS training could be attributed to both muscular and neural adaptations. Both changes selectively involved the monoarticular vastii muscles. **Key Words:** STRENGTH GAINS, EMG ACTIVITY, MUSCLE ACTIVATION, HYPERTROPHY, KNEE EXTENSORS

The use of electromyostimulation (EMS) has been previously employed as a means of strength training in healthy humans (11,15–18,23,25). Many authors have indeed reported an increase in maximal voluntary contraction (MVC) following multiple EMS sessions (15–17,23,25), especially for the most often stimulated quadriceps femoris muscle (15,17,23,25). However, the underlying mechanisms responsible for this strength improvement remain unclear.

Several EMS studies have suggested that neural factors, rather than changes at the muscular level, largely account for the training-induced strength gains, particularly in the case of programs lasting 4 wk or less (16,18,25). For example, Maffiuletti et al. (16) reported a significant increase in plantar flexor MVC that was accompanied by an enhancement in both muscle activation and soleus electromyographic (EMG) activity following 4 wk of EMS training. Moreover, the dose–response relationship between quadriceps stimulation and activation of selected brain regions (26), but also cross-education effects (11) clearly demonstrated that EMS activated the neural system. All these findings indicated that neural adaptations probably occur after multiple sessions of involuntary resistance training.

Recently, Bickel et al. (4) showed that an acute bout of EMS was sufficient to stimulate molecular-level responses. Such changes indicated the initiation of hypertrophy processes in quadriceps muscle of both able-bodied and spinal cord–injured subjects. Thus, changes at the muscular level could also be expected after multiple sessions of EMS training. However, the effect of an EMS training program on muscle hypertrophy remains ambiguous in the literature, due mainly to the training duration adopted (19,24,25,27) and EMS parameters selected (24,27). For example, two studies (24,27) observed an impressive increase in quadriceps muscle size after 8–9 wk of EMS training, whereas others did not report such changes after EMS programs lasting 4 wk (19,25). It can, therefore, be hypothesized that muscle hypertrophy might occur as a result of an EMS training program lasting more than 4 wk.

The aim of the present study was to investigate the effects of 4 and 8 wk of EMS training on the neural and muscular properties of the knee extensor muscles, with particular emphasis on the time course of adaptations. To our knowledge, this study was the first to present a combined analysis of both muscular and neural factors after multiple sessions of EMS training. The EMG activity and muscle activation obtained during MVC of the knee extensor muscles were used to analyze neural adaptations. Torque and EMG responses obtained under electrically evoked contractions, muscle ACSA and vastus lateralis (VL) pennation angle, both measured by ultrasonography imaging, were assessed to study potential changes occurring at the muscle level.

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METHODS

Approach to the Problem and Experimental Design

This experiment was conducted to examine the neuromuscular adaptations induced by 4 and 8 wk of EMS training program of the knee extensor muscles. The EMG activity and muscle activation obtained under MVC was used to assess neural adaptations. Torque and EMG responses obtained under electrically evoked contractions, muscle anatomical cross-sectional area (ACSA) and VL pennation angle, both measured by ultrasonography imaging, were examined to analyze muscular changes. These variables were measured in two groups of subjects, one of which underwent a training program (i.e., electrostimulated group (EG)); the other received no exercise training (i.e., control group (CG)). The training program consisted of 32 × 18-min sessions of isometric (bilateral) EMS over an 8-wk period, with four sessions per week. All subjects were tested on four occasions: 2 wk (W-2) before baseline and at baseline (B) to assess interreliability measurements. Subjects were then retested after 4 (WK4) and 8 (WK8) wk of EMS training. Three to four days of rest separated the 16th and the 32nd training sessions from the WK4 and WK8 testing sessions, respectively. CG subjects were also retested after 4 and 8 wk of habitual daily activities. All measurements were carried out on the right leg. The independent variables were the time at which the measurement was taken (i.e., B, WK4, and WK8) and the group of subjects (i.e., EG and CG). Dependent variables were MVC, EMG activity and muscle activation obtained during MVC, evoked contractions (twitch and doublet stimulations) and associated maximal M wave, quadriceps and individual muscle ACSA, and VL pennation angle.

SUBJECTS

Twenty male students gave written informed consent to participate in this study. They were randomly assigned to EG, composed of 12 subjects (age 23.5 ± 5.0 yr, height 178.4 ± 8.9 cm, weight 73.7 ± 9.4 kg, means ± SD) or to CG (N = 8, age 24.3 ± 1.6 yr, height 176.4 ± 4.7 cm, weight 69.3 ± 7.4 kg, means ± SD). None of them had engaged in systematic strength training or EMS in the 12 months preceding the beginning of the experiments, but some were active in recreational sports. Approval for the project was obtained from the University of Burgundy committee on human research. All procedures used in this study were in conformity with the Declaration of Helsinki.

