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Technical Note

Determination of Thigh Muscle Stiffness Using Magnetic Resonance Elastography

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Purpose: To measure the elastic properties of the vastus lateralis (VL), vastus medialis (VM), and sartorius (Sr) muscles using magnetic resonance elastography (MRE).

Materials and Methods: To obtain a normative database of the aforementioned muscles, oblique scan directions were prescribed passing through each muscle. Shear waves were induced into the muscles using pneumatic and mechanical drivers at 90 and 120 Hz, respectively. These drivers were attached to the distal end of the right thigh with the knee flexed at 30°. The foot was placed in a footplate containing MR-compatible load cells to record the force during a contraction (10% and 20% of the maximum voluntary contraction).

Results: The shear moduli measured at rest in the VL ($N = 12$), VM ($N = 14$), and Sr ($N = 13$) were 3.73 ± 0.85 kPa, 3.91 ± 1.15 kPa, and 7.53 ± 1.63 kPa, respectively. The stiffness of both vasti increased with the level of contraction, while the stiffness of the Sr remained the same.

Conclusion: The MRE technique was able to approximate the stiffness of different thigh muscles. Furthermore, the wave length was sensitive to the morphology (unipennate or longitudinal) and fiber composition (type I or II) in each muscle.

Key Words: magnetic resonance elastography; thigh muscle; elastic properties

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THE ROLE OF MUSCLE is to generate force by cross-linking actin and myosin and transmit that force

through the tendon. The mechanical properties of muscle may reflect physiological changes in muscle in both relaxed and contracted conditions. Therefore, it is necessary to measure the *in vivo* mechanical properties of muscles in order to understand the changes that occur in muscle as a result of pathologies and treatments.

Previously, physiologic changes in muscle were determined by invasive and noninvasive techniques. Biopsy has been used to characterize muscle composition (i.e., myosin type, enzymes, etc.) and diagnose pathological muscle (1). Electromyography (EMG) is a noninvasive (i.e., surface) or invasive (i.e., fine-wire or needle) technique, which enables the study of muscular activity. The EMG signal is influenced by fiber composition (slow (type I) or fast (type II)) and fiber size (2,3). The EMG signal can be correlated with the developed force in an isometric contraction, but it does not quantify the mechanical properties of muscle.

The *in vivo* stiffness of soft tissues can be estimated by palpation. This technique, which consists of estimating the resistance (elasticity) of the tissue, is used to detect some types of cancer. However, tumors cannot be detected in small or inaccessible regions with this technique. The spatial distribution of tissue stiffness has been explored with sonoelastography and elastography techniques. The sonoelastography technique is the only *in vivo* technique currently used to determine Young's modulus. This technique uses ultrasound processes with externally applied vibration. In a study using the sonoelastography technique, the quadriceps muscles showed increased stiffness with loads and frequencies (4). However, the field of view (FOV) of this ultrasound technique is limited, and it cannot observe a group of muscles.

To our knowledge, the only noninvasive technique capable of quantifying the *in vivo* mechanical properties and imaging the entire spatial distribution of muscle elasticity is magnetic resonance elastography (MRE) (5–7). MRE is a novel noninvasive phase-contrast MR technique that is capable of visualizing small displacements (on the order of microns) from applied shear waves. The stiffness of the soft tissue can be estimated from the measured wave.

MRE is a promising noninvasive method for following the effects of diseases and treatment in skeletal muscle. In a previous study of the lower limbs, the stiffness of

