Vastus lateralis fatigue alters recruitment of musculus quadriceps femoris in humans

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1Department of Life Sciences (Sports Sciences), The University of Tokyo, Meguro, Tokyo 153-8902, Japan; 2Department of Exercise Science, The University of Georgia, Athens, Georgia 30602; and Departments of 3Physiology, 4Kinesiology, and 5Radiology, Michigan State University, East Lansing, Michigan 48824

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Akima, Hiroshi, Jeanne M. Foley, Barry M. Prior, Gary A. Dudley, and Ronald A. Meyer. Vastus lateralis fatigue alters recruitment of musculus quadriceps femoris in humans. J Appl Physiol 92: 679–684, 2002; 10.1152/japplphysiol.00267.2001—This study tested the hypothesis that fatigue of a single member of musculus quadriceps femoris (QF) would alter use of the other three muscles during knee extension exercise (KEE). Six men performed KEE with the left QF at a load equal to 50% of the 4 × 10 repetitions maximum. Immediately after EMS, subjects repeated the KEE. Transverse relaxation time (T2)-weighted magnetic resonance images were taken before and after each bout of KEE and at 3 and 30 min of EMS to assess use and stimulation, respectively, of the QF. T2 of each of the QF muscles was increased 8–13% after the first KEE. During EMS, T2 increased (P < 0.05) even more in VL (10%), whereas it decreased (P < 0.05) to pre-KEE levels in m. vastus medialis (VM) and m. rectus femoris (RF). The VL and, to some extent, the m. vastus intermedius were stimulated, whereas the VM and RF were not, thereby recovering from the first bout of KEE. Isometric torque, initially 30% of maximal voluntary, was reduced to 13% at 3 min and 7% at 30 min. T2 was greater (P < 0.05) after the second than the first bout of KEE, especially the increase for the VM and RF. These results suggest that subjects were able to perform the second bout with little contribution of the VL by greater use of the other QF muscles. The simplest explanation is increased central command to the QF such that the intended act could be accomplished despite acute fatigue of one of its synergists.

neuromuscular modulation; electromyostimulation; plasticity; magnetic resonance imaging

FORCES GENERATED BY MUSCLE to execute intended movements are regulated by the central nervous system and proprioceptive information (18, 31, 32, 39). Descending command from the central nervous system regulates motor unit recruitment and firing rate so that the desired motor task can proceed (8–10). Motor unit recruitment is mainly used to increase force in large muscles, such as the quadriceps femoris (QF) and the biceps brachii (15, 29). In the QF, it has been demonstrated that recruitment of musculus rectus femoris (RF) does not necessarily coincide with that of the three m. vasti during repetitive isometric or isokinetic knee extension exercise (KEE) (6, 7, 20, 28, 42). This may reflect the fact that the RF is biarticulate, whereas the three vasti are more clearly synergistic, acting only about the knee joint. That apparent synergists may be more or less engaged for a given movement has also been reported among human neck muscles for head extension (13, 14). Considering these observations, it is reasonable to speculate that recruitment can be modulated by afferent feedback during certain conditions, for example fatigue, to maintain required performance. The strong afferent linkages among the vasti but not the RF suggest that the three monoarticulate synergists would show increased use in concert (31). On the other hand, increased central command per se, in an effort to execute the intended act, could explain increased recruitment to maintain force over repeated contractions (8).

Muscle recruitment during exercise has been studied using conventional techniques such as electromyogram (EMG). Whereas magnetic resonance (MR) imaging (MRI) has been used to acquire anatomical information (4, 5, 22), use of human skeletal muscle has also been assessed with exercise-induced contrast shift in transverse relaxation time (T2) of MR images (1–3, 6, 7, 14, 21, 33–35, 42). It has been demonstrated that this contrast shift is correlated with integrated EMG activity (1), related to isometric torque induced by electromyostimulation (EMS) (2), increases with exercise intensity (1, 2, 21, 26, 30, 33, 36) and the metabolic state of skeletal muscle (37, 40, 42), and can discriminate use among relatively small synergistic muscles (13, 14) and neuromuscular compartments (3). Thus exercise-induced contrast shift in MR images seemed ideal to assess neuromuscular plasticity among synergists.
Others have often required subjects to perform repetitive, fatiguing contractions with a given muscle group and assessed electrical or mechanical signals to examine alterations in use among synergists (20, 28). We took the novel approach of using EMS to fatigue one of the QF muscles and assessed use of the four individual QF muscles during KEE before and after this EMS with MRI. We tested the hypothesis that subjects would be able to perform submaximal KEE, despite a fatigued m. vastus lateralis (VL) by increased use of the other QF muscles, i.e., m. vastus medialis (VM), m. vastus intermedius (VI), and RF.