EMS Training

Training session. One week before the beginning of the stimulation period, the EG subjects participated in one practice session to familiarize themselves with stimulation parameters. The training program consisted of 32 × 18-min sessions of isometric (bilateral) EMS over an 8-wk period, with four sessions per week. Forty isometric contractions were carried out during each training session. During the stimulation, subjects were seated on a machine typically used for strength training of the quadriceps muscle (Multi-Form, La Roque D'Anthéron, France) with the knee joint fixed at a 60° angle (where 0° corresponds to full extension of the knee). Straps were consistently fastened across the pelvis to minimize hip and thigh motion during the contractions. Three 2-mm-thick, self-adhesive electrodes were placed over each thigh. The positive electrodes, measuring 25 cm^2 (5 × 5 cm), which had membrane depolarizing properties, were placed as close as possible to the motor point of the VL and vastus medialis (VM) muscles. The negative electrode measuring 50 cm^2 (10 × 5 cm) was placed 5–7 cm below the inguinal ligament. For each individual, the set of the electrodes was changed at the end of the fourth week of training. A portable battery-powered stimulator (Compex, Sport P, Medicompex, Ecublens, Switzerland) was used. Rectangular wave pulsed currents (75 Hz) lasting 400 μs were delivered with a rise time of 1.5 s, a steady tetanic stimulation time of 4 s, and a fall time of 0.75 s (total duration of the contraction: 6.25 s). Each stimulation was followed by a pause lasting 20 s (duty cycle: 24%). Intensity was monitored online and was gradually increased throughout the training session to a level of maximally tolerated intensity, which varied between 30 and 120 mA, according to the pain threshold of each subject. No subject reported serious discomfort. Each session was preceded by a standardized warm-up, consisting of 5 min of submaximal EMS at a freely chosen intensity (5 Hz, pulses lasting 200 μs). The stimulation characteristics of the present study were selected according to the recommendations of several authors (9,14). Such an EMS training protocol has been successfully used in our laboratory to increase knee extensor muscle strength (15,17).

EMS evoked force measurements. The individual level of isometric force developed during EMS was randomly measured using an isokinetic dynamometer once during the first 4 wk of training and once again during the last 4 wk of training with the testing position detailed below (see section on torque measurements). Subjects underwent the standardized warm-up EMS as described previously and then performed two MVC of the knee extensor muscles, separated by 2 min of rest. Subjects then completed the entire EMS training session and the evoked force was stored by means of commercially available software (Tida, Heka Elektronik, Lambrecht/Pfalz, Germany) for further analysis. The evoked force between the sixth and the 10th contractions were averaged and subsequently divided by the highest MVC obtained before the EMS training session. The force produced by EMS ranged indeed from 47 to 93% of the MVC (mean 68 ± 13%).

Measurements

Torque measurements. Instantaneous isometric torque at the knee joint was recorded using a Biodex isokinetic dynamometer (Shirley, NY). The subjects were placed in a seated posture with the trunk–thigh angle at 90°

and the knee flexed at 60° (where 0° corresponds to the full extension of the knee), defined here as the training position. Each subject was securely strapped to the test chair with two crossover-shoulder harnesses and a belt across the hip joint. The axis of the dynamometer was aligned with the anatomical knee joint axis, and the lever arm was attached 2–3 cm above the lateral malleolus with straps. To allow biceps femoris EMG recordings, a board (thickness: 3 cm) was placed underneath the subject with a hole where the electrodes were placed so as to avoid any compression between the surface electrodes and wire on the seat. Subjects were asked to cross their arms during the testing procedure. Gravity correction was performed to account for the weight of the limb.

Electrical stimulation. The femoral nerve was stimulated using a cathode ball electrode (0.5 cm diameter) pressed and maintained by the same experimenter in the femoral triangle, 3–5 cm below the inguinal ligament. The anode was a large electrode (10 × 5 cm; Medicompex SA, Ecublens, Switzerland), located in the gluteal fold. Rectangular pulses of 1-ms duration were used, 400-V maximal voltage (Digitimer DS7, Hertfordshire, UK). The individual stimulation intensity was set by progressively increasing the stimulus intensity until there was no further increase in peak twitch torque (i.e., the highest value of the knee extensor twitch torque) nor in concomitant peak-to-peak M-wave amplitudes. This intensity was further increased by 20% (i.e., supramaximal intensity) and then maintained for single and paired stimulations (10-ms interspike interval). Individual supramaximal intensities were between 45 and 100 mA.

Experimental procedure. Testing procedure and recordings started with four single pulses each separated by 8 s, and three paired stimuli, each separated by 6 s, during which subjects were asked to relax. Then, subjects were instructed to perform two MVC of the knee extensor muscles. Paired stimuli were also delivered 3 s over the isometric plateau (superimposed doublet) and 3 s after the contraction (potentiated doublet) to assess muscle activation according to the twitch interpolation technique (1). Finally, two MVC of the knee flexor muscles were performed. The total duration of these efforts was approximately 5 s. A third knee extension and/or flexion MVC was performed if more than 5% difference was observed with respect to the highest MVC. A 3-min rest period was allowed between series of stimulations and between MVC to eliminate the effects of fatigue.

EMG recordings. Surface EMG activity of the VL, VM, rectus femoris (RF), and biceps femoris muscles was recorded bipolarly, during voluntary and electrically evoked contractions, by silver chloride circular electrodes with a diameter of 20 mm and a recording diameter of 10 mm. The electrodes were fixed lengthwise over the middle of the muscle belly with an interelectrode (center-to-center) distance of 20 mm. This site was determined in pilot testing by eliciting at a given intensity the greatest M-wave amplitude for each muscle via femoral nerve stimulation. This procedure was performed so as to avoid the innervation zone and therefore to obtain the optimal amplitude of EMG response. The reference electrode was attached to the patella of the contralateral leg. The placement of each electrode was marked on the skin with indelible ink, so that it could be exactly repositioned from session to session. Low resistance (<5 kΩ) between the two electrodes was obtained by abrading the skin with emery paper and cleaning with alcohol. EMG signals were amplified with a bandwidth frequency ranging from 15 Hz to 5.0 kHz (common mode rejection ratio = 90 dB; impedance = 100 MΩ; gain = 1000).

