ORIGINAL ARTICLE

Nonuniform Activity of Human Calf Muscles During an Exercise Task

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ABSTRACT. Segal RL, Song AW. Nonuniform activity of human calf muscles during an exercise task. Arch Phys Med Rehabil 2005;86:2013-7.

Objectives: To determine the distribution of leg muscle activity during heel raises using magnetic resonance imaging (MRI) with special emphasis on quantifying activity across multiple axial sections and to determine if there are differences among portions of active muscles.

Design: Pre- and postexercise (heel raise) T2-weighted time measurements were assessed by using repeated-measures analysis of variance (ANOVA) and *t* tests.

Setting: Laboratory and MRI suites.

Participants: Eight healthy volunteers.

Intervention: Unilateral heel raises every 2 seconds for at least 60 seconds.

Main Outcome Measures: Percentage changes from T2-weighted magnetic resonance images of the lateral gastrocnemius, medial gastrocnemius, peroneus longus, soleus, and tibialis anterior muscles, across 10 axial sections, exercise bouts, and a pre-exercise condition.

Results: The lateral gastrocnemius, medial gastrocnemius, peroneus longus, and soleus had significantly larger changes in T2 time from pre-exercise times than did the tibialis anterior for whole muscles as determined by using repeated-measures ANOVA and post hoc analyses. The medial gastrocnemius had a significantly greater change in T2 time than the lateral gastrocnemius. Proximal axial sections of the lateral gastrocnemius, medial gastrocnemius, and soleus had significantly larger changes in T2 time from pre-exercise than did distal sections.

Conclusions: This work reconfirms that multiple muscles contribute to plantarflexor forces and additionally shows an apparent proximal versus subvolume organization of activity within the gastrocnemius, medial gastrocnemius, and soleus but not the peroneus longus. This proximal versus distal organization of muscle activity needs further investigation. There may be clinical implications for therapeutic interventions that require accurate placement of electrodes such as biofeedback.

Key Words: Magnetic resonance imaging; Muscles; Rehabilitation.

MUSCLES THAT WOULD BE PREDICTED to perform similar functions based on origin and insertion may have differential activity depending on the task. Several investigators have shown that muscles and their subvolumes produce off-sagittal torques.[1-4] For example, the triceps surae (lateral gastrocnemius, medial gastrocnemius, soleus) of the cat not only produce plantarflexion torques but also varying degrees of abduction torques, especially the medial gastrocnemius muscle.[4] Studies of naturally occurring tasks that require unilateral limb support such as unilateral hip abduction and unilateral heel raises have been used to suggest differential activation of portions of the triceps surae. Mouchnino et al,[5] by using a unilateral hip abduction task, found that the medial gastrocnemius was more active than the lateral gastrocnemius. In addition, preliminary data from our laboratory suggest differential activation of the gastrocnemii muscles during heel raises.[6] During unilateral heel raises, mediolateral (ML) ankle support becomes important. Thus, the differential activity of the lateral gastrocnemius and medial gastrocnemius may be important to control ML sway, and in addition the peroneus longus may change its activity to help provide this stability.[7] The factors or task requirements that dictate the combinations of muscle units used to produce necessary torques are critical data for clinicians and motor control researchers. Indeed, just knowing which muscles or subvolumes of muscles (putative compartments) are differentially activated among tasks has not been completely studied in human subjects.[8]

A relatively new approach to study global muscle activity involves using T2-weighted magnetic resonance (MR) images before and after exercise.[9-11] Quantification of muscle activity is obtained by measuring the activity-induced changes in the signal intensity of spin-spin relaxation time (T2)-weighted (dynamic) MR images. Tissue contrast in MR images is dependent on proton density and the selected parameters in scanning and processing the images. Exercise is known to produce changes in the amount and distribution of water in skeletal muscle, and at the present time a shift in the water distribution is the purported mechanism for changes in T2-weighted images.[12]

Price et al[13] have shown what appear to be appropriate spatial distributions of leg muscle activation within single axial sections but not through whole muscles after plantarflexion and dorsiflexion against a pneumatically controlled resistance. In addition, Tesch[14] has shown that there is plantarflexor activity with heel raises using magnetic resonance imaging (MRI), but there was no quantification of data or sufficient documentation of the experimental protocol. Recently, Yanagisawa et al,[15] in a more quantitative study, have observed changes in plantarflexor muscle T2 time, but we are not sure whether the heel-raise task was unilateral or bilateral, and these investigators did not look for subvolume activation. Therefore, the purpose of this study was to determine the distribution of leg muscle activity (particularly lateral gastrocnemius vs medial gastroc-

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nemius) during heel raises using MRI with special emphasis on quantifying activity across multiple axial sections and to determine if there are differences among portions of active muscles.

METHODS

Overview

All subjects had pre- and postexercise T2 sequences and pre-exercise T1 sequences of the right or both legs while secured in a volumetric coil. The T1-weighted images were used to help define the anatomy within axial sections. Subjects performed heel raises after the pre-exercise scans. T2-weighted sequences were performed immediately after each exercise bout, and there was a rest period of at least 40 minutes between exercise bouts. Forty minutes of rest was chosen because T2 time recovers back to rest values by 30 minutes,[16] and we wanted to have a rest period that left no doubt about the return to pre-exercise values.