**METHODS**

**Subjects.** Six men participated in this study. Their age, height, and weight averaged $32 \pm 7$ (SD) yr, $180 \pm 7$ cm, and $79 \pm 10$ kg, respectively. The procedures, purposes, and risks associated with the study were explained, and written, informed consent was obtained from each subject before participation. The study was approved by the Institutional Review Board of the University of Georgia.

**General design.** Use of the four individual QF muscles during KEE was assessed under two conditions: without and with fatigue of the VL induced by EMS (Fig. 1). On 1 test day, subjects were tested for $4 \times 10$ repetitions maximum (RM), the heaviest load that could be lifted for four sets of 10 repetitions with 1 min between sets, and maximum voluntary contraction (MVC) torque. On a separate test day, MR images of the left thigh were collected at rest (pre-Ex1), immediately after KEE with a load equal to 50% of the $4 \times 10$ RM (post-Ex1), after 3 min of EMS (stim3), after 30 min of EMS (pre-Ex2), and immediately after KEE was repeated (post-Ex2). Thus five sets of serial MR images (pre-Ex1, post-Ex1, stim3, pre-Ex2, and post-Ex2) were taken for each subject. Muscle use during KEE was determined by quantifying increases of T2 in MR images. The sequence of tests used in this study is summarized in Fig. 1.

**EMS.** Transcutaneous EMS (Theratouch, RICH-MAR) was applied to the lateral aspect of the QF with the intent of stimulating and fatiguing the VL, essentially as done previously (2). Voltage was delivered via two 7.6 $\times$ 10.2-cm electrodes (Free Form, UNI-PATCH, Wabasha, MN) applied to the skin. One was placed 4–6 cm proximal to the superior aspect of the patellar over the VL, and the other was placed 7–12 cm distal to the greater trochanter over the VL. Electrodes remained in place except for MRI. Outlines of the electrodes were traced with an oil-based marker to reposition them over repeat scans. Stimulation consisted of 3-s trains of 200-µs biphase pulses (50-µs delay) delivered at 50 Hz with a 3-s on and 3-s off duty cycle. EMS was applied during the first KEE bout at a current that was just perceptible. This was done not to stimulate the QF, but for timing to ensure that each repetition of KEE was performed during the “off” period of the EMS duty cycle. Subsequently, EMS was applied to activate and fatigue the VL beginning 30 min after the post-Ex1 images. Current was set to induce a torque equal to 30% MVC and was applied for 30 of the last 40 min between the first and second bout of KEE, which is the 10-min difference being used for the 5 min it took to take MR images after 3 and after 30 min of stimulation. This EMS was continued during the second bout of KEE to maintain fatigue of the VL. One again, a KEE repetition was performed during the off period of the EMS duty cycle.

**Torque measurement.** Torque imposed on the axis of rotation of the lever arm of a custom-made ergometer was recorded essentially as done precisely (12, 24). Tests were conducted with the subject seated on a padded bench with an adjustable backrest tilted 15° beyond vertical. Restraining straps across the thigh were used to stabilize the subject. The leg was attached to a lever arm with a Velcro strap across the shin. It was hinged at its point of attachment with the bench top but was held 55° below horizontal by a load cell (model 20000A, Rice Lake Weighing Systems, Rice Lake, WI) assembly mounted between the lever arm (30 cm from the hinge) and the front of the bench. The signal from the load cell was stored on a computer (Macintosh PowerBook 2400c, Apple). The highest average for a 500-ms window was considered maximal torque for a given contraction.