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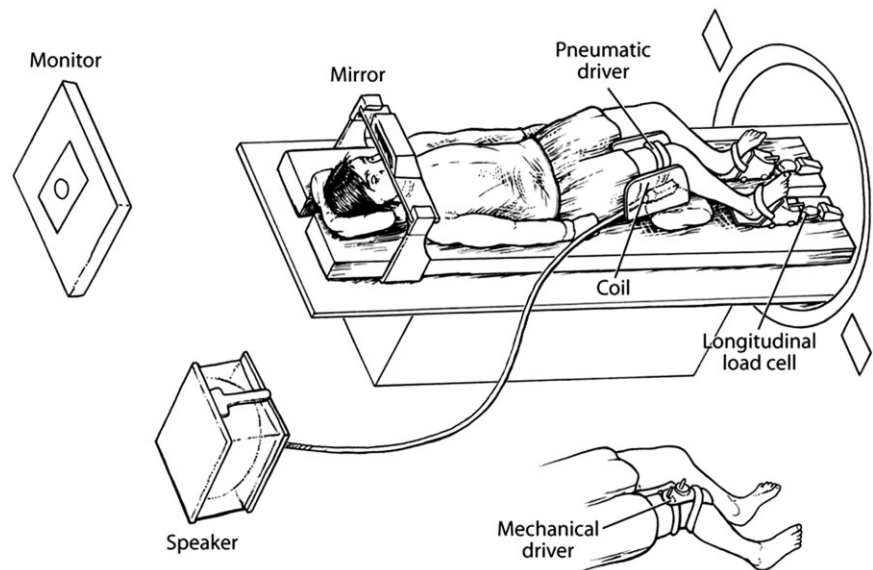


Figure 1. Custom leg press used to position the knee in 30° of flexion. Load cells in the footplate assembly (see insert) were used to record 10% and 20% of the MVC. The mechanical and pneumatic drivers were positioned one-third of the distance between the base of the patella and the greater trochanter. A mirror was placed over the eyes so that the volunteer could receive visual feedback, indicating when 10% and 20% of the MVC were obtained.

the tibialis anterior, the medial and lateral heads of the gastrocnemius, and the soleus was characterized with plantar and dorsi-flexing moments while the EMG activity was recorded (8). A strong correlation was found between the MRE and EMG results. In a subsequent study, an increase in stiffness when those skeletal muscles were passively stretched was observed (7). When this technique was applied to patients with stroke and poliomyelitis, differences in stiffness between healthy and pathological muscles were observed (9).

The purpose of this study was to develop the MRE technique to obtain a database of the stiffness of thigh muscles in healthy asymptomatic volunteers. Methods used in previous MRE studies were adapted to visualize propagating shear waves in the thigh muscles. The drivers used to induce shear waves and the imaging parameters (e.g., the direction of the scan plane, sensitization direction of the gradient, and the frequency of the applied shear waves) were investigated. Our long-term goal is to use the database of the elastic properties of the vastus lateralis (VL), vastus medialis (VM), and sartorius (Sr) to improve our understanding of the changes in muscle stiffness that occur with pathologies that affect the proximal muscles, such as hyperthyroidism, in which the proximal muscle wasting is less than the decrease in muscle strength (10,11).

MATERIALS AND METHODS

Participants

Fourteen volunteers (four males and 10 females, mean age = 25.2 ± 1.78 , range = 23–28, mean BMI = 22.11 ± 4.14) participated in this MRE study. The study was approved by the institutional review board, and informed consent was obtained from the volunteers.

Experimental Setup

The volunteers lay supine in a 1.5T General Electric Signa MRI machine. The right leg was placed in a posi-

tioning device (Fig. 1). An adjustable device maintained the shoulders in a fixed position and the right knee was positioned in 30° of flexion. The right foot was placed on a footplate and secured with Velcro® straps. The footplate was composed of two MR-compatible load cells (Interface, Scottsdale, AZ, USA) to measure the horizontal and vertical forces, respectively. A custom-made program (LABVIEW; National Instruments, Austin, TX, USA) was used to record the forces and give the volunteer visual feedback to ensure that the desired force was maintained. The MRE tests were conducted in the relaxed position (no contraction), with 10% or 20% of maximum voluntary contraction (MVC).