Data analysis. Mechanical and EMG traces were digitized online (sampling frequency 2 kHz) and stored by means of commercially available software (Tida, Heka Elektronik, Lambrecht/Pfalz, Germany). Only the highest knee extensor and knee flexor MVC were considered for analysis. MVC torque and EMG were analyzed over a 500-ms period once the torque had reached a plateau and before the superimposed stimuli. The root mean square (RMS) EMG values of VL, VM, and RF muscles were calculated and then normalized to the peak-to-peak amplitude of the maximal M wave (i.e., RMS/M ratio) for respective muscles. Muscle activation was estimated according to the following formula, that is, percent activation = (1 – superimposed doublet/potentiated doublet) × 100. The level of coactivation was calculated by normalizing the RMS values of the biceps femoris when this muscle was acting as an antagonist to the RMS obtained when this muscle was acting as an agonist, that is., during knee flexion, and was expressed as a percentage. Concerning the electrically evoked contractions, EMG and mechanical signals were averaged and peak-to-peak amplitude and duration of the VL, VM, and RF maximal M wave were measured. The following twitch contractile properties were analyzed: 1) peak twitch (Pt), the highest value of twitch torque production; 2) time-to-peak twitch (TPT), the time to obtain twitch maximal torque, calculated from the origin of the mechanical signal; 3) half-relaxation time (HRT), the time to obtain half of the decline in twitch maximal torque. For the paired stimuli, only the peak torque (Pt_{PS}) was measured.

Measurement of muscle ACSA. B-mode ultrasonography (Esaote Biomedica, AU5, Florence, Italy) with a 50-mm, 7.5-MHz linear-array probe was used to obtain axial-plane images of the quadriceps muscle, using previously applied methods validated in the VL muscle (21,22). All measurements were performed after the subjects had been in the supine position for at least 20 min to allow fluid shift to occur (3). During all measurements, the subjects were instructed to relax their leg muscles. Scans were taken in the axial plane at the level of 50% of the distance between the upper border of the superior patella and the greater trochanter. This position was marked on the skin with indelible ink. Orientated in the axial plane, the probe was aligned perpendicularly to the lateral side of the VL muscle and moved across a premarked section over echo-absorptive external markers fixed to the skin from a lateral to medial position. The probe was coated with a water-soluble transmission gel to provide acoustic contact. Great care was taken to consistently apply minimal pressure during scanning to avoid compression of the underlying structures.

Scanning was recorded onto SVHS videotape and then acquired using frame-capture software (Adobe Premier version 5.1, Adobe Systems). Single scans were identified for further analysis. Using the lines cast by the external markers as references, scans were fitted using a contour matching program. All the scans were performed by the same investigator. The four individual muscles (VL, VM, RF, and vastus intermedius, i.e., VI) were measured separately by use of an image analysis program (NIH Image version 1.61, National Institutes of Health, Bethesda, MD). The mean of five consecutive morphometric analyses of each image was used to calculate $ACSA_{VL}$, $ACSA_{VM}$, $ACSA_{RF}$, and $ACSA_{VI}$. The mean ACSA of the quadriceps muscle ($ACSA_Q$) was then calculated by summing up the mean ACSA of the four individual muscles of the quadriceps. The image analyses were performed by a single investigator, who was blinded to the identity of the subject.

Measurement of muscle architecture. The pennation angle of the VL muscle was measured *in vivo* using real-time B-mode ultrasonography with a 50-mm, 7.5-MHz linear-array probe in the same condition described above (see Measurement of Muscle ACSA section). The width of the VL was measured at 50% of the length of the thigh and the center of the width was marked on the skin with indelible ink. At this position, the probe was positioned perpendicular to the dermal surface of the VL muscle and oriented along the median plane of the muscle. The probe was coated with a water-soluble transmission gel to provide acoustic contact without depressing the dermal surface. Pennation angle was defined as the angle between the fascicular path and the deep aponeurosis of the VL muscle. For each individual, four images at rest were obtained within the same experimental session. Data analysis was performed with the same digitizing software used for the ACSA determination. A mean of three pennation angles was assessed on each ultrasound image and thus a mean of 12 pennation angles was calculated.

Statistical analysis. To assess the interday (i.e., W-2 and B) and intraday (i.e., for individual muscle ACSA and for the pennation angle) variability of the present measurements, coefficients of variation (i.e., CV = SD/mean × 100) were calculated for each subject. The interday and intraday reproducibility of the variables was quantified with intercorrelation coefficients (ICC) based on repeated-measures ANOVA with testing session as the independent variable and on Cronbach's alpha, respectively. Normality of the data was checked and subsequently confirmed using the Kolmogorov–Smirnov test. Two-factor (group (EG vs CG) × session (B, WK4, WK8)) ANOVA with repeated measures on session were used to compare the dependent variables. When significant interactions were found, Tukey *post hoc* analysis was performed. Linear regression analysis (Pearson's product–moment correlation) was used to compare the degree of association between variables. Statistical power values were calculated for various significant differences and ranged from 0.329 to 0.931 (Table 1). Significance was accepted when $P < 0.05$. The statistical analyses were performed using Statistica software for Microsoft Windows (StatSoft, version 6.1, Tulsa, OK). All data are expressed as means ± SD in the text and as means ± SE in the figures.

TABLE 1. Statistical power associated with the two-way ANOVA repeated measures.

Variable	B-WK4	WK4-WK8	B-WK8
MVC	0.573	0.405	0.931
VL RMS/M	0.615	—	0.804
VM RMS/M	0.763	—	0.719
Muscle activation	0.432	—	0.631
KE ACSA	—	0.343	0.504
VL ACSA	—	0.329	0.493
VM ACSA	—	—	0.375
VI ACSA	—	0.339	0.386
Pennation angle	—	0.395	0.826

Data are presented when statistical significant differences ($P < 0.05$) were found ($N = 12$).

