Muscle Tissue Characterization Using Quantitative Sonoelastography: Preliminary Results

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***Abstract*—A quantitative sonoelastographic technique for skeletal muscle tissue characterization is introduced. Experimental data was collected in both *ex vivo* bovine and *in vivo* human skeletal muscle tissue. Crawling wave sonoelastographic data was processed using a quantitative technique for estimating local shear wave speed distributions. Results on *ex vivo* skeletal muscle samples demonstrate shear wave anisotropy and existence of fast and slow shear waves corresponding to propagation parallel and perpendicular to muscle fibers. Comparison of relative frequency-dependent changes between shear wave speed estimates for both shear wave propagation parallel and perpendicular to muscle fibers suggests increased viscoelastic effects for the former. Preliminary sonoelastographic data from two healthy human subjects was acquired in the relaxed rectus femoris muscles. Results demonstrate that quantitative elasticity data can be reproducibly acquired *in vivo*. Overall, preliminary results are encouraging and quantitative sonoelastography may prove clinically feasible for the *in vivo* characterization of skeletal muscle in health and disease.**

Keywords-crawling waves; elasticity imaging; quantitative sonoelastography; tissue characterization.

I. INTRODUCTION

Throughout the last two decades, elasticity imaging has evolved into a promising clinical tool. Of particular interest, sonoelastography is an ultrasound-based elasticity imaging modality that uses Doppler techniques to estimate tissue motion (in the form of propagating shear waves) induced using low amplitude and low frequency mechanical sources [1]. Using a modified pulsed Doppler ultrasound system, local qualitative estimates of tissue elasticity can be imaged in real-time to depict relative changes in tissue stiffness. In general, soft tissues containing a stiff focal lesion or mass yield a corresponding local decrease in the magnitude of the shear wave displacement field [2]. In a more recent development, crawling wave sonoelastography was introduced [3]. With this technique, slowly moving shear wave interference patterns (termed crawling waves) are generated using a pair of mechanical sources and imaged using sonoelastography. The advantage to this sonoelastography derivative is that crawling wave spatial properties reflect local tissue elastic properties [4]. Combination of crawling wave principles and a computationally efficient shear wave speed estimator has allowed realization of quantitative sonoelastographic imaging [5].

Several elasticity-based techniques for characterizing skeletal muscle tissue have been presented in the literature [6-10]. Despite encouraging results, there still remains a clinical need for a robust technology capable of producing real-time tissue elasticity estimates *in vivo*, which could find application in such areas as sports medicine and physical therapy. To that end, our group has initiated a research project to address this apparent clinical void. In this paper, we present preliminary results using a novel quantitative sonoelastographic technique adapted for skeletal muscle characterization.

II. THEORY

A. Principles of crawling wave motion

It has been shown in [3] that shear wave interference patterns can be generated using two vibration sources and imaged using sonoelastography. Moreover, if the two sources vibrate at slightly offset frequencies, such as f_S and $f_S + \Delta f_S$, then the interference patterns slowly propagate toward the higher frequency source at an apparent speed equal to $c_S \cdot \Delta f_S / 2 f_S$ where c_S denotes the true shear wave speed. Termed crawling wave sonoelastograms, these images reflect shear wave propagation patterns and allow for estimation of the spatial elastic properties. Specifically, since the local spacing between crawling wave pattern bands is equal to one-half of the shear wavelength λ, analysis of spatial features allows estimation of the governing shear wave speed distribution as follows

$$c_S = 2 f_S \lambda \, . \quad (1)$$

Since tissues like skeletal muscle are highly anisotropic (due to fascicle ordering) and measurements are dictated by fiber orientation, we have elected to designate the quantity estimated at a given shear wave frequency as the shear wave speed.

B. Quantitative sonoelastography

Analysis of crawling wave spatial patterns allows estimation of the local elastic properties in skeletal muscle tissue. Given shear wave interference displacement fields, the shear wave speed distribution in two-dimensional (2D) space can be estimated by evaluating the phase of the 2D autocorrelation function $r(m', n')$ of the analytic signal $\hat{u}(m, n)$

$$r(m', n') = \sum_{m=0}^{M-m'-1} \sum_{n=0}^{N-n'-1} \hat{u}^*(m, n) \hat{u}(m + m', n + n') , \quad (2)$$

at lags $(m'=1, n'=0)$ and $(m'=0, n'=1)$, where * denotes complex conjugation. Note that the analytic displacement field is computed using Hilbert transform methods [5]. Eqn. (2) assumes the observation window consists of M axial samples and N lateral samples. The mean shear wave speeds $\langle c_S \rangle_m$ and $\langle c_S \rangle_n$, estimated independently and relative to the m-axis and n-axis, respectively, are expressed as

$$\langle c_S \rangle_m = \left| \frac{2\pi(2f_S + \Delta f_S)T_m}{\tan^{-1}\left\{ \frac{\mathrm{Im}[r(1,0)]}{\mathrm{Re}[r(1,0)]} \right\}} \right| \tag{3}$$

and

$$\langle c_S \rangle_n = \left| \frac{2\pi(2f_S + \Delta f_S)T_n}{\tan^{-1}\left\{ \frac{\mathrm{Im}[r(0,1)]}{\mathrm{Re}[r(0,1)]} \right\}} \right|. \tag{4}$$

Using (3) and (4), the 2D mean shear wave speed estimate $\langle c_S \rangle_{2D}$ can be found using the following expression

$$\langle c_S \rangle_{2D} = \frac{\langle c_S \rangle_m}{\sqrt{\left(\frac{\langle c_S \rangle_m}{\langle c_S \rangle_n} \right)^2 + 1}}. \tag{5}$$

Since (5) produces a local shear wave speed estimate, quantitative sonoelastograms are formed by one-sample shifting the kernel throughout the shear wave displacement field and properly mapping the resultant estimate.

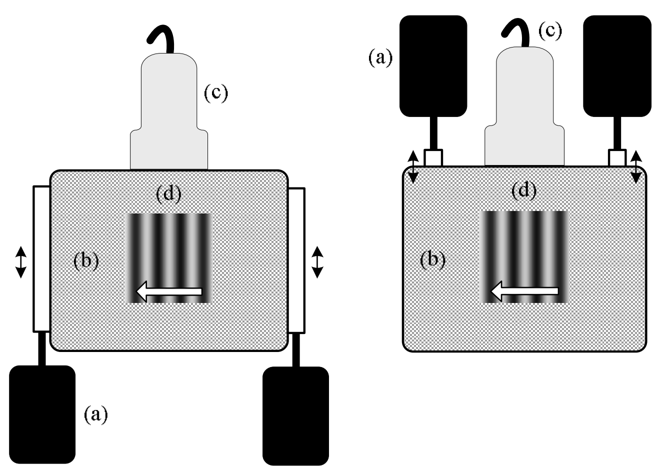

Figure 1. Illustration of setups used for *ex vivo* (left) and *in vivo* (right) experiments. Two mechanical sources (a) vibrate at slightly offset frequencies (double arrows) and are coupled to the tissue surface (b). Slowly moving shear wave displacement fields are produced and imaged using an ultrasound probe (c) for a given region-of-interest (d) as these crawling waves propagate through the muscle tissue.

III. Materials and Methods

Sonoelastographic results were obtained using the experimental setups illustrated in Fig. 1. For both setups depicted, a two-channel signal generator (Model AFG320, Tektronix, Beaverton, OR, USA) produced two low frequency signals that were then passed through power amplifiers (Model 2706, Brüel & Kjaer, Naerum, Denmark). Subsequently, these amplified signals were input to the mechanical sources (Model 4810, Brüel & Kjaer, Naerum, Denmark) that were each fit with custom-made rectangular-shaped contacts for coupling source vibrations to the tissue surface.

Bovine skeletal muscle samples were obtained from a local meat market. Two different beef sirloin specimens, each measuring approximately 10 x 10 x 5 cm (length x width x height), were studied at room temperature using the *ex vivo* setup depicted in Fig. 1. For *ex vivo* studies, shear waves were polarized perpendicular to muscle fibers and propagation was produced either parallel or perpendicular to fiber orientation. A vibration frequency range of 150 to 350 Hz (in 50 Hz increments) was used and sonoelastographic crawling wave motion was established by utilizing a source frequency difference (offset) of 0.2%. Source amplitudes (typically less than 200 μm) were adjusted for each vibration frequency and prior to data collection to produce well-formed shear wave interference patterns.

Preliminary *in vivo* experiments on human skeletal muscle tissue were conducted to assess the clinical feasibility of quantitative sonoelastography. Specifically, two healthy male volunteers were studied and experimental sonoelastographic data was collected in the relaxed rectus femoris muscles using the setup described in Fig. 1. Using a frequency range of 80 to 200 Hz (in 20 Hz increments) and an offset of 0.2%, shear wave polarization and propagation was excited perpendicular and parallel to muscle fibers, respectively. As noted above, source amplitudes were adjusted prior to data collection to maximize shear wave signal-to-noise ratios.

For all experiments, a modified GE Logiq 9 ultrasound system (GE Medical Systems, Milwaukee, WI USA) was used for scanning and demodulated colorflow data saved for offline processing. Shear wave speed images were produced using the 2D autocorrelation-based estimation technique (see Section IIB) applied to reconstructed crawling wave sonoelastograms. Prior to data processing, images were downsampled in the axial dimension to closely match the pixel count in the lateral dimension and to minimize computation time. A fixed kernel size of 24-by-24 samples (approximately 1.0 cm^2) was used in order to minimize estimator noise levels. Finally, shear wave speed statistics were computed from quantitative sonoelastogram sequences (equating to one spatial wavelength of crawling wave motion) to represent a global estimate of tissue elasticity for a given region-of-interest.

IV. Results

In the first set of validation experiments, quantitative sonoelastography was evaluated using *ex vivo* bovine skeletal muscle specimens. Representative crawling wave and shear wave speed sonoelastograms are depicted in Fig. 2 for both shear wave propagation parallel and perpendicular to muscle fibers. Notice that shear wave speed estimates are higher for shear waves propagating parallel to muscle fibers as compared to propagation perpendicular to fiber orientation. These results demonstrate shear anisotropy in skeletal muscle tissue and the existence of fast and slow shear wave propagation [10]. A summary of frequency-dependent shear wave speed estimates from the *ex vivo* skeletal muscle samples are illustrated in Fig. 3. Comparing relative changes between dispersive shear wave speed estimates for both shear wave propagation parallel and perpendicular to muscle fibers suggests increased viscoelastic effects for the former.

For the second set of validation experiments, *in vivo* tissue characterization using quantitative sonoelastography was assessed in the relaxed rectus femoris muscles of two healthy male subjects. A summary of the dispersive shear wave speed estimates are illustrated in Fig. 4. In general, quantitative elasticity estimates from healthy skeletal muscle tissue tend to increase with frequency suggesting a viscoelastic process and akin to that observed in the *ex vivo* studies. Moreover, agreement between *in vivo* quantitative sonoelastographic estimates from contralateral muscles demonstrates intrapatient reproducibility albeit based on limited data.

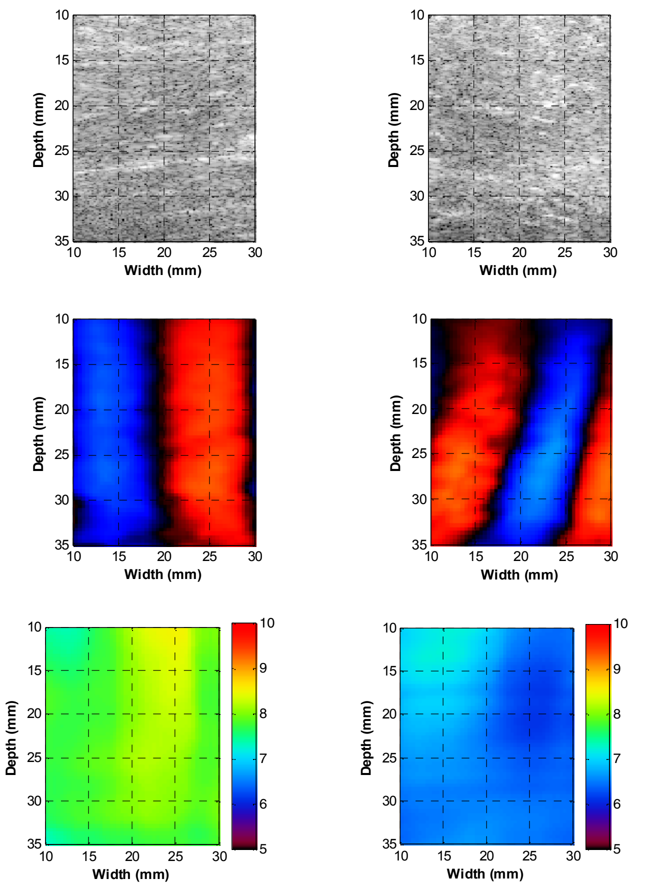

Figure 2. Experimental sonoelastographic results from *ex vivo* skeletal muscle specimens including: B-scan US (top), crawling wave (middle), and shear wave speed (units of m/s) (bottom) images. Results are depicted for shear wave polarization perpendicular to muscle fibers (200 Hz) and shear wave propagation parallel (left) and perpendicular (right) to muscle fibers.

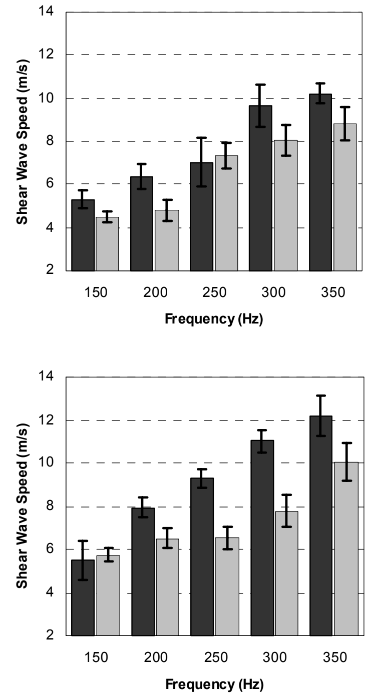

Figure 3. Summary of *ex vivo* shear wave speed estimates from bovine skeletal muscle tissue. Results from two different specimens, top and bottom, respectively, are depicted as a function of frequency for shear wave polarization perpendicular to muscle fibers and shear wave propagation parallel (black) and perpendicular (gray) to muscle fibers.