Shear waves were applied to the thigh muscles with a mechanical ($N = 7$ VL, $N = 10$ VM, $N = 9$ Sr) or pneumatic ($N = 5$ VL, $N = 4$ VM, $N = 4$ Sr) driver. Each driver was positioned on the thigh one-third of the distance from the patellar tendon to the greater trochanter. The mechanical driver was attached with Velcro® straps to the top of the thigh. It was composed of a coil of copper wire with a hollow aluminum core driven with an alternative current of variable potential, which induced shear waves into the thigh muscles at 120 Hz. The pneumatic driver consisted of a remote pressure driver (i.e., a large active loudspeaker) connected to a long hose. A smaller silicone tube was wrapped around the subject's thigh and connected to the remote pressure driver. This system created a time-varying pressure wave, which caused the tube around the thigh to expand or contract with the remote driver at 90 Hz. A custom-made Helmholtz surface coil was placed around the thigh before the scan was obtained.

MRE

A gradient-echo sequence was used to obtain the axial image of the thigh muscle (Fig. 2). To determine the best imaging plane to consistently obtain propagating waves, three series of parallel oblique slices were drawn on both the medial and lateral side. The VL was ob-

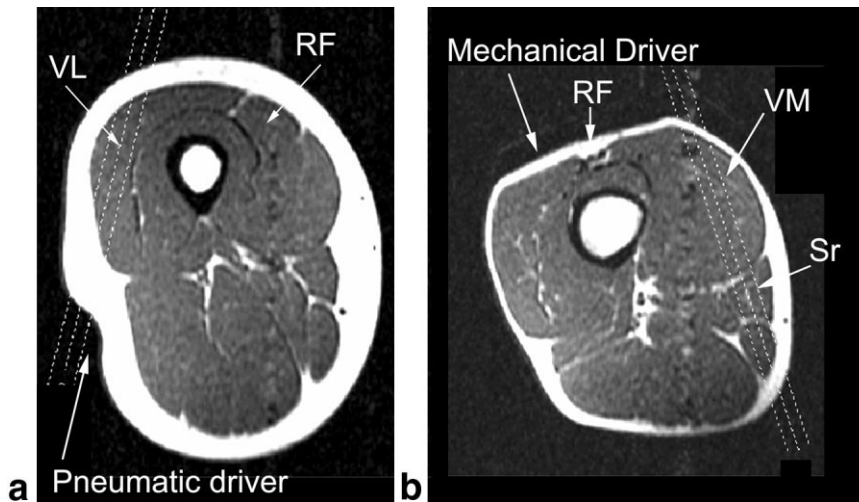


Figure 2. Location of the thigh muscles in the lateral (**a**) and medial (**b**) sides. The oblique lines are used to prescribe the two-dimensional images used in the MRE scans. The indentation in image a is caused by the clamp in the pneumatic driver, while the flattened area in b is caused by the contact area from the mechanical driver.

served in the lateral side. On the medial side the stiffness of the VM and Sr was measured.

The MRE pulse sequence, which included a motion-encoding gradient oscillating at the same frequency as the driver (120 Hz and 90 Hz), was applied to image the displacement of the shear waves. When the MRE images were collected, four phase offsets were obtained. The flip angle was 45° and the FOV was 24×24 cm. The acquisition matrix was 256×64 , which was interpolated to 256×256 . The TR was 275 and 350 msec when the shear waves were induced at 120 and 90 Hz, respectively. The TE corresponded to the minimum spin-echo time that allowed for motion encoding. The acquisition times were two minutes 34 seconds and three minutes 30 seconds at 120 and 90 Hz, respectively.

Image Processing and Data Analysis

A profile was drawn along the wave propagation in the muscle of interest (Fig. 3). The wavelengths were manually measured for each thigh muscle, and the average value (obtained over four offsets) was recorded. Assuming that the muscle is linear elastic (due to the small displacement of the wave), locally homogeneous, isotropic, and incompressible, the shear modulus (μ) can be calculated with the following equation:

$$\mu = \rho f^2 \lambda^2$$

where ρ is the muscle density ($\cong 1000 \text{ kg/m}^3$), f is the frequency (Hz) of the prescribed shear wave, and λ (m) is the measured wave length.