RESULTS

Reliability of measurements. Table 2 shows the interday reproducibility and variability of all the dependant variables. ICC and CV ranged from 0.799 to 0.964 and from 0.9% to 14.83%, respectively, except for the coactivation level (ICC = 0.680 and CV = 19.70%). Intraday reproducibility ranged from 0.995 to 0.999 and from 0.900 to 0.911 for ACSA and for the pennation angle, respectively. CV was between 0.53% and 0.95% and between 3.32% and 3.88% for ACSA and the pennation angle, respectively.

TABLE 2. Interday reproducibility (ICC) and variability (CV) between the two testing sessions (i.e., WK-2 and B) for respective variables ($N = 20$).

Variables	ICC	CV (%)
MVC		
Knee extensor (N·m)	0.868*	4.72
Knee flexor (N·m)	0.883*	4.78
EMG activity, activation, and coactivation		
RF RMS/M	0.824*	12.86
VL RMS/M	0.846*	12.67
VM RMS/M	0.799*	9.19
Biceps femoris RMS EMG (mVs)	0.906*	14.83
Muscle activation (%)	0.865*	3.21
Coactivation level	0.680**	19.70
Contractile properties		
Pt (N·m)	0.877*	6.39
TPT (ms)	0.957*	3.39
HRT (ms)	0.856*	6.40
Pt_{PS} (N·m)	0.895*	5.70
M-wave amplitude		
RF (mV)	0.873*	11.92
VL (mv)	0.888*	9.55
VM (mV)	0.851*	8.75
M-wave duration		
RF (ms)	0.940*	3.89
VL (ms)	0.888*	8.76
VM (ms)	0.940*	8.05
Muscle ACSA and muscle architecture		
RF (cm^2)	0.964*	1.82
VL (cm^2)	0.938*	1.72
VM (cm^2)	0.964*	1.60
VI (cm^2)	0.911*	1.78
Quadriceps (cm^2)	0.962*	0.95
Pennation angle (°)	0.812*	3.21

MVC, maximal voluntary contraction; EMG, electromyography; RMS, root mean square; RF, rectus femoris; VL, vastus laterlis; VM, vastus medialis; Pt, peak torque; TPT, time to peak twitch; HRT, half relaxation time; Pt_{PS}, peak twitch associated with paired stimuli; ACSA, anatomical cross-sectional area; VI, vastus intermedius.
* Significant at $P < 0.001$.
** Significant at $P < 0.01$.

No significant baseline differences were observed between the two groups for any of the measured variables.

MVC, EMG activity, and activation level. Knee extensor MVC increased significantly between B and WK4 (+15 ± 11%, $P < 0.001$), between WK4 and WK8 (+11 ± 11%, $P < 0.001$) and between B and WK8 (+27 ± 15%, $P < 0.001$) in the EG (Fig. 1A). No significant changes in MVC of the knee extensor muscles occurred in the CG (238 ± 49, 233 ± 44, and 244 ± 46 nm at B, WK4, and WK8, respectively).

Muscle activation increased significantly in the EG between B and WK4 (+5 ± 6%, $P < 0.05$, Fig. 1B) and between B and WK8 (+6 ± 6%, $P < 0.01$). No significant changes were observed in muscle activation in the CG (88 ± 8%, 87 ± 7%, and 89 ± 6% at B, WK4, and WK8, respectively).

Significant group × session interactions ($P < 0.01$, Fig. 2A and B) were found for VL and VM but not for RF RMS/M ratio ($P > 0.05$, Fig. 2C). In the EG, VL and VM RMS/M ratios increased significantly between B and WK4 (+44 ± 19% and +42 ± 31%, respectively, $P < 0.05$) and between B and WK8 (+69 ± 56% and +39 ± 25%, respectively, $P < 0.001$) (Fig. 2A and B). No significant changes in VL and VM RMS/M ratios occurred in the CG (Fig. 2A and B).

A significant negative correlation ($r = 0.720$, $P < 0.01$; statistical power: 0.777), fitted with a linear function, was found between the muscle activation values at baseline and the MVC relative gains between B and WK8 (Fig. 3). This relationship showed that the lower the voluntary activation level was, the greater the strength gains.

There was no interaction for group × session ($P > 0.05$) for MVC of the knee flexor muscles nor for biceps femoris RMS values. Knee flexor MVC for B, WK4, and WK8 were 122 ± 23, 135 ± 29, and 131 ± 34 nm in the EG and 118 ± 21, 119 ± 10, and 122 ± 19 nm in the CG, respectively. Biceps femoris RMS values for B, WK4, and WK8 were 0.15 ± 0.06, 0.15 ± 0.06, and 0.17 ± 0.08 mV in the EG and 0.15 ± 0.07, 0.17 ± 0.09, and 0.14 ± 0.07 mV in the CG, respectively.

No significant group × session interaction was observed for the level of coactivation ($P > 0.05$). The level of coactivation for B, WK4, and WK8 were 9.0 ± 3.9, 10.1 ± 4.5, and 10.0 ± 3.3% in the EG and 8.1 ± 3.1, 7.8 ± 4.2, and 9.0 ± 3.4% in the CG, respectively.

Contractile properties and M waves. No significant group × session interactions were noted for Pt, TPT, HRT, or Pt_{PS} ($P > 0.05$, data not shown) nor for either M-wave amplitude or duration in the three muscles ($P > 0.05$, data not shown).