**Exercise protocol.** The KEE was performed at the MRI facility to permit image collection immediately after exercise (1, 2, 6, 7, 14, 21, 33–35). Subjects performed four sets of 10 repetitions of concentric (extension phase)–eccentric (flexion phase) contractions with a load equal to 50% of the $4 \times 10$ RM with the use of a plate-loaded knee extension machine (Badger-Magnum, Milwaukee, WI). One minute of rest was taken between sets. Each action was performed through the same range of motion (knee joint angle: $80–180^\circ$, $180^\circ$ = full extension) at a rate of 3-s exertion (1.5 s: extension, 1.5 s: flexion) with 3-s rest between efforts. The first and second bouts of KEE were separated by 1 h and 10 min: 5 min for the post-Ex1 images, 25 min of rest, 3 min of EMS, 5 min for the first and second bout of KEE, 5 min for the post-Ex2 images, and then 5 min of rest.

**Image acquisition and analysis.** The KEE was performed at the MRI facility to permit image collection immediately after exercise (1, 2, 6, 7, 14, 21, 33–35). Subjects performed four sets of 10 repetitions of concentric (extension phase)–eccentric (flexion phase) contractions with a load equal to 50% of the $4 \times 10$ RM with the use of a plate-loaded knee extension machine (Badger-Magnum, Milwaukee, WI). One minute of rest was taken between sets. Each action was performed through the same range of motion (knee joint angle: $80–180^\circ$, $180^\circ$ = full extension) at a rate of 3-s exertion (1.5 s: extension, 1.5 s: flexion) with 3-s rest between efforts. The first and second bouts of KEE were separated by 1 h and 10 min: 5 min for the post-Ex1 images, 25 min of rest, 3 min of EMS, 5 min for the first and second bout of KEE, 5 min for the post-Ex2 images, and then 5 min of rest.

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Standard spin-echo MR images of the left thigh were taken using a 1.5-T superconducting magnet (Signa, General Electric, Milwaukee, WI) essentially as done previously (1, 2, 6, 7, 14, 21, 33–35). Thirteen 10-mm-thick transaxial images (repetition time = 1,500 ms; echo time = 30 and 60 ms) of the left thigh spaced 10 mm apart were collected using 1.0 number of excitations with a whole body coil. A 256 × 128 matrix was acquired with one excitation and a 32-cm field of view. Total MR image collection time was 3 min and 30 s. Ink marks on the thigh aligned with crosshairs of the imager allowed for similar positioning in the magnet bore over repeat scans.

MR images were transferred to a computer for calculation of T2 using a modified version of the public domain National Institutes of Health (NIH) Image program (written by Wayne Rasband at NIH and available from the Internet by anonymous ftp from ftp://rsbweb.nih.gov/pub/nih-image.nihimage162_fat.hqx). After spatial calibration (32 cm/256 pixels = 0.125 cm/pixel), a region of interest was defined by tracing the outline of each muscle of the QF, i.e., VL, VM, VI, and RF. Muscle activation during KEE and EMS was evaluated by determining T2 for each muscle. Data were averaged over the 13 images for each subject.

To evaluate reproducibility of T2 in individual muscles of the QF, MR images of the nonexperimental (right) thigh for two subjects of this study were taken after two bouts of KEE separated by ~60 min. A high correlation was observed between T2 before EMS and after the second bout of KEE (r = 0.934, P < 0.0001), and the average values for a given muscle did not differ over bouts. In addition, no significant difference was observed in resting T2 between bouts (data not shown).

Statistics. T2 data were analyzed with a two-way (muscle × time), and torque data with a one-way ANOVA with repeated measures over time. Significant main effects and interactions were compared using the least squares difference post hoc test. All analyses were performed using the SuperANOVA for Macintosh statistical package. The level of significance was set at P < 0.05. Data are presented as means ± SD.

RESULTS

EMS-induced torque. Torque was 93 ± 12 N·m at the beginning of EMS. This corresponded to 30 ± 5% of MVC. Torque rapidly decreased (P < 0.0001) to 40 ± 9 N·m (13% of MVC and a 56 ± 10% decrease) by 3 min of EMS. It slightly recovered during the 5 min taken for the stim3 MR images (53 ± 20 N·m; P < 0.0001) and subsequently decreased (P < 0.0001) during the next 27 min of EMS. Torque immediately before the second bout of KEE was 22 ± 5 N·m (7% of MVC and a 76 ± 6% decline).

