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Mapping of electrical muscle stimulation using MRI

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ADAMS, GREGORY R., ROBERT T. HARRIS, DANIEL WOODARD, AND GARY A. DUDLEY. *Mapping of electrical muscle stimulation using MRI.* J. Appl. Physiol. 74(2): 532–537, 1993. —The purpose of this study was to map the pattern of muscle contractile activity elicited by electromyostimulation (EMS). A secondary interest was to determine whether EMS evoked a different pattern of contractile activity than voluntary (VOL) efforts. These objectives were addressed by examining the pattern and extent of contrast shift in magnetic resonance (MR) images after isometric actions of the left m. quadriceps of seven subjects had been elicited by EMS (1-s train of 500-μs sine wave pulses at 50 Hz) or by VOL means. For both conditions, five sets of 10 muscle actions were executed at each of the three force levels equal to 25, 50, and 75% of maximal VOL isometric torque. There were 1-s, 1.5-min, and 30-min rests between muscle actions, sets, and torque levels, respectively. Transaxial proton MR images (TR/TE = 2,000/30, 60) of m. quadriceps femoris were obtained with a 1.5-T imager at rest and after completion of the five sets of isometric actions at each force level. MR image contrast shift, as indicated by T_2 values >1 SD above the mean resting muscle T_2, was calculated per pixel. Torque declined ~18% ($P < 0.05$) during each EMS set independent of the preset relative force level but recovered between sets. EMS increased T_2 values above rest (29 ± 0.2 to 36 ± 0.5, $P < 0.05$) in regions of muscle dispersed throughout a given cross section. The pattern of muscle stimulation, as reflected by increased T_2 values, varied markedly among subjects. VOL efforts did not cause fatigue nor appreciably increase T_2 [13% of m. quadriceps femoris cross-sectional area showed an elevated ($P < 0.05$) T_2 at the highest relative force]. The results suggest that the location of muscle stimulated via EMS cannot be taken for granted across subjects. It is also suggested that EMS stimulates the same fibers repeatedly, thereby increasing metabolic demand and T_2 values. VOL efforts, in contrast, appear to be performed by more diffuse asychronous activation of skeletal muscle even at forces up to 75% of maximal to maintain performance.

electromyostimulation; magnetic resonance imaging

MAGNETIC RESONANCE IMAGING (MRI) is finding increased use in research that requires anatomic information. One unique aspect of MRI is the contrast enhancement that occurs in muscle after exercise (9–12, 16, 27, 30, 31). Although the exact mechanism for the contrast shift is not known, increases in the time constant for decay of 63% of the magnetic resonance (MR) signal (T_2) may be related to previous contractile activity and the associated metabolic response. The finding that exercise-induced contrast shifts occur in healthy individuals, but not in those afflicted with McArdle's disease, has been used to suggest that increases in T_2 in previously active muscle are related to glycogenolysis and/or lactate production because of the inability of these patients to catabolize glycogen (12). Support for this arises from the observation that T_2 is correlated with both pH and the inorganic phosphate-to-phosphocreatine ratio (31). Adams et al. (1) recently showed, in addition, that both integrated electromyography activity and T_2 of the long and short head of m. biceps brachii increased as a linear function of load when forearm curls were performed. The long head of m. triceps brachii showed no changes in integrated electromyography activity or T_2. It was suggested, therefore, that contrast shifts in MRI reflect the pattern and extent of muscle use that occurred during exercise. Venous occlusion causes little or no increase in T_2, thereby indicating that exercise-induced contrast shifts are not the result of simple vascular dilation (9). It is also unlikely that increased perfusion per se is responsible for MR image signal contrast shifts because T_2 increases after exercise performed with vascular occlusion (11).

Electromyostimulation (EMS) of skeletal muscle is commonly used in rehabilitation and research and even as an adjunct to strength training (5, 6, 8, 19, 23, 34). The use of EMS to reestablish motor control in paraplegics is also an important area of study (22). These applications of EMS have occurred without clear knowledge of which muscles and/or muscle regions were being stimulated.