Muscle size. In the EG, $ACSA_Q$ increased significantly between WK4 and WK8 (+4 ± 2%, $P < 0.001$, Fig. 1C) and between B and WK8 (+6 ± 2%, $P < 0.001$), whereas a trend toward a significant increase was observed between B and WK4 (+2 ± 2%, $P = 0.06$). Within the individual muscles of the quadriceps, a significant group × session interaction was observed for the VL, VM, and VI muscles ($P < 0.001$), but not for the RF muscle ($P > 0.05$, Table 3). In the EG, $ACSA_{VL}$ and $ACSA_{VI}$ increased significantly between WK4 and WK8 (+5 ± 6% and + 5 ± 3%, respectively, $P < 0.001$) and between B and WK8 (+8

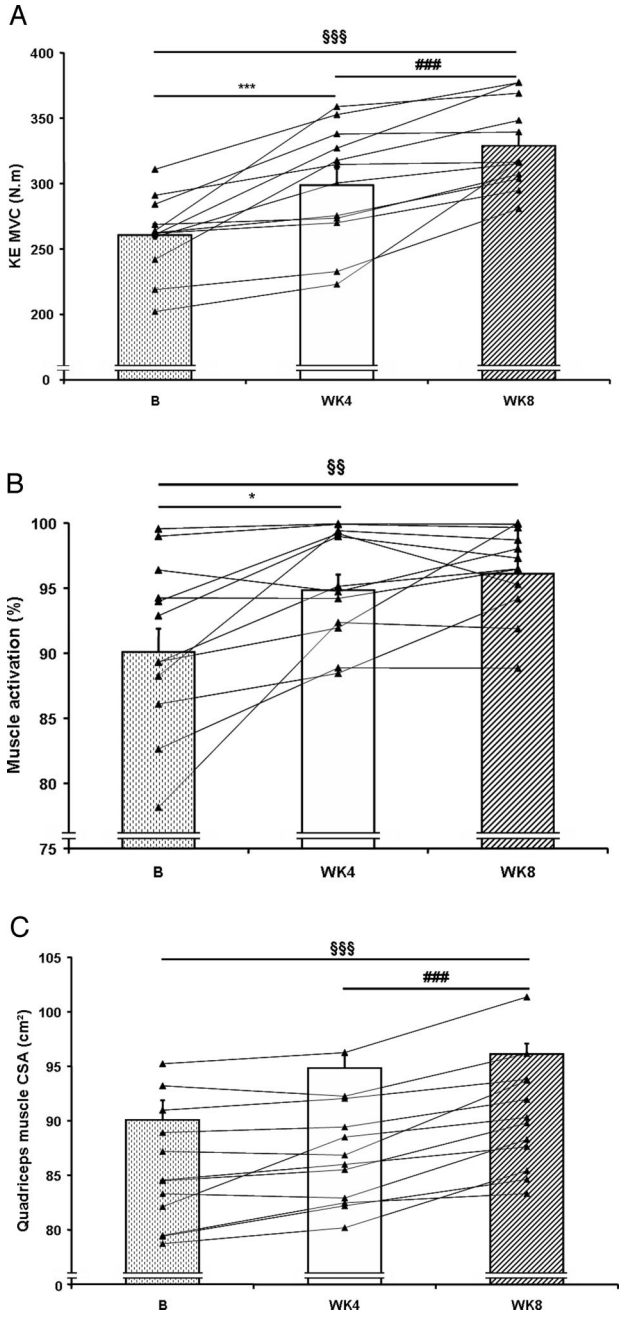

FIGURE 1—(A) Maximal voluntary torque produced by the knee extensor (KE) muscles at baseline (B), following the 4-wk (WK4) and 8-wk (WK8) period for the electrostimulated group (EG, $N = 12$). (B) Knee extensor maximal muscle activation for the electrostimulated group (EG, $N = 12$), at baseline (B), following the 4-wk (WK4) and the 8-wk (WK8) periods. (C) Quadriceps muscle ACSA measured at 50% of the distance between the upper border of the superior patella and the greater trochanter by use of ultrasonography imaging, at baseline (B), following the 4-wk (WK4) and the 8-wk (WK8) period in the electrostimulated group (EG, $N = 12$). Data were obtained by the addition of the mean ACSA of the four individual muscles of the quadriceps. Triangle symbols and columns show individual values and group mean values, respectively. SE is indicated by error bars. Significant difference between B and WK4 conditions: *$P < 0.05$; ***$P < 0.001$. Significant difference between WK4 and WK8 conditions: $^{\#\#\#}P < 0.001$. Significant difference between B and WK8 conditions: $^{\S\S}P < 0.01$; $^{\S\S\S}P < 0.001$.