T2. Figure 2, A–E, shows representative MR images at pre-Ex1, post-Ex1, stim3, pre-Ex2, and post-Ex2, respectively. T2 for each of the four QF muscles and its relative change for the VM and RF are shown in Figs. 3 and 4, respectively. There was a significant two-way interaction, muscle by time (P < 0.0001), for T2. The four muscles showed a 8–13% increase in T2 for the first bout of KEE. Subsequently, T2 of the VL showed a further increase during EMS, whereas it decreased to resting levels for the VM and RF over this time. About one-half of the increase in T2 of the VI evoked by the first bout of KEE was resolved during EMS. Performance of the second bout of KEE resulted in a higher T2 than that evident after bout 1. This was true for the VM and RF because of a larger KEE-induced increase from rest. In contrast, T2 for the VL was higher because the modest increase elicited by the second bout of KEE was imposed on the marked increase induced by EMS. The VI showed an intermediate response. It was partially stimulated; thus the increase that was about the same for both bouts of KEE was superimposed on a moderately elevated T2 for bout 2.

![Figure 2: Representative transaxial transverse relaxation time (T2)-weighted MR images of left thigh from a subject at pre-Ex1 (A), post-Ex1 (B), stim3 (C), pre-Ex2 (D), and post-Ex2 (E). Four sets of 10 unilateral concentric (extension phase)-eccentric (flexion phase) actions were performed using quadriceps femoris with a load equal to 50% of 4 × 10 RM. Note that contrast shifts were observed at VL and a part at stim3 and pre-Ex2 of MR images. VL, vastus lateralis; VM, vastus medialis; VI, vastus intermedius; RF, rectus femoris.](http://jap.physiology.org/)

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DISCUSSION

The novel finding of this study was that inherent use of the four QF muscles during submaximal KEE was acutely modified so that the exercise could be accomplished after force output of the VL had been almost abolished (see Fig. 2). All four muscles showed moderate use during 4 × 10 RM KEE, with a load equal to 50% of maximum as reflected by contrast shift in MR images. Application of EMS to the lateral thigh for 30 min evoked substantial torque loss, namely 75%, and marked contrast shift in the VL. The VM and RF recovered during this time, whereas the VI was partially activated by EMS and thus showed incomplete recovery. Subsequent repeat performance of the KEE was viewed as more difficult by the subjects, but all accomplished the task. Fatigue of the VL necessitated greater use of the VM and RF, as reflected by contrast shift in MR images, to perform the submaximal KEE. The fact that exercise-induced contrast shifts in T2-weighted images correlate with integrated EMG activity (1), increase with exercise intensity (1, 2, 21, 30, 33, 36), and relate to isometric torque with EMS (2) supports the notion of greater use of these two QF muscles for the second rather than the first bout of KEE. These responses are considered to be acute modifications of neuromuscular coordination among the synergistic muscles to perform the exercise.

In general, voluntary movements are controlled by descending command signals that originate in the motor cortex (8, 17, 18, 39). It is believed that there is a motor program that results in a sequential, coordinated firing of specific motoneurons to produce a given movement such as KEE (8, 18). In this study, the motor program was apparently modified due to fatigue of the VL, such that the VM and RF were used to a greater extent for the second bout of KEE. If increased central command was responsible for the greater use of the QF muscles, how might this have occurred: more motor units recruited and/or an increased firing frequency? Thickbroom et al. (39) demonstrated that there was an increase in the spatial distribution (i.e., area) of functional MRI signals within the central sulcus and an increase in the summed signal from all activated regions of the sensorimotor cortex during isometric handgrip exercise with increasing levels of force. A similar result has been demonstrated by Dettmers et al. (17). They found, using (H215O) positron emission tomography, a logarithmic increase in regional cerebral blood flow in a number of motor areas, including the primary sensorimotor cortex, as force increased during dynamic index finger flexion. With regard to motor unit evaluation during force exertion, Conwit et al. (15) reported that there was a relationship between motor unit size (recruitment), which was estimated by the size of surface motor unit action potential, and force generation (5–100% knee extension MVC) of the VM muscle (r = 0.82, P < 0.001). Finally, Kukulka and Clamann (29) demonstrated that motor unit recruitment in a large muscle such as the biceps brachii continues over the entire force range. Thus it seems reasonable that greater motor unit recruitment in the VM and RF, reflected in the larger increase in T2, allowed performance of the second bout of KEE, despite fatigue of the VL. Force output of the QF per se would not have been greater for the second bout of KEE, but fatigue of the VL would have necessitated greater contribution from its synergists.

Afferent proprioceptive feedback probably also contributed to the acute neuromuscular adaptation observed in this study (32). It has been suggested that proprioceptors, such as muscle spindles and Golgi tendon organs, provide information about limb position and force through cortical pathways (31). Nichols et al. (31) demonstrated that there were strong monosynap-
tic Ia linkages among the vasti muscles; however, the linkages between individual vasti muscles and the RF were weaker. Thus one possibility was that fatigue of the VL would cause greater use of the other vasti but not the RF. However, the RF, in addition to the VM, showed greater use during KEE when the VL was fatigued. Based on this result, we suggest that alterations in the neuromuscular motor patterns of the QF did not result from proprioceptive systems alone.

The firing rate of motoneurons is also important for voluntary force production (15). According to Conwit et al. (15), firing rate of active motoneurons in the knee extensors (VM) increases with force increments >30% of MVC, thereby augmenting force. However, motor unit recruitment makes a greater contribution than an increase in firing frequency to force augmentation in large muscles such as the VM (16, 29). Based on these results, we suggest that increased motor unit recruitment was mainly responsible for the greater contrast shift in the VM and RF after the second than first bout of KEE, even though the relative contribution of recruitment vs. firing frequency to the increase in T2 is difficult to ascertain (30).

There is little information concerning the pattern of skeletal muscle activation by surface EMS (2, 24, 41). Activation of the QF can be variable among subjects when low forces are evoked and electrodes are placed over the distal VM and proximal VL (2). However, we also knew that electrode placement over the proximal and distal VL could result in substantial activation of this muscle if sufficient force were evoked (2). Accordingly, force evoked by EMS in this study with the just-mentioned electrode placement was set to 30% of MVC because the VL occupies ~30% of the volume of the QF (4, 5). As shown in Fig. 2, the VL was mainly activated. Thus its T2 increased further after the first bout of KEE during EMS. In contrast, the increase in T2 of the VM and RF evoked by the first bout of KEE decreased to baseline during EMS, indicating that these muscles were not stimulated. A portion of the VI was stimulated; thus the increase in its T2 evoked by the first bout of KEE did not decay to baseline during EMS. Based on these results, we suggest that the force loss during EMS was mainly due to fatigue of the VL. Similarly, it is proposed that the greater use of the VM and RF for Ex2 vs. Ex1 was due to fatigue of the VL. Although it cannot be completely ruled out that the EMS applied during Ex2 had some effect on voluntary muscle use, this seems unlikely. First, force loss during EMS was marked; thus the perception for EMS was comparable for Ex1 and Ex2. Second, we have shown that the nature of the in vivo speed torque relation for the QF is comparable when muscle actions are evoked by EMS vs. voluntary effort and that these relations are similar to those found for affected skeletal muscle in clinically complete spinal cord-injured patients or skeletal muscle in situ or in vitro (19). Third, at least for the tetanic superimposition technique, EMS actually decreases voluntary force (25).

Greenhaff et al. (23) have demonstrated that glycogen loss occurs in both type I and II fibers during EMS (50 Hz, 1.6-s/1.6-s duty cycle), suggesting that both fiber types are stimulated. A similar result has been shown by Kim et al. (27). Adams et al. (2) have also suggested that muscle fibers are uniformly stimulated during EMS (50 Hz, 1-s/1-s duty cycle). Based on these studies, it seems reasonable to predict that the pattern of force loss during EMS would mirror the fatigue resistance properties of the three major fiber types: I > IIa > IIb (10, 11, 38). Assuming that the metabolic profile of most (fast) but not all (some of the slow) of the stimulated fibers would not allow energy supply to meet energy demand, one would predict a rapid and precipitous decline in force during EMS. Most of the 76% decline in torque occurred during the first 3 min of EMS; thereafter, performance was maintained at a low level. Based on these results and those in the previous paragraph, we suggest that the force output ability of the VL was markedly compromised by EMS.

In summary, we tested the hypothesis that fatigue of the VL would alter use of the QF muscle during KEE. Moderate use of the QF was observed during KEE. Fatigue of the VL, evoked by EMS, increased use of the other three QF muscles, especially the VM and RF, when the KEE was repeated. The simplest explanation is increased central command to the QF, such that the intended act could be accomplished, despite acute fatigue of one of its synergists. It is also likely, however, that motor unit firing was altered by peripheral feedback on spinal circuits.

REFERENCES