Statistical Analysis

We performed analyses of variance (ANOVA) and t-tests with the software Statgraphics 5.0 (Sigma Plus, Maryland, USA) to study the change in stiffness between the thigh muscles in the relaxed and contracted conditions.

RESULTS

Figure 3 showed shear waves in the VL, VM, and Sr muscles. Moreover, it is possible to measure the stiff-

ness of more than one muscle per acquisition (e.g., the VM and Sr muscles were measured simultaneously; Fig. 3, medial side). It was possible to consistently visualize the wave propagating through the VL when the oblique plane was oriented as shown in Fig. 4. When the scan plane was oriented closer to vertical or horizontal (Fig. 4), it was not possible to visualize waves when the muscle was relaxed and contracted. On the medial side, waves were consistently observed when the two-dimensional image clearly showed a triangular VM bounded by the Sr and rectus femoris (RF). In volunteers with a small RF, it was also possible to visualize waves in the VM and Sr (Fig. 3).

The shear moduli measured at rest in the VL ($N = 12$), VM ($N = 14$), and Sr ($N = 13$) were $3.73 \pm 0.85 \text{ kPa}$, $3.91 \pm 1.15 \text{ kPa}$, and $7.53 \pm 1.66 \text{ kPa}$, respectively. The results of the statistical analysis showed that the Sr had significantly greater stiffness ($P < 0.01$) than the vasti, while there was no significant difference between the two vasti.

When the volunteers were asked to contract their thighs at 10% MVC, the stiffness of the VL and VM was $6.11 \pm 1.15 \text{ kPa}$ ($N = 4$) and $4.83 \pm 1.68 \text{ kPa}$ ($N = 6$), respectively. There was a significant ($P < 0.1$) increase (about 2.51 kPa) in the stiffness of the lateral muscle (VL), while the VM did not show a significant increase in stiffness for that level of contraction (Fig. 5). There was no change in the Sr muscle ($N = 3$) stiffness at 10% MVC.

With a level of 20% MVC, the stiffness of the VL and VM was $8.49 \pm 4.02 \text{ kPa}$ (VL, $N = 3$) and $6.40 \pm 1.79 \text{ kPa}$ (VM, $N = 5$), respectively. There was a significant increase in the stiffness of the VM (1.57 kPa) from 0% to 20% MVC. The stiffness of the Sr muscle ($N = 3$) did not increase significantly (about 1.31 kPa) from 0% to 20% of the MVC.

DISCUSSION

The purpose of this study was to measure the stiffness of the thigh muscles with the MRE technique. To the best of our knowledge, this study is the first to assess the measurement of skeletal muscle activity in the