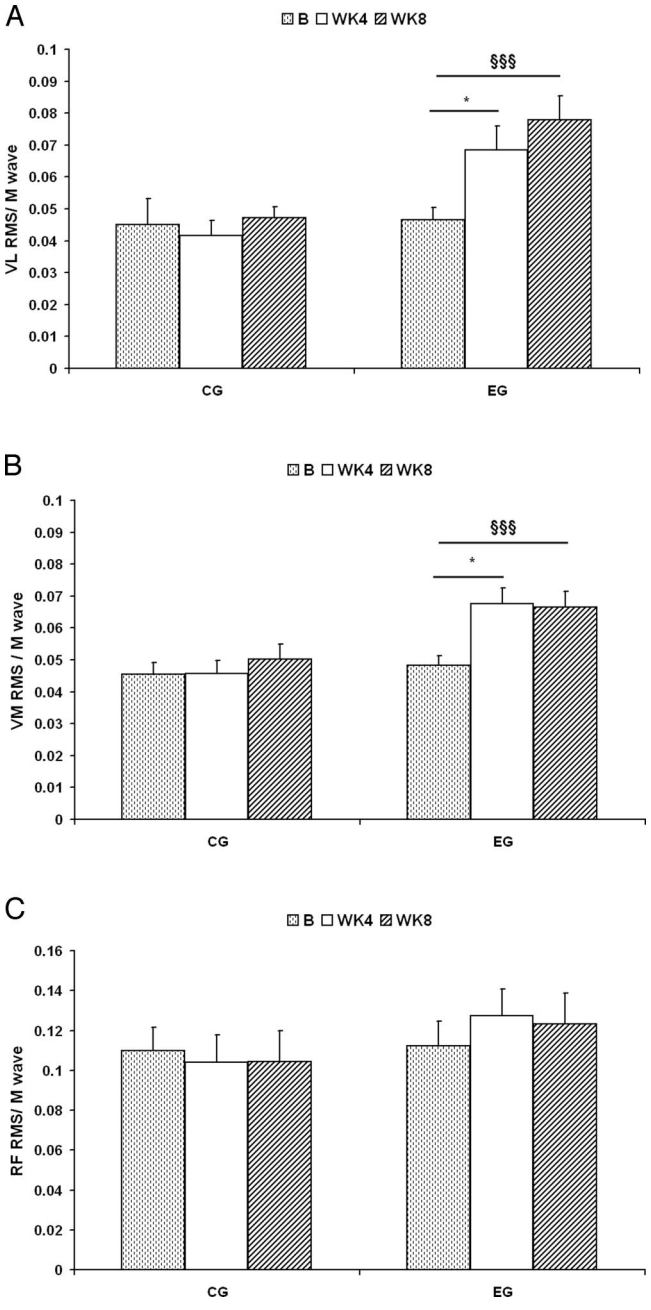

FIGURE 2—Normalized EMG activity (RMS/M ratio) for respective muscles obtained during maximal voluntary knee extension, at baseline (B), following the 4-wk (WK4) and the 8-wk (WK8) periods for the control group (CG, $N = 8$) and the electrostimulated group (EG, $N = 12$). (A) VL, (B) VM, (C) RF. All values are means ± SE. Significant difference between B and WK4 conditions: $^{*}P < 0.05$. Significant difference between B and WK8 conditions: $^{§§§}P < 0.001$.

± 5% and +6 ± 4%, respectively, $P < 0.001$). In the EG, $ACSA_{VM}$ showed a trend toward a significant increase between WK4 and WK8 (+3 ± 3%, $P = 0.07$), whereas a significant increase was observed between B and WK8 (+5 ± 5%, $P < 0.001$). $ACSA_Q$ (82 ± 4 cm^2, 82 ± 5 cm^2, and 82 ± 4 cm^2 at B, WK4, and WK8, respectively), $ACSA_{VL}$, $ACSA_{VI}$, and $ACSA_{VM}$ remained unchanged in the CG.

Muscle architecture. In the EG, the VL pennation angle increased significantly between WK4 and WK8 (+7 ± 7%, $P < 0.05$, Fig. 4) and between B and WK8 (+14 ±

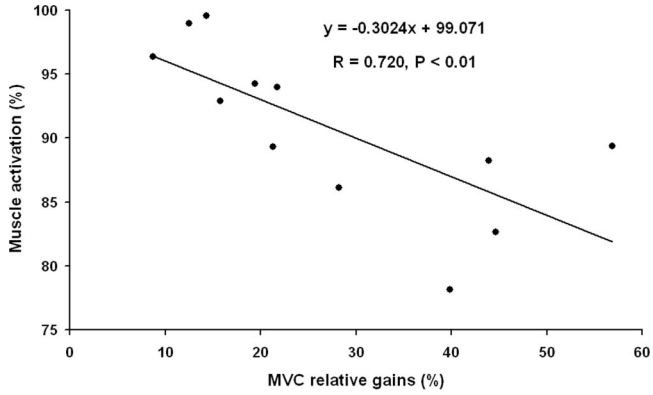

FIGURE 3—Individual data of knee extensor maximal voluntary contraction (MVC) relative gains between baseline and 8-wk period conditions plotted against maximal muscle activation values at baseline for the EG ($N = 12$). Data are fitted with a linear regression function.

7%, $P < 0.001$), whereas a trend toward a significant increase was observed between B and WK4 (+6 ± 8%, $P = 0.06$). No significant changes in the pennation angle were observed in the CG (Fig. 4).

It should be noted that all 12 subjects showed an increase in the main parameters between B and WK8, namely, knee extensor MVC (which ranged from 9% to 57%), muscle activation (which ranged from 1% to 18%), and quadriceps muscle ACSA (which ranged from 3% to 10%).

DISCUSSION

Although EMS has been largely employed as a means of strength training, the physiological adaptations by which EMS increases voluntary strength have been poorly investigated. This study demonstrated that the significant increase in quadriceps muscle MVC observed after 8 wk of EMS training was accompanied by a significant increase in 1) muscle activation, 2) normalized EMG activity of the VL and VM muscles but not of the RF muscle, 3) quadriceps muscle ACSA, and 4) VL fiber pennation angle. The data also indicated that 1) neural adaptations mainly occurred during the first 4 wk of EMS training, whereas changes in muscle mass and architecture became significant between weeks 4 and 8 of the training program and 2) both neural and muscular adaptations mainly affected the monoarticular vastii and not the biarticular RF muscle.