We used contrast shifts in MR images in the present study in an attempt to map regions of thigh muscle that had been stimulated by transcutaneous EMS. A second interest was to compare the distribution of muscle contractile activity with EMS vs. voluntary (VOL) activation.

METHODS

Subjects. Two females and five males participated in this study. All had served in previous studies in which lower body strength was measured (6) or took part in general physical conditioning regimens. None, however, performed lower body heavy-resistance training. Their age, height, and weight averaged 30 ± 2 yr, 177 ± 4 cm, and 74 ± 5 (SE) kg, respectively. The procedures, purpose, and risks associated with the study were explained and written consent was provided. The study was approved by the Human Research Review Board at the Kennedy Space Center, FL.

General design. The influence of muscle contractile activity on signal intensity of T_2-weighted MR images was

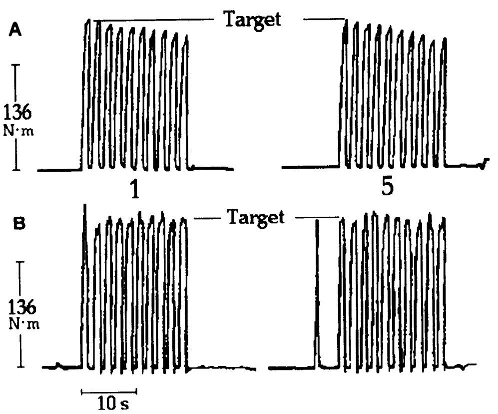

FIG. 1. Representative torque records for first (1) and last (5) set of 10 unilateral isometric actions of m. quadriceps femoris at 75% (target) of maximal voluntary isometric torque (MVIT) for 1 subject. Ten actions were induced by electromyostimulation (EMS; *A*) or voluntary (VOL; *B*) means.

studied under two conditions. On one test day, EMS was applied to m. quadriceps femoris via surface electrodes to induce isometric actions. On a separate test day, VOL efforts were used to induce contractile activity in m. quadriceps femoris. Three familiarization sessions were conducted before testing to introduce subjects to tetanic (50 Hz) EMS and to (re)establish their maximal voluntary isometric torque (MVIT). The MVIT tests were performed as described previously (6). We found a test-retest of $r > 0.90$ ($P < 0.001$) for VOL torque using this approach (6). Torque equal to 25, 50, and 75% of MVIT was subsequently calculated for each subject.

Force measurement. Torque imposed on the axis of rotation of the level arm of an ergometer (7) by contraction of m. quadriceps femoris during unilateral isometric actions was measured during EMS and VOL efforts. Tests were conducted with the subject seated on a padded bench with an adjustable backrest tilted 10° beyond vertical. Restraining straps across the waist and thigh were used to stabilize the subject. The leg was attached to a lever arm with a velcro strap across the shin. The lever arm consisted of a padded aluminum plate on which the leg rested. It was hinged at its point of attachment with the bench top but was held 0.96 rad (55°) below horizontal by a load cell assembly mounted between the lever arm (30 cm from the hinge) and the front of the bench. The signal from the load cell was sent to a Daytronic (Miamisburg, OH) load cell signal conditioner and subsequently to a Gould strip chart recorder.

EMS. Stimulation occurred via transcutaneous EMS with use of a system developed by this laboratory (7). The system consists of an IBM computer that controls output from a Krone-Hite (Avon, MA) waveform generator and voltage from a battery-powered amplifier. Voltage was delivered via two 76 × 114-mm carbonized rubber electrodes (Tenzcare, 3M, St. Paul, MN) applied to the skin. One electrode was placed 4–6 cm proximal to the superior aspect of the patella over the belly of m. vastus medialis, and the other was placed 10–15 cm distal to the greater trochanter over m. vastus lateralis. Electrodes remained in place during rest between exercise bouts when the MR images were taken, and every effort was made to place them in the same location across subjects. Stimulation consisted of a 1-s train of 500-μs sinusoidal pulses with an interval between pulses of 19.5 ms. Pulses were thus delivered at a frequency of 50 Hz. EMS was used to induce five sets of ten 1-s isometric actions at each of three different force levels equal to 25, 50, and 75% of MVIT. There was 1 s of rest between the 1-s actions, 90 s between sets, and 30 min between relative force levels. EMS intensity, reflected by peak current at the electrode-skin interface, was held constant during and across sets at each relative torque level for any given subject.