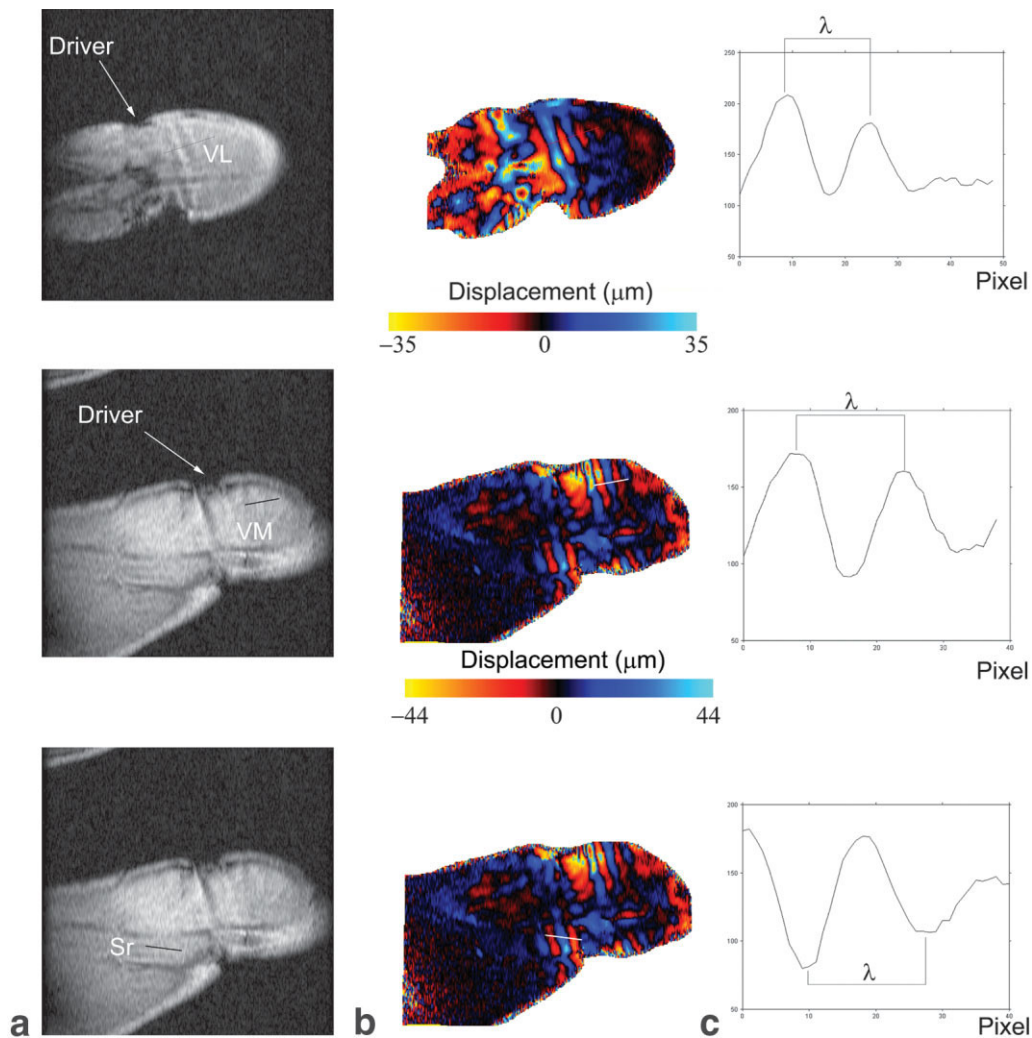


Figure 3. a: MRI picture of the oblique plane prescribed in the lateral (VL) and medial (VM and Sr) sides of the thigh. **b:** Phase image reflecting the wave's displacement with the profile drawn through the propagated wave. **c:** Representation of the wave traveling along the profile.

thigh using MRE. The MRE technique successfully represented the propagation of the waves in the lateral (through the VL) and medial (through the VM and Sr) sides of the thigh along the muscle fibers. Inside the Sr the waves followed a longitudinal direction, while inside the VM the wave traveled obliquely as prescribed by the fiber orientation. Moreover, the shape of the wave was influenced by the fiber orientations. Round waves were observed within the Sr, while elliptical waves were seen within the VM. The muscle boundaries were identified in the phase image because the waves did not cross the aponeurosis membrane.

The stiffness of skeletal muscles in a relaxed condition was measured in previous studies (7,12). The shear modulus for the biceps brachii was 17.9 ± 5.5 kPa (12) and 23.8 ± 6.68 kPa (13) in two separate studies. The stiffness of the muscles in the lower leg was also investigated. Specifically, the stiffness values were 8.7 ± 2.8 kPa in the flexor digitorum profundus (12), 12.5 ± 7.3 kPa in the soleus (12), 9.9 ± 6.8 kPa (12) and 22.04 ± 3.46 kPa in the gastrocnemius muscle (7), and 12.3 ± 4.5 kPa in the tibialis anterior (7). The differences ob-

served could be due to differences in the experimental setups used, including positioning of the muscle and frequency of the shear wave.