Reliability measurements. The variables considered in the present study demonstrated a low variability (CV < 15%) and a high degree of reproducibility (ranging from 0.799

TABLE 3. Individual muscle ACSA at baseline (B), following the 4-wk (WK4) and the 8-wk (WK8) period for the control group (CG) and the electrostimulated group (EG).

	CG			EG		
	B	WK4	WK8	B	WK4	WK8
VL (cm^2)	28.4 ± 2.0	27.8 ± 2.0	28.1 ± 1.6	28.4 ± 2.2	29.0 ± 1.9	30.6 ± 2.6*†
VI (cm^2)	27.9 ± 1.9	27.6 ± 1.9	27.8 ± 1.8	28.4 ± 2.3	28.7 ± 2.4	30.1 ± 1.9*†
VM (cm^2)	15.0 ± 1.4	15.1 ± 1.1	15.0 ± 1.2	16.6 ± 1.2	16.9 ± 1.2	17.4 ± 1.0†
RF (cm^2)	11.2 ± 0.8	11.3 ± 0.8	11.2 ± 0.8	12.2 ± 1.2	12.4 ± 1.1	12.5 ± 1.3

VL, vastus lateralis; VI, vastus intermedius; VM, vastus medialis; RF, rectus femoris. CG: $N = 8$; EG: $N = 12$. All values are means ± SD. * $P < 0.001$, significant difference between WK4 an WK8 conditions. † $P < 0.001$, significant difference between B and WK8 conditions.

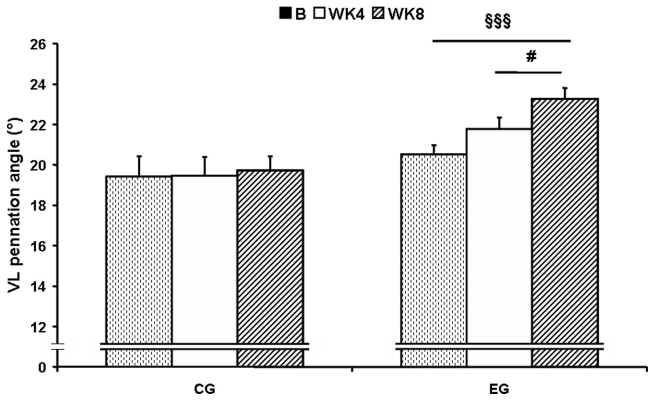

FIGURE 4—The vastus lateralis (VL) muscle fiber pennation angle obtained at 50% femur length by use of ultrasonography imaging, at baseline (B), following the 4-wk (WK4) and the 8-wk (WK8) periods for the control group (CG, $N = 8$) and the electrostimulated group (EG, $N = 12$). All values are means ± SE. Significant difference between WK4 and WK8 conditions: $^{\#} P < 0.05$. Significant difference between B and WK8 conditions: $^{\S\S\S} P < 0.001$.

to 0.964) between two different testing sessions (i.e., W-2 and B). According to Stokes (28), CV lower than or equal to 15% could be considered acceptable in biological systems. Moreover, similar CV and ICC values have been reported in the literature for MVC (29), muscle activation (1,29), muscle ACSA (21,22) and the VL pennation angle (8).

Maximal muscle strength. An average increase of 27% in MVC of the knee extensor muscles was observed after 8 wk of EMS training. These results are consistent with those reported in the literature after EMS training of the quadriceps muscle in healthy humans (15,17,23). Another interesting finding of the current study is the correlation observed between baseline muscle activation values and the strength gains at the end of EMS training, which indicated that muscle activation might be considered as an index of training status, where the lower activation values at baseline are associated with the greater training-induced gains in MVC strength. Thus, the present study demonstrated, at least for EMS training, that the lower the muscle activation was, the greater the strength gains.

Time course of neural versus muscular changes. This study was the first to report the time course of neural and muscular changes following multiple sessions of involuntary training. The gains in maximal voluntary strength observed at the end of the present EMS training program are attributable to both muscular and neural adaptations (see Fig. 1). After the first 4 wk of training, muscle activation significantly increased, whereas a trend toward a significant increase in both muscle ACSA and the VL pennation angle was observed. These results are in accordance with Maffiuletti et al. (16), who reported an increase in both muscle activation and soleus EMS activity after 4 wk of EMS training on the plantar flexor muscles, whereas Martin et al. (19) did not observe changes in muscle mass when using the same training program. Moreover, our results also showed that after 8 wk of EMS training, changes in muscle mass and architecture became significant and muscle activation was still higher than at baseline. To our knowledge, only a few studies (24,27) have used an EMS training program lasting 8 wk or more in healthy humans, and they reported impressive quadriceps muscle hypertrophy in agreement with the present study. Thus, by using a combined analysis of both muscular and neural factors after 4 and 8 wk of an EMS training program, our results clearly demonstrated that neural adaptations account for the initial voluntary strength improvement, whereas muscular changes took part in the further increase in strength.

Neural adaptations. In the present study, two different methods were used to assess neural adaptations of the knee extensor muscles. Muscle activation estimated by using the twitch interpolation technique significantly increased by 6% after training, thus indicating that EMS training enhanced the overall activity of the quadriceps muscle. These results are in agreement with those reported by Maffiuletti et al. (16) on the plantar flexor muscles after 4 wk of EMS training. Such activation increases could be ascribed to changes occurring at the supraspinal but also at the spinal level. Indeed, EMS evokes action potentials in both intramuscular nerve branches (12) and cutaneous receptors, thus inducing force production directly by activation of motor axons and indirectly by reflex recruitment of spinal motor neurons (5). However, a previous study performed in our laboratory (16) found no changes in resting soleus H-reflex amplitude after 4 wk of EMS training, therefore suggesting that the mechanisms accounting for the strength gains could be an increased volitional drive from the supraspinal centers. This last suggestion is reinforced by the study of Smith et al. (26), who reported that EMS applied over the quadriceps femoris muscle activated specific neural regions in a dose–response manner. However, further research is warranted to accurately determine the neural mechanisms responsible for the voluntary strength improvement.