VOL efforts. The intent of the VOL trials was for each subject to mimic his/her EMS protocol. The number, magnitude, and timing of the VOL unilateral isometric actions of m. quadriceps femoris were the same as described for EMS. Subjects watched a computer screen that graphically displayed their actual torque output and the desired pattern of torque development they were to follow (10 cycles of 1-s effort followed by 1-s rest with torque equal to 25, 50, or 75% of MVIT). At least two practice sessions using this system were completed during the week before data collection.

MRI. Subjects were imaged before exercise and immediately (2.8 ± 0.1 min) after completion of the five sets at each relative torque level. Transaxial MR images were acquired at a field strength of 1.5 T by use of a Signa (General Electric, Milwaukee, WI) imaging system. T_2-weighted images (TR/TE 2,000/30, 60) were collected with use of a 25-cm-diameter extremity coil. A 256 × 128 matrix was acquired with one excitation and a 20-cm field of view. Five 10-mm slices were collected at 5-mm intervals with the third cross section centered between the stimulation electrodes. This resulted in sampling a 7-cm region along the length of the thigh. The volume element or voxel size was 0.78 × 1.6 × 10 mm. An indelible ink mark midway between the two electrodes was aligned with the illuminated cross hairs of the imager, and both lower limbs were held in a fixed position with a foot brace to ensure consistent positioning in the magnet bore over repeat MR images. We have found a test-retest reliability for repeat measures of muscle morphology [e.g., cross-sectional area (CSA) of m. quadriceps femoris by slice] of $r > 0.95$ ($P < 0.05$) using this approach.

TABLE 1. *Stimulated muscle cross-sectional area, torque, and T_2 of stimulated muscle after EMS of m. quadriceps femoris evoked unilateral isometric actions*

	MVIT, %		
	25	50	75
% Muscle CSA, cm^2	19.0±0.8	34.0±2.6	54.0±3.8
Torque decrease, %	20.1±2.5	17.3±1.0	15.2±0.6
EMS T_2 (stimulated)	36.2±0.4	36.2±0.4	36.8±0.5

Values are means ± SE. Electromyostimulation (EMS) was used to elicit forces equal to 25, 50, and 75% of maximal voluntary isometric torque (MVIT). % Muscle CSA, relative area of m. quadriceps femoris with a T_2 1 SD > the mean T_2 of resting muscle. Values represent the mean of five transaxial slices of the thigh. EMS T_2, average T_2 of this stimulated muscle; torque decrease, average decrease in torque ($P < 0.05$) during each five sets of 10 isometric actions. Torque recovered between sets and relative force levels. There was less ($P < 0.05$) of a decline in torque at the 75 than 25% EMS level.