In this study the vasti had less stiffness than the Sr. This may indicate that the propagation of the waves was influenced by the muscle fiber orientation. The fiber orientation is unipennate in the VL and VM, and longitudinal in the Sr. Similarly, the biceps brachii, which is a bipennate muscle, exhibited a higher muscle stiffness (17.9 ± 5.5 kPa and 23.8 ± 6.68 kPa) than the other muscles, which have different fiber orientations (12,13).

The shear modulus increased with the level of contraction (10% or 20% of the MVC) for the VL and VM. Similarly, other muscles showed a similar increase in muscle stiffness with contraction (9,13). A previous sonoelastography study that measured quadriceps elasticity under static contraction also found an increase in the elasticity with the applied load (4).

At 10% MVC, we observed a faster increase of stiffness for the VL compared to the VM. This phenomenon may be related to the nature of the muscle, and more

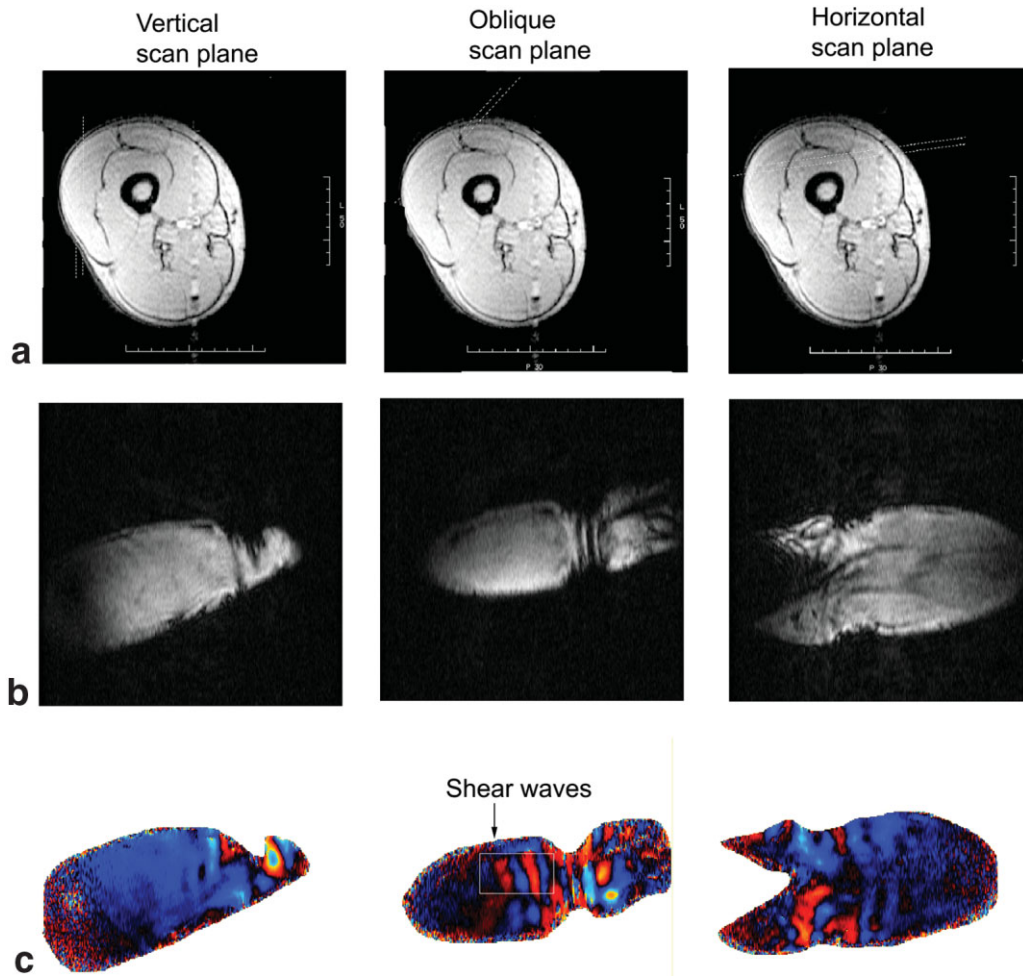


Figure 4. **a:** Axial scans used to prescribe the two-dimensional slices (vertical, oblique, and horizontal) from which the MRE images were obtained. **b:** Oblique MR image. **c:** Phase images obtained with a vertical, oblique, and horizontal scan plane. The waves were identified in the phase images with only the oblique scan plane. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

especially to the myosin type, which plays an important role during contraction. The fiber composition of the quadriceps muscles was previously characterized in different studies (14). The VM is composed of more slow fibers (type I; 50%) than the VL (30%) (15). This result means that the VL is composed of more fast fibers (type

II), which enables a faster contraction. This difference in fast and slow fiber types (16,17) could explain the significant increase in muscular stiffness for the VL at 10% MVC.

The overall EMG median frequency was higher for the VL and lower for the VM (2). Additionally, the variability

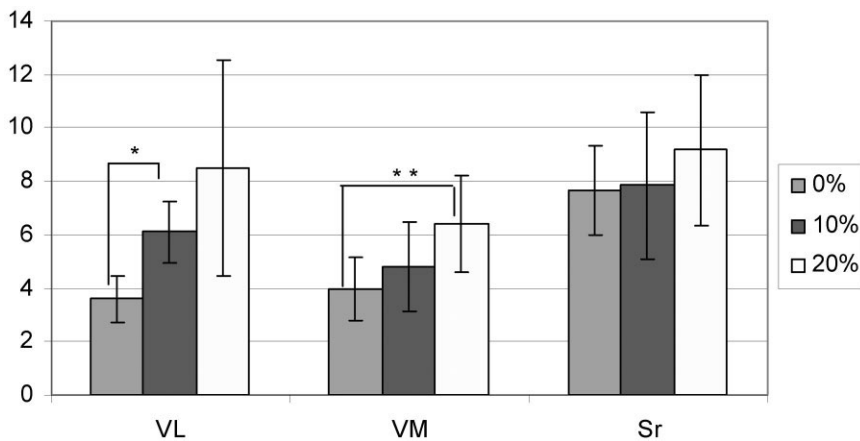


Figure 5. Representation of the muscle stiffness in relaxed and contracted positions with 10% and 20% MVC (** $P < 0.01$, * $P < 0.1$), respectively.

of the median frequency was significantly higher for the VL than for the VM and RF, with no gender difference, which may indicate that the VL has a greater morphological variation than the VM or RF (2). These findings are consistent with the higher variation in VL stiffness observed.

No muscle stiffness changes were measured in the Sr muscle, with 10% and 20% of the MVC. This may be due to the function of the muscles. The vasti extend the knee, while the Sr flexes the knee. The leg press isolated the knee extensors, and therefore the Sr muscle fibers contracted minimally during the examination.

In conclusion, this study shows that the MRE technique was able to estimate the shear modulus in the thigh muscles studied. One of the most challenging parts of this study was our attempt to define an oblique two-dimensional plane through the vasti in which waves would consistently be observed. With careful selection of oblique scan planes, shear waves were observed in the VL, VM, and Sr muscles in the relaxed and contracted states. Additionally, the wave length was sensitive to the morphology (unipennate or longitudinal) and fiber composition (type I or II) of each muscle.

This new noninvasive MRE technique may be useful for clinical research and diagnosis. For example, in pathologies such as Graves' disease, biopsies are taken from the VL to elucidate the effect of the disease on that muscle. However, this procedure is invasive, and investigators may accidentally biopsy the vastus intermedius. The MRE technique, which allowed us to determine the muscle stiffness of different thigh muscles, could be helpful means of improving diagnostic procedures and elucidating the effects of pathologies and treatments. Given the results of this study, we speculate that the MRE technique may have a potential clinical role in characterizing muscle pathologies, such as myopathy, as well as other conditions, such as spasticity and denervation.

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