Participants

Eight subjects (3 men, 5 women; mean age, 25±2y) without impairment participated in the study. The procedures, purposes, and risks of the study were explained, and then subjects read and signed an informed consent form either at Emory University or Duke University. Each institutional review board approved the study. All subjects had limb range of motion and strength within normal limits. They understood the commands related to the task performed.

Task

Unilateral heel raises were performed at a rate of about 1 every 2 seconds for between 60 and 120 seconds. The original intent was to do 2 levels of exercise intensity to determine if the spatial distribution of T2 time change increased with increased intensity. This would help address whether muscles were organized in subvolumes (ie, compartmentalized). However, not every subject could complete the 120 seconds. The sequence of durations was randomized. Subjects stood upright supported only by their right lower limb. To maintain balance, the subject's fingers were gently in contact with the MRI table that was directly in front of him/her. The left hip and knee were slightly flexed, not allowing the left foot to make contact with the floor. The right knee was approximately at full extension so that most motion was from the right ankle joint. Because all subjects could not complete a 120-second epoch, all data reported in this study were from 1-minute epochs.

Equipment and Protocol

Images were attained with a 1.5T (Children's Healthcare of Atlanta) or a 4T (Duke University) scanner.[a] The calibration and reliability of both scanners was determined each day by MRI technicians by using phantoms containing substances with known T1 and T2 times. Scout images were used to assure that most proximal images included the tibial condyles. To maximize repeatability of limb placement in the scanner, marks made on the skin of each subject were aligned to matching marks on the volumetric coil before each scan or they were secured in a leg-holding device that was fitted to the inside of the coil. A head volumetric coil was used for 4 subjects in the 4T scanner, whereas a knee coil was used with the 1.5T scanner. Although the field 4T scanner allows for more spatial resolution, the spatial distribution of activity does not appear different for subjects. This is probably because in both scanners each pixel represents dozens of muscles fibers and not individual muscle fibers. Although the absolute T2 times were higher from the 4T scanner, there were no systematic differences in percent change between the 2 scanners.

T1-weighted sequences. T1-weighted axial images of the leg were obtained with a standard sequence. Scan parameters were as follows: 10-mm slice thickness, 5-mm interslice gap, 16-cm field of view (FOV) (except FOV for head coil sessions was 24–26cm), 256×192 matrix, 2 excitations averaged, 500-ms repetition time (TR), and 14-ms echo time (TE).

T2-weighted sequences. T2-weighted axial images of the leg were obtained with a standard 4 echo pulse sequence: TR/TE=2000/30, 60, 90, and 120ms. Scan parameters were as follows: 10-mm slice thickness, 5-mm interslice gap, 16cm FOV (except FOV for head coil sessions was 24–26cm), 256 frequency encoding steps, 192 phase encoding steps, and 1 excitation. Total scan time was approximately 6.5 minutes.

Data processing. MR images were transferred to a Silicon Graphics Dual-Processor Octane workstation[b] for postprocessing. Images taken at different TEs were fit to a monoexponential time curve to extract the T2 values based on the following equation:

$$S = So\ EXP(-t/T2)$$

where S is the MR image intensity at a given TE, So is the original MRI signal intensity, t is the TE, and T2 is the spin-spin relaxation time. The fitting algorithm was performed on a pixel-by-pixel basis, and maps of T2 values and their standard deviations (SDs) were generated for pre- and postexercise conditions. These maps were then transferred to computer workstations, and regions of interest (ROI) were analyzed using Scion Image[c] or custom software in Matlab[d] and C. Great care was used to avoid inclusion of nearby fat and fascia in measurements but otherwise included all of the muscle represented in each axial section. Thus, ROIs varied in size across axial sections and muscles as the muscles' shape and size changed. The pre-exercise T1 images were used to delineate the anatomy used for the ROIs. In addition, several cross-sectional textbooks of anatomy were used to assist in the anatomic demarcations.[17]

Data and Statistical Analyses

T2 times were converted into percentage change from pre-exercise T2 time to normalize among subjects and the 2 scanners used. Mean and SD percentage change in pixel value were calculated for each region of interest for all subjects and conditions. Means of muscle ROIs from axial sections were averaged across all sections for whole-muscle analyses. Means of muscle ROIs from axial sections were averaged for proximal and distal sections for subvolume analyses. Differences in pixel-by-pixel percent change in T2 times of active whole muscles were analyzed by using repeated-measures analysis of variance (ANOVA). The α level was set at .05. If the main effect and interactions were significant, post hoc comparisons (Tukey honestly significant difference [HSD] test) were made to look at differences among all muscles (adjusted *P* value for multiple comparisons) and also to look at differential activity between the lateral gastrocnemius and medial gastrocnemius (paired comparison was made by using the Tukey HSD test). For subvolume analysis, axial sections were grouped into proximal, middle, and distal thirds. A paired test was used to assess differences in percentage change in T2 times between groups of only proximal and distal sections for each muscle because we could not be completely confident about the consistency of what would be considered a middle section (ie, some middle sections could be part of proximal and others part of distal).