REAL-TIME VISUALIZATION OF MUSCLE STIFFNESS DISTRIBUTION WITH ULTRASOUND SHEAR WAVE IMAGING DURING MUSCLE CONTRACTION

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ABSTRACT: A stand-alone ultrasound shear wave imaging technology has been developed to quantify and visualize Young's modulus distribution by remotely applying ultrasound radiation force and tracking the resulting microvibrations in soft tissues with ultrafast ultrasound imaging. We report the first preliminary data that detected the distribution of local muscle stiffness within and between resting and contracting muscles at different muscle lengths with this technology. This technique may assist clinicians in characterizing muscle injuries or neuromuscular disorders.

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Information on muscle mechanical properties is essential in clinical practice as well as in biomechanical research on movement disorders and muscle injuries. In clinical practice for disorders such as spasticity in stroke, spinal cord injury, or multiple sclerosis, "muscle tone" is assessed qualitatively and subjectively with manual operations. The "trigger point" in myofascial pain is detected with manual palpations at the "hard" region. Although different terms are used in different fields of clinical practice, the muscle characteristics described by these terms are related to muscle stiffness. One of the most relevant parameters used to quantify stiffness (or elasticity) of soft tissues is the Young's (or elastic) modulus.[1] The Young's (or elastic) modulus is defined as the slope of the stress–strain curve of a material in the elastic deformation region as a local mechanical property of the constituent material. Hence, quantitative measurement of the distribution of Young's modulus (i.e., local muscle stiffness) within or between muscles could improve the accuracy of assessment of muscle stiffness.

Currently available mobile devices for muscle stiffness measurement have the following limitations in quantifying the spatial distribution of Young's modulus in muscle. For estimation of static behavior of muscles, a portable device is available that utilizes indentation of the skin surface by applying external force with a small rod and analyzing its penetration.[2,3] Similarly, recently described ultrasound devices use static elastography to estimate muscle stiffness from user-induced compression at the skin surface and tissue deformation detected with an ultrasound scanner.[4,5] However, neither device can yield Young's modulus, because the stress within muscle tissues is unavailable due to unknown stress dissipation by the skin and subcutaneous fat with both and variable compression by the user with the latter device. Dynamic elastography techniques measure the propagation velocity of mechanical vibrations (e.g. shear waves) with imaging analyses to directly calculate the local Young's modulus of soft tissues, where faster velocity indicates greater Young's modulus.[6,7] The techniques have been developed for the combined use of large mechanical vibrators and ultrasound imaging[8–10] or magnetic resonance imaging (magnetic resonance elastography),[11–13] although the latter is not mobile. However, the existing dynamic elastography technologies have inherent limitations. They require large mechanical vibrators, and application techniques may constrain measurement conditions, including the mobility, ease of use, awareness of measurement, and, additionally, accessibility and cost efficiency for magnetic resonance elastography.

In aiming to resolve these limitations, we explored the feasibility of a newly invented stand-alone ultrasound device (Aixplorer; SuperSonic Imagine, Aix-en-Provence, France) in which the same handheld ultrasound probe induces and detects propagating shear waves within the tissues in real time.[14,15] Based on the characterization of shear wave propagation for a single region in a single muscle (biceps),[14] we report the first preliminary data on Young's modulus distributions within and between multiple muscles in various conditions obtained as a color-coded image with this new stand-alone mobile technology. We predicted

Abbreviations: *c*, propagation velocity; *E*, Young's modulus; ρ, muscle density; ROI, region of interest

Key words: dorsiflexion; elastography; plantarflexion; spasticity; Young's modulus

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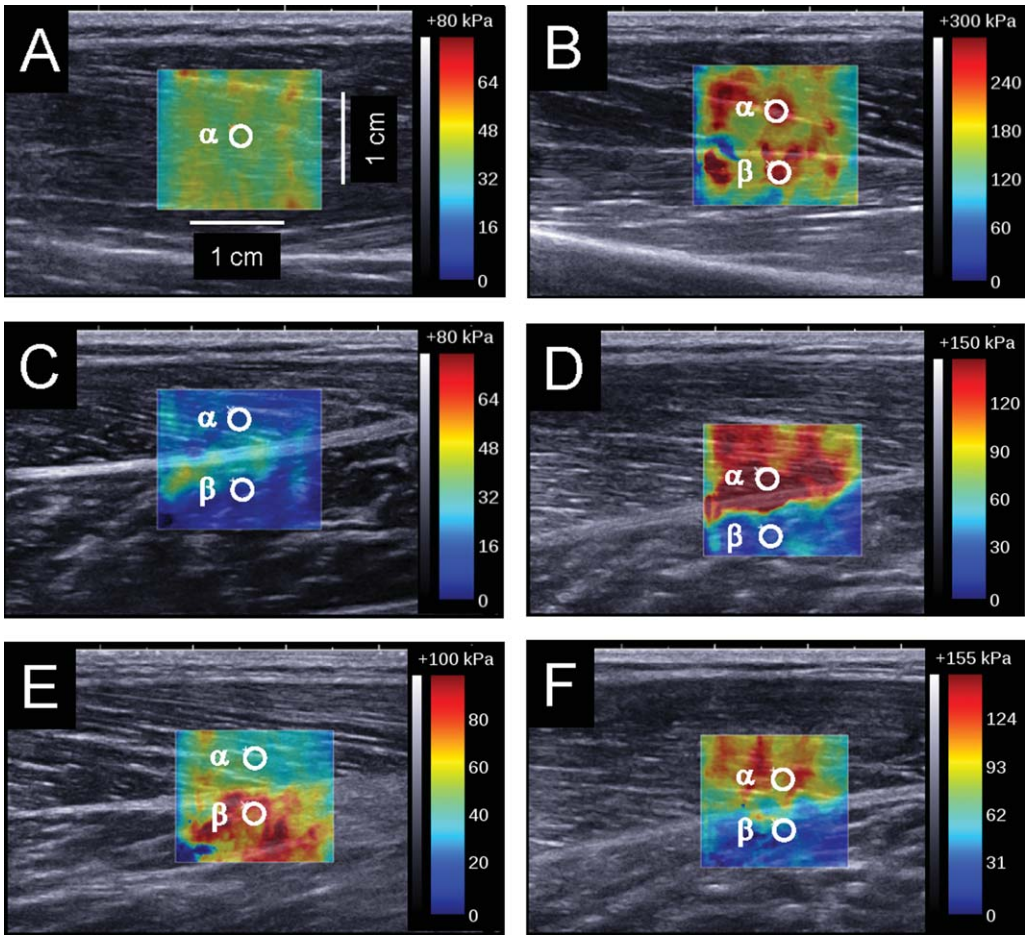

FIGURE 1. Color-coded presentation of local muscle stiffness (Young's modulus) superimposed on the longitudinal B-mode ultrasound image of lower leg muscles. The Young's modulus distribution within the 15 × 15 mm region of interest (ROI) on the B-mode image (50 × 30 mm) was visualized as the color-coded map (stiffer areas were coded in red and softer areas in blue). The spatial average (± SD) values for Young's modulus in the selected circular area (2-mm diameter; denoted with α or β) was calculated. The dimension scales are the same across panels, whereas the color-coding scales are variable. **(A)** Tibialis anterior at rest in the knee-extended position. **(B)** Tibialis anterior during contraction in the knee-extended position. **(C)** Medial gastrocnemius (area above the mid-aponeurosis) and soleus (area below the mid-aponeurosis) at rest in the knee-extended position. **(D)** Medial gastrocnemius and soleus during contraction in the knee-extended position. **(E)** Medial gastrocnemius and soleus during contraction in the knee-flexed position. **(F)** Medial gastrocnemius and soleus during quiet standing.

that Young's modulus of a muscle is greater in conditions with increased muscle contraction intensity, because muscle stiffness is known to increase with contraction intensity.[8–10]

METHODS

A healthy subject (male, 42 years) was seated with the foot attached to a rigid bar in the neutral ankle position (90°) and the knee flexed (90°) or extended (0°) to test if Young's modulus of contracting medial gastrocnemius is lower when its involvement is less in the knee-flexed position.[16–19] The subject performed static contraction of his dorsiflexors or plantarflexors to exert 30% of his maximal voluntary contraction to test if Young's modulus increases with contraction. In addition, the subject performed quiet standing on both feet to test if Young's modulus of plantarflexor muscles during standing is less than that during plantarflexion in line with the reported difference in muscle activity.[20,21] The medial gastrocnemius and soleus muscle were the major muscles tested for two reasons. First, their distinct characteristics in muscle activity between the aforementioned conditions have been identified. Second, concurrent measurement of Young's modulus of both muscles is possible with the new ultrasound technology. The experimental procedure was in accordance with the Declaration of Helsinki (1975).

The acoustic radiation force induced by focused ultrasound beams[22] was used to generate two energetic planes of transient and low-frequency (100–600 Hz) shear waves propagating within the soft tissues with sufficient amplitude. The transient shear wave propagation deep in several muscles in the lower leg was then captured with a set of high-rate ultrasound insonifications

(5000 frames/s) using a 50-mm linear-array probe (8 MHz). The local shear wave propagation velocity, c, in the direction of the muscle–tendon unit was then measured locally in the region of interest (ROI, 15 × 15 mm square) (Fig. 1). For each pixel of the ROI, Young's modulus, E, was deduced from:

$$E = 3\rho c^2 \quad (1)$$

where density ρ is assumed to be constant (1000 kg m^{-3}) in human soft tissues.[7,8,23] The distribution of Young's modulus in the muscle–tendon unit direction was visualized as a color-coded map (500-μm resolution, scale adjusted) superimposed on the longitudinal B-mode echographic image in real time (<0.1 s). The spatial average (±SD) of Young's modulus in selected circular areas (2-mm diameter; α and β in Fig. 1) was calculated for comparable locations between conditions.

RESULTS

The subject did not perceive muscle vibrations. The ROI was chosen to center the mid-depth for the tibialis anterior and to cover both the medial gastrocnemius and soleus for the plantarflexors at the mid-belly. The Young's modulus in tibialis anterior at rest (Fig. 1A) was relatively homogeneous with the average (±SD) Young's modulus of 40.6 ± 1.0 kPa around the middle of the ROI. Apparently, Young's modulus about high-echoed areas was high, and it became more obvious with muscle contraction (258.1 ± 15.0 kPa and 268.2 ± 25.0 kPa; Fig. 1B). The greater Young's modulus about high-echoed areas is likely attributable to the involvement of thick and stiff connective tissues, which became stiffer with force application.

In plantarflexors, Young's modulus at rest (Fig. 1C) was comparable between medial gastrocnemius (area above the mid-aponeurosis, 16.5 ± 1.0 kPa) and soleus (area below the mid-aponeurosis, 14.5 ± 2.0 kPa) in the knee-extended position. During contraction in the knee-extended position (Fig. 1D), the increase in Young's modulus was more prominent in medial gastrocnemius (225.4 ± 41.0 kPa), especially about the high-echoed aponeurosis, than in the soleus (55.0 ± 5.0 kPa). In the knee-flexed position, contraction of plantarflexors (Fig. 1E) increased Young's modulus in medial gastrocnemius (41.2 ± 2.0 kPa) less than in soleus (76.8 ± 7.0 kPa). These results are consistent with greater stiffness in the lengthened muscle and greater engagement of the biarticular gastrocnemius muscle in the knee-extended position.[16–19]

During quiet standing (Fig. 1F), the trend for a greater increase in Young's modulus for medial gastrocnemius (111.2 ± 5.0 kPa) than for soleus (36.3 ± 17.0 kPa) was similar to plantarflexion (Fig. 1D), although the overall increases were less. The smaller Young's modulus during standing compared with plantarflexion was in line with smaller plantarflexor activity during quiet standing (<10% MVC),[20,21] because local muscle stiffness increases with muscle activity.[8–10]

DISCUSSION

The findings were consistent with the prediction, and Young's modulus of the resting and contracting muscle in this study were within the range of reported values from magnetic resonance elastography (5–40 kPa in resting muscle, up to 300 kPa with contraction).[11–13] The observed distributions of Young's modulus that were consistent with the literature supported the feasibility of the new stand-alone ultrasound technology as a promising mobile device. Although not a mobile technology, the applicability of magnetic resonance elastography to pathological muscles has been demonstrated[11,24] as a tool that may have potential for analysis of large muscle areas, including three-dimensional analysis, if the attenuation of propagating shear vibrations are moderate. On the other hand, this ultrasound technology has an advantage in that it is mobile, does not require vibrators, has a better resolution in the Young's modulus distribution (typically 500 μm vs. >1 mm in magnetic resonance elastography), and is virtually real time (several frames per second vs. several minutes acquisition time in magnetic resonance elastography). In this study we tested only limited samples with regard to the type and number of subjects and the number of ROIs and analyzed areas (that resulted in large variability in data). Further systematic examination should warrant application of the new mobile imaging technology in clinical practice and basic research on movement disorders and muscle injuries.

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