Although muscle activation values observed in this study are in accordance with those previously reported in the literature (2), the twitch interpolation technique does not permit an investigation of the activation of individual muscles and thus the potential selective effect of EMS training on monoarticular vastii as opposed to biarticular RF muscle. The RMS EMG values obtained during MVC were indeed normalized to the respective M wave to better characterize neural activation of each muscle composing the quadriceps femoris. Both VL and VM EMG activity significantly increased, whereas no changes were observed for the RF muscle following 8 wk of EMS training. Similar to the present findings obtained on the monoarticular vastii muscles, EMG activity from the soleus muscle has been found enhanced following 4 wk of EMS training (16). On the other hand, it is not surprising to observe that RF EMG activity was not significantly higher after our single-joint EMS training program because this muscle was not directly stimulated by the electrodes during the training sessions. Despite the relatively high coefficient of variation in RMS/M ratios (12%) and the limits of EMG signal extraction (7), our results were corroborated by the fact that all 12 subjects showed an increase in muscle activation at the end of the training program.

Muscular changes. This study demonstrated a significant increase of quadriceps muscle ACSA with EMS training in healthy humans. The absolute values at baseline (80–85 cm^2) are consistent with those reported in the literature (20). Due to the length of time scanning and data analysis associated with the ultrasonography imaging method, only a single ACSA was performed in the midregion of the muscle, and this might result in an overestimation of the increase in ACSA (22). However, this technique has been recently demonstrated as valid and reliable in detecting changes in muscle size (21,22).

Thus, the increase in muscle ACSA observed after our EMS training could be ascribed, at least in part, to changes at the muscular level, which is in line with the observations of Bickel et al. (4). Indeed, these authors recently showed that an acute bout of EMS was sufficient to stimulate a molecular-level response, which indicated the initiation of hypertrophy processes in quadriceps muscle of able-bodied subjects. Nevertheless, the mean changes in muscle ACSA observed in our study were lower (6% vs 10%) than those previously reported in the literature (24,27). However, these two studies (24,27) stimulated the quadriceps muscle during both lengthening and shortening actions, whereas our EMS protocol involved isometric contractions. Despite such discrepancies, our results demonstrated that multiple sessions of EMS training induced quadriceps muscle hypertrophy.

B-mode ultrasonography provides sufficient image quality to allow delineation of individual muscles (21), and in the present study, the ACSA of the four constituent muscles of the quadriceps was measured separately. These values are very similar to those reported in the literature for the same scanning region (20). The ACSA of the three vastii muscles (i.e., VI, VL, and VM) increased significantly (5–8%), but no changes were observed for the RF muscle after the 8 wk of EMS training. The EMS protocol involved isometric contractions at a knee joint angle of 60°. Herzog et al. (10) demonstrated, from force-length relations assessed on human cadavers, that the individual force produced by the three vastii muscles reached their maximal values at the angle considered in our study, whereas only a small force production was obtained for the RF muscle. Thus, the amount of stimulation provided during training on the quadriceps muscle might have induced high tension on the monoarticular vastii muscles but not on the biarticular RF, therefore resulting in selective hypertrophy. The findings of the current study indicated that both neural and muscular adaptations occurred mainly on the monoarticular muscles, suggesting that such preferential individual muscle hypertrophy might be dependent on the selective enhancement of the neural drive to these muscles. Although the statistical power values for both quadriceps and individual (i.e., VL, VM, VI) muscle ACSA were not high enough, the quadriceps muscle ACSA increased in all 12 subjects after the 8-wk EMS training program.

The VL pennation angle values reported before training are in accordance with those observed by Fukunaga et al. (8) in the same testing conditions (i.e., 19–20°). This study is the first to report that EMS training resulted in a marked increase (14%) of the VL pennation angle. Thus, the 14% increase in the pennation angle would allow the concentration of a large number of contractile elements along the tendon (13). Also, the steeper muscle fiber pennation angle might largely contribute to the increase in muscle ACSA and thus play a role in the strength gains observed at the end of the EMS training program.

The analysis of the mechanical and electrical (i.e., M wave) twitch parameters evoked at rest by single and paired supramaximal electrical stimulation provide an indication of changes in excitation-contraction coupling. In the present study, none of these properties was altered as a result of training. The fact that 8 wk of EMS training did not affect excitation-contraction coupling properties is in line with prior results obtained on the triceps surae (16) and adductor pollicis muscle (6) following 4–6 wk of EMS training.

Practical applications of EMS training. The results of the present study clearly demonstrated that EMS training programs may induce both neural and muscular adaptations in healthy humans. Thus, the benefits of EMS should be useful in the design of rehabilitation programs to minimize the loss of quadriceps muscle function before, during, and after an immobilization period. Furthermore, considering the linear relationship between baseline muscle activation values and strength gains at the end of EMS training, muscle activation might provide an useful index of strength gains, at least in intact systems.

In conclusion, the present study demonstrated that neural as well as muscular adaptations are responsible for the quadriceps MVC torque increment obtained after 8 wk of EMS training. The former mainly accounted for the larger proportion of initial strength increment, whereas the latter took part in the further increase in strength. Both neural and muscular changes affected mainly the monoarticular vastii rather than the biarticular RF muscle, probably due to the specificity of muscle solicitation.

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