Evaluation of Shear Properties in Muscle Tissue Via Novel Superficial Elastography Technique

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Abstract—Noninvasive measurement of the mechanical properties of soft tissue is of significant clinical interest. Recent work has demonstrated the ability of ultrasound (US) elastography techniques to measure shear modulus and shear viscosity of bicep muscle and liver tissue in vivo using specialized equipment. The objective of this study was to evaluate a new elastography technique in the upper trapezius muscles in patients with acute neck pain. Ultrasound RF data were acquired from both symptomatic and asymptomatic (pain free) subjects. The upper trapezius muscle was externally vibrated at frequencies in the range of 60 – 200 Hz. The phase of the received RF signals were used to compute the shear wave images that represent the phase of the externally-induced vibration as it travels through the tissue. The spatial gradient of the vibration phase yielded the shear wave velocity, which was used to estimate shear modulus and shear viscosity based on the shear Voigt model for viscoelastic materials. Myofascial Trigger Points (MTrPs) in the upper trapezius had significantly higher shear modulus (12.5±4.1 kPa) than normal tissue sites (6.4±2.4 kPa) (P<0.05). The approach presented here provides a quick and effective method for quantitatively measuring region specific shear properties in both normal and symptomatic muscle tissue, and can be easily translated to a clinical setting using commercially-available equipment.

Index Terms— Myofascial Trigger Points, Neck Pain, Shear Wave Elastography, Biomechanics.

I. INTRODUCTION

Elastic properties of soft tissue are of great clinical interest [1-5]. In the past decade, new imaging techniques have developed to quantitatively estimate shear mechanical properties of soft tissue in vivo via magnetic resonance elastography (MRE) [6, 7] and ultrasound (US) elastography [8-10]. Shear wave elastography utilizes shear waves that may be induced externally [11, 12], or through the radiation force of ultrasound [13, 14]. For viscoelastic materials, such as most soft tissue, the mechanical properties include both an elastic modulus and a viscous modulus [15, 16] estimated via the Voigt model [17, 18]. Shear wave elastography has been previously used to measure shear properties of liver [18, 19], breast [9, 10], bicep [8, 18], trapezius [6, 7], and rectus femoris muscle [20]. However, these proposed methods have traditionally relied on specialized equipment.

Our objective was to develop and evaluate a method for quantitative elastography of skeletal muscle based on a clinical ultrasound system and off-the-shelf components. We validated our elastography technique and model by reproducing in vivo biceps brachii muscle shear properties, which have been well studied in the literature [8, 18, 21]. To further demonstrate the clinical utility of our method, we investigated the viscoelastic properties of the upper trapezius muscle in normal subjects as well as patients with chronic neck pain. The upper trapezius is of great interest because it is frequently painful and the site of the commonly occurring myofascial trigger points (MTrPs). MTrPs are stiff, discrete, palpable tender nodules that can be found in the belly of a taut band of muscle and are a characteristic finding in myofascial pain syndrome (MPS) which is believed to affect almost 23.8 million Americans each year [22-24]. We hypothesized that the soft tissue mechanical properties of active MTrPs in symptomatic patients are different from normal muscle tissue in asymptomatic (i.e., pain-free) subjects.

II. METHODS

A. Subject Selection and Physical Exam

Men or women with acute cervical pain and met inclusion criteria (i.e., having an active MTrP in one or both upper trapezi) underwent a thorough musculoskeletal evaluation to rule out potential causes of their symptoms other than MTrPs. Patients were classified as active if they were experiencing pain consistently over the past 3 months. A total of 16 subjects were studied, 8 normal subjects (i.e., no palpable MTrPs) and 8 active subjects (i.e., those with palpable active MTrPs).

Subjects underwent a physical examination as previously described [25]. Briefly, the presence or absence of MTrPs in the upper trapezius muscle was determined following Travell and Simon’s criteria according to standard clinical practice [26]. Palpation was in the central region of the upper trapezius muscle within 6 cm of the muscle's midline (approximately...
midway between the cervical vertebrae and the acromion process). Sites were considered normal if no palpable nodule was found. Active sites had at least one palpable nodule that was both spontaneously painful and exacerbated the subject’s symptomatic (not all had referred) pain upon palpation. The sites being analyzed were at least 5 cm apart from one another. Only the examiner knew the clinical status of the subjects (i.e., whether they had cervical pain or not) and classifications of the marked sites. The sonographers were blinded to the clinical status when acquiring ultrasound data. Only active and normal patient data is presented in this study, latent MTrPs were excluded due to the very low sample size.

B. Handheld Vibrator to Perform Shear Wave Elastography

A handheld vibrator was fabricated using a DC motor with an offset weight attached to it (Mini DC Motor 7.8V, Battery Space, Richmond, CA) contained in a Delrin plastic housing. A variable power supply (0-30 VDC Lab power Supply, All Electronic Corp., Van Nuys, CA) was used to drive the motor at 4 different frequencies: 60 Hz, 110 Hz, 160 Hz, and 200 Hz.

Ultrasound imaging was performed using the SonixRP US system (Ultrasoundix Corp, Vancouver, BC) and a 5-14 MHz linear array transducer. The raw radiofrequency (RF) data were collected at a high frame rate of 522 frames/sec. Each frame consisted of 64 scan lines, 50% sector size, and imaging depth of 2.5 cm. The data were processed online using the Ulterius software development kit (Ultrasoundix Corp, Vancouver, BC) and Matlab (Mathworks, Natick MA) to interactively produce shear wave phase angle images as well as B-mode images. The interactive phase images were used to verify that the propagating shear wave was captured and ensure consistency of data collection. The data acquisition was repeated if a propagating shear wave did not produce a satisfactory image.

C. Techniques for Estimation of Shear Wave Velocity

The received RF data were processed using a Hilbert transform to generate the complex analytical signals and were demodulated to baseband. The envelope of the analytical signals formed the B-mode image. A conventional autocorrelation algorithm [27] was used to estimate the instantaneous velocity of the tissue. The instantaneous velocity was filtered using a median filter and a moving average filter in the lateral direction to suppress isolated phase peaks at speckle boundaries. The temporal frequency of the shear wave was estimated using the Fourier Transform and a histogram of estimated frequencies was generated using overlapping temporal windows. The phase offset at the mode frequency for each axial/lateral coordinate was used to produce an image of the shear wave phase in the lateral and axial dimensions (Fig.2&3). A region of interest was then selected on these phase images and the shear wave propagation speed, $C_s$, was estimated from the spatial gradient of the phase using,

\[ C_s = \omega \frac{\Delta r}{\Delta \theta} \]  

(1)

where $\Delta \theta$ is the difference in phase angle over lateral distance ($\Delta r$), and $\omega$ is the shear wave vibration frequency in radians.

For each region of interest, an average phase gradient was estimated from three measurements. These shear wave propagation speeds at different frequencies were then fit to a Voigt model for viscoelastic materials to estimate the shear modulus ($\mu_1$) and shear viscosity ($\mu_2$) as follows:

\[ C_s = \sqrt{\frac{2(\mu_1^2 + \omega^2 \mu_2^2)}{\rho(\mu_1 + \sqrt{\mu_1^2 + \omega^2 \mu_2^2})}} \]  

(2)

where $\rho$ is the tissue density (1060 kg/m$^3$). The values for shear modulus and shear viscosity were determined using a least squares fit of measured shear wave velocities to the Voigt model using an optimization algorithm (Microsoft Excel solver tool).

D. In vivo Validation Using Bicep Brachii

The viscoelastic properties of the biceps brachii have been extensively studied in the literature. To validate our proposed technique in vivo, we estimated the shear modulus and shear viscosity properties of the bicep brachii in a group of healthy volunteers ($n=6$) for comparison to literature values. Subjects were seated comfortably, with their dominant arm resting on a table with their elbow bent at 90° and instructed to relax their arm and not flex/contract their bicep muscles. The long head of the biceps brachii were imaged using ultrasound while simultaneously being vibrated with the handheld vibrator at four different frequencies.

E. Statistical Analysis

Values for shear modulus and shear viscosity were averaged for each patient and categorized as active MTrPs, surrounding muscle tissue of active sites, and normal asymptomatic upper trapezius muscle tissue. Statistical analysis was performed using PASW 18 (SPSS) using One-Way ANOVA (analysis of variance) with Tukey post hoc test for normally distributed data. Data is presented at mean±SD and statistical significance was determined when $P < 0.05$. 

Figure 1: Plots of shear modulus for bicep brachii. Shear wave speeds were calculated from phase lag plots to measure the phase lag over a given distance. Dotted lines denote reported literature values for bicep shear modulus.
III. RESULTS

A. In vivo Validation in Bicep Brachii

B-mode images of the long head of the bicep brachii in the healthy volunteers revealed homogeneous fiber alignment in the area of interest. Phase images indicated fairly uniform phase lag with uniform spatial gradient along the tissue for all vibration frequencies. The average phase lag over the imaged area was calculated as the slope of the linear fit of phase angle and distance along the bicep. All linear fits used for this study had an R² > 0.80. The Voigt model fit yielded a shear modulus of 12.5±3.4 kPa and shear viscosity of 7.7±4.0 Pa•s. All shear modulus values measured via US elastography were within the range of reported literature values (Fig. 1). Measured shear values for bicep brachii were highly repeatable with differences between repeated runs less than 5 kPa (Fig. 1).

B. Preliminary Results in the Normal Upper Trapezius vs Trapezius with Active MTrPs

B-mode images of normal upper trapezius appear very similar to the bicep brachii, having uniform fiber orientation throughout the tissue. Subjects with active trigger points showed spherical or band-like hypoechoic (darker) regions along with an increase in fiber alignment heterogeneity, as has been reported previously by our group [25, 28]. Elastography imaging yielded phase plots that showed a different pattern of spatial phase gradients between normal tissue and sites with active MTrPs.

![Figure 2: Plots of Shear modulus and shear viscosity for normal upper trapezius, and active trigger points in the trapezius “*” denotes significant difference with normal trapezius (P < 0.05).](image)

From the spatial phase gradients, shear modulus and shear viscosity were calculated for normal tissue, active MTrPs, and its surrounding muscle tissue (SMT). Active MTrPs measurements were taken using the B-mode images to distinguish the boundaries of the MTrPs based on hypoechoogenicity. Active MTrPs (12.5±4.1 kPa) were significantly stiffer in shear modulus than normal tissue (6.4±2.4 kPa) in the upper trapezius (P < 0.05)(Fig.6). There were no significant differences in shear viscosity between normal sites (8.0±1.4 Pa•s) and active MTrPs (9.6±4.0 Pa•s).

IV. DISCUSSION

This study presents a new US method, usable in clinical settings, to measure mechanical shear properties of superficial soft tissues in the body via US elastography. Our study utilizes off the shelf equipment to superficially vibrate and measure mechanical shear properties of muscle tissue 0-4 cm from the skin’s surface, in an office-based setting.

To validate our shear wave elastography system we performed in vivo tests in the bicep brachii to replicate literature values previously determined using alternative proposed methods. The results of the bicep brachii experiments, generated values were within the range of previously published literature values of shear moduli for the bicep brachii (~8 - 24 kPa) [8, 18]. The measured shear viscosity was highly variable (7.7±4.0 Pa•s), and also was within reported literature values [8, 18]. These results confirmed that our office-based technique is capable of replicating elastography measurements reported using MRE [21] or supersonic shear waves [8, 18] and we could measure shear properties in a relatively homogeneous muscle with uniform fiber alignment.

The proposed method would be suitable for most musculoskeletal applications less than 4cm in depth; however, the applicability of this method for deeper tissue must be investigated in the future. Additionally, the technique is very sensitive to the alignment of the US probe and sensitive to the position of the handheld vibrator in order to achieve a proper coupling of the shear wave in the muscle. The shear wave can be missed if the massager and US probe are positioned correctly. The alignment problem was addressed by providing interactive visualization of the phase image allowing the user to adjust the position of the probe and massager to ensure the shear wave propagation. Another limitation is the inability to measure shear properties of skeletal muscle perpendicular to the fiber direction. The mechanical properties of muscle are known to be highly anisotropic [15, 29]. In this study, shear properties were only estimated parallel to the fiber direction. It was found that shear waves traveled more efficiently along fibers in the parallel direction compared to the perpendicular direction. Shear waves from superficial vibrations were rapidly absorbed when traveling perpendicular to the fiber direction (data not shown). Lastly, we use a relatively simplistic Voigt model for viscoelastic materials to estimate shear modulus and shear viscosity of skeletal muscle that assumes a homogeneous linear material. This may not be optimal for soft tissue that is highly anisotropic and very heterogeneous in its extra cellular makeup. However, the Voigt model has been widely used and accepted in the literature and enabled the distinction between normal and symptomatic tissue in our study.

This study presents a new US elastography method that measures shear properties of superficial soft tissues. The method was validated through in vitro and in vivo studies, and demonstrates the feasibility of measuring shear properties of skeletal muscle tissue. One potential clinical application of this method is to provide an objective assessment of soft tissue and the identification of MTrPs and surrounding tissue. This may have important applications for diagnosis and treatment evaluation of MTrPs and MPS.
REFERENCES