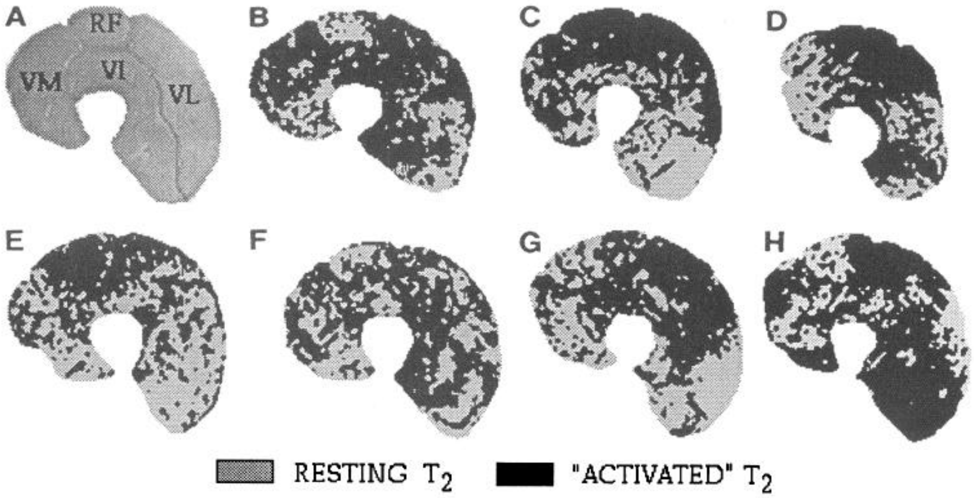

FIG. 2. Representative single slice proton density image (*A*) and T_2 maps (*B–H*) showing different patterns of contractile activity of m. quadriceps femoris in 7 subjects after EMS that induced a torque equal to 75% of MVIT. *A*: muscles are rectus femoris (RF), vastus medius (VM), vastus intermedius (VI), and vastus lateralis (VL). *B–H*: single slices from approximately the same anatomical region in 7 subjects showing resting (Resting T_2) and stimulated (Activated T_2) muscle.

MR image files were stored on nine-track tape and transferred to a MacIntosh IIfx computer with use of a Qualstar tape drive. Calculation of muscle CSA and T_2 was made using a modified version of the Image software program (National Institutes of Health). The CSA of m. quadriceps femoris was determined by integration over an operator selected region of interest on the native (proton density) image. This region of interest was stored and used as an anatomic template for T_2 measurements. T_2 was calculated[1] for the entire data set and the image was reconstructed with T_2 as the picture element (pixel) attribute. The mean T_2 of m. quadriceps femoris at rest was determined by eliminating pixels with a T_2 <20 and >35, and averaging the remaining values. After EMS, T_2 values greater than the resting means ± 1 SD were considered to represent muscle that had performed contractile activity. The CSA represented by these "activated" pixels was calculated for each image. The area of pixels with T_2 values greater than the resting mean ± 1 SD in control images was subtracted from the areas in the post-EMS or VOL images that reflected prior contractile activity.

Statistics. Standard methods were used to calculate means ± SD and SE. Simple linear regression was used to examine relationships between selected variables. A one- or two-way analyses of variance with repeated measures was used to analyze T_2, muscle CSA, and torque data where appropriate. Data were arcsine transformed before analyses if in relative or ratio form.

RESULTS

EMS resulted in a decline ($P < 0.05$) in torque during each set with full recovery between sets (Fig. 1). The average decline per set was slightly greater for the 25 than 75% torque level (Table 1). There was no fatigue during each set or over sets for the VOL efforts.

EMS resulted in varying patterns of apparent muscle contractile activity (Fig. 2). Some subjects showed marked T_2 shifts in m. rectus femoris and the inferior aspect of m. vastus lateralis, whereas others did not. There was no indication that the current delivered on the anterior surface of the thigh reached muscles such as the adductors in the posterior compartment (data not shown). VOL efforts resulted in minimal change in T_2 (i.e., 13% of muscle CSA showed increased values at 75% MVIT).

There was a strong linear relationship between absolute muscle CSA that showed contractile activity and torque with EMS (Fig. 3). EMS current steps producing 25, 50, and 75% of MVIT resulted in complementary linear increases in the percent CSA of m. quadriceps femoris that showed contractile activity (Table 1, Figs. 4 and 5). The mean T_2 of stimulated muscle was the same for each relative torque level (Table 1).

DISCUSSION

To date, use of EMS in both clinical and research settings has been carried on without knowledge of the anatomic field affected by the applied current. The results of the present study suggest that MRI is a useful tool for determining patterns of muscle stimulation with EMS. Moreover, EMS does not appear to induce uniform contractile activity in a given region of muscle across subjects.

As defined by T_2 changes in MR images, the regions stimulated by EMS varied noticeably among the seven subjects (Fig. 2). It has generally been assumed that EMS activates primarily superficial portions of muscles (18). As depicted in Figs. 2 and 5, however, some of the muscle that was stimulated was deep, even at low levels of EMS. In several cases (Fig. 2, *B*, *D*, and *F*) the deepest portions

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[1] T_2 was calculated as follows: $T_2\ (\mathrm{ms}) = (\mathrm{Tb} - \mathrm{Ta})/\ln(\mathrm{Sa}/\mathrm{Sb})$, where T_2 is mean T_2 for the tissue within a pixel, Ta is time the first spin echo was collected (30 ms), Tb is time the second spin echo was collected (60 ms), Sa is signal level at the pixel in first image, and Sb is signal level at the pixel in the second image.

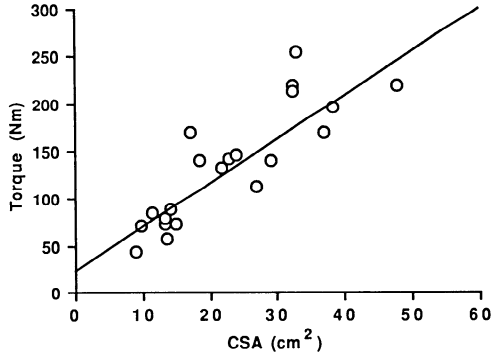

FIG. 3. Relationship between stimulated muscle cross-sectional area (CSA) as determined by magnetic resonance imaging (MRI) and torque of m. quadriceps femoris during unilateral isometric actions induced by EMS (torque = CSA × 4.87 + 23.3, $r^2 = 0.74$, $P < 0.001$). Each data point is average CSA of stimulated muscle in 5 transaxial slices of thigh of a given subject plotted vs. corresponding EMS-induced torque of 25, 50, or 75% of MVIT expressed in absolute terms.

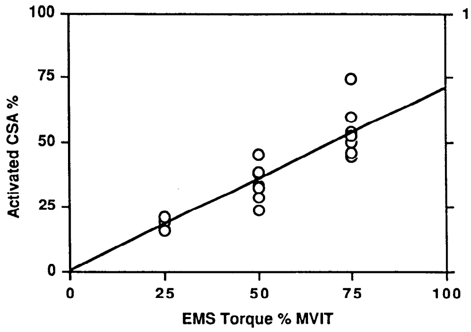

FIG. 4. Relative area of m. quadriceps femoris activated by EMS during unilateral isometric actions plotted as a function of torque expressed relative to MVIT. Stimulated percent of CSA (CSA%) is average of 5 transaxial slices of thigh (stimulated CSA% = torque (%) × 0.703 + 0.77, $r^2 = 0.82$, $P < 0.001$). Data predict EMS could elicit MVIT when only 71.1% of muscle CSA was stimulated assuming a continued linear relationship.

of m. vastus intermedius had been stimulated, whereas adjacent areas in m. vastus lateralis were relatively quiescent. These variations in stimulation most likely result from differences in muscle architecture and electrode placement among subjects. In regard to the latter suggestion, moving both electrodes to the lateral aspect of m. vastus lateralis markedly changed the pattern of stimulation of m. quadriceps femoris (Fig. 6).

The results of this study indicate different contrast shifts in MR images of skeletal muscle when isometric actions were induced by EMS vs. VOL means. Differences in the decay of T_2, which last ~30 min after increased contractile activity (9), cannot account for these responses because images were obtained ~3 min after exercise for both conditions. We suggest that the more exaggerated contrast shifts after EMS were due to a difference in the pattern of muscle contractile activity between the two conditions. It has been put forth for some time that skeletal muscle is activated at relatively "low" rates in an asychronous manner during VOL efforts to optimize performance while minimizing metabolic demand (4, 20). Synchronous activation at higher frequencies can be used to develop comparable force, but fatigue is often a consequence of such a strategy. It seems reasonable that the tetanic EMS of a given portion of m. quadriceps femoris on a repeat basis in the present study caused an exaggerated metabolic demand for the required force development, thereby resulting in fatigue within each set as well as marked MR image contrast shifts of the stimulated muscle. Remember, the prescribed EMS force levels were established by determining the current necessary to elicit a given percentage of maximal VOL force. Fifty-four percent of the CSA of m. quadriceps femoris could be stimulated to elicit 75% of MVIT. The same or even a larger relative proportion of m. quadriceps femoris could have been recruited asychronously at a lower frequency (15) during the VOL efforts to achieve the same force. This would minimize metabolic demand and MR image contrast shifts of the muscle engaged in the VOL activity.

The results of the present study show that there was a linear relationship between the CSA of m. quadriceps femoris that showed increased contractile activity after EMS and torque (Fig. 3). EMS via 1-s trains of 500-μs pulses at 50 Hz was used in the present study. This would result in near maximal force development of the stimulated muscle (14). It seems reasonable, therefore, that increments in force could only be achieved by increases in the amount of muscle that was stimulated. This linear relationship between stimulated muscle CSA and torque also suggests that surface EMS does not preferentially activate fast-twitch type II muscle as is generally believed (8, 28, 29). The CSA of stimulated muscle would have had to increase asymptotically to maintain step increases in torque if fast, compared with slow, muscle develops greater force per unit CSA, as has been suggested (25, 35). Likewise, recent studies have shown that EMS induces marked glycogen and phosphocreatine depletion in type I and type II fibers, thereby reflecting activation of both fast and slow muscle (13, 26). As suggested by Knaflitz and co-workers (18), the location of motoneuron branches seems to be the primary determining factor in activation of skeletal muscle via transcutaneous EMS.

It has been argued for some time as to whether there are neural inhibitory mechanisms that limit maximal VOL activation of a given muscle or muscle group (2, 3, 6, 17, 32, 33). With the assumption of a continued linear

TABLE 2. *Resting T_2 values of skeletal muscle*

Ref.	Field	n	Spin Echo Parameters (TR/TE)	Muscles	T_2
22	0.15T	1	2,500/30, 60, 90, 120	leg and arm	29–39
16	0.22T	4	2,000/34, 65	v. lateralis	29.0±3.0
			(20 wk later)	v. lateralis	28.4±4.0
19	0.35T	1	1,000/56	quadriceps	27
12	0.35T	16	2,000/30, 60	forearm	28.0±1.0
27	1.5T	5	1,000/20, 40, 60, 80	thigh	25.5±0.3
9	1.5T	8	2,000/30, 60, 90, 120	tibialis ant	29.7±0.8
		8		gastrocnemius	28.6±0.9
1	1.5T	7	2,000/30, 60, 90, 120	biceps b	28.1±0.4
		7		triceps b	
Present	1.5T	7	2,000/30, 60	knee extensors	29.0±1.0
		6	(56 ± 7 days later)	knee extensors	28.6±1.4

T_2 values are means ± SE; n, no. of subjects. v. lateralis, vastus lateralis; quadriceps, quadriceps femoris; tibalis ant, tibalis anterior; biceps b, biceps brachii; triceps b, triceps brachii. Twenty weeks later and 56 ± 7 days later, same subjects were reimaged after the indicated interval.

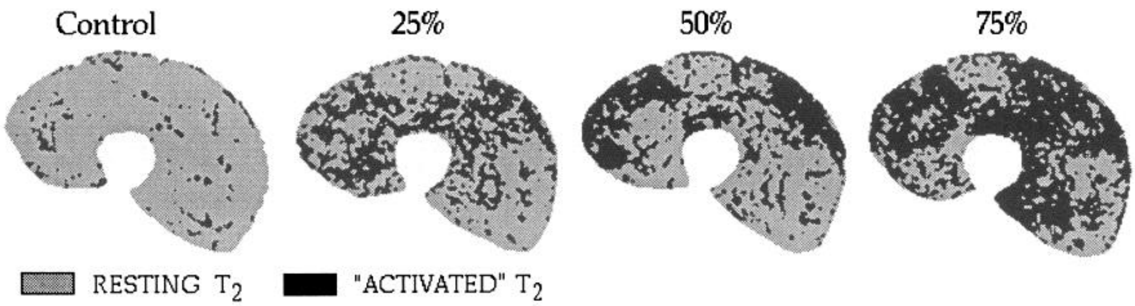

FIG. 5. Representative single slice T_2 maps of m. quadriceps femoris from 1 subject at rest (control) and after EMS at a level that elicited an initial torque equal to 25, 50, or 75% of MVIT. Dark regions represent data set elements with T_2 values considered to be in stimulated range.

response, extension of the regression line in Fig. 4 indicates that EMS activation of 71% of m. quadriceps femoris CSA would produce 100% of MVIT. This suggests that the subjects in this study were not able to voluntarily activate 100% of m. quadriceps femoris, and thus MVIT was substantially (~30%) less than predicted. Whereas this lack of activation by VOL means may seem large, others have suggested that as much as one-half of the force generating capacity of m. quadriceps femoris is not realized during maximal VOL isometric efforts (33).

The designation of muscle as having performed contractile activity when the T_2 was greater than the mean resting $T_2 \pm 1$ SD, as done in the present study, is open to question. The validity of this approach is supported by several observations. The T_2 for resting muscle in this investigation was similar to that reported in several other studies (Table 2). We found a linear relationship between stimulated muscle CSA and torque that should have occurred because it is generally accepted that these two variables for a given muscle or muscle group are strongly related. The relationship between stimulated muscle CSA and torque found in this study was used to suggest that subjects could elicit ~70% of the force generating capacity of m. quadriceps femoris during maximal VOL efforts. The extent of this lack of activation is comparable to what we reported previously based on differences in the nature of the speed-torque relationship of m. quadriceps femoris when muscle actions were induced by EMS vs. VOL means (6).

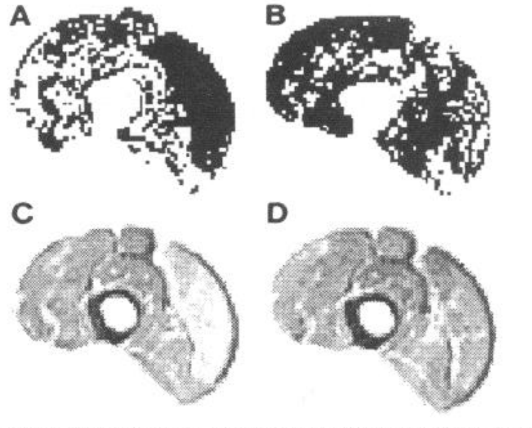

FIG. 6. Representative single slice proton density image (*C* and *D*) and T_2 map (*A* and *B*) from 1 subject showing influence of electrode placement on EMS-induced contractile activity. *B* and *D*: 1 electrode was placed 4–6 cm proximal to superior aspect of patella over belly of m. vastus medialis, and other was placed 10–15 cm distal to greater trochanter over m. vastus lateralis. *A* and *C*: both electrodes were placed over belly of m. vastus lateralis 5 cm apart. Five sets of 10 unilateral isometric actions were induced (see METHODS for more detail) with electrode configuration described in *B* and *D*. After one-half hour of rest, electrodes were placed as described in *A* and *C*, and EMS protocol was repeated with the same peak current. Note extensive stimulation of m. vastus lateralis in *A* and *C* compared with *B* and *D* as reflected by white region of native image and dark pixels in T_2 map.

In summary, the results of the present study show that transcutaneous EMS induces marked increases in T_2 in some regions of MR images of human skeletal muscle but not in others. Performance of the same exercise protocol with VOL efforts caused small if any changes in T_2. It is suggested that the T_2 changes with EMS arose from repeat stimulation of the same skeletal muscle, which gave rise to marked metabolic demand and some fatigue. It is suggested that asychronous use of the motor unit pool occurred during the VOL efforts, in contrast, to limit metabolic demand and maintain performance. The pattern of artificial muscle stimulation was not exclusively superficial, but rather dispersed and different among subjects. It is also suggested, therefore, that stimulation of a given region of muscle via surface EMS may not be taken for granted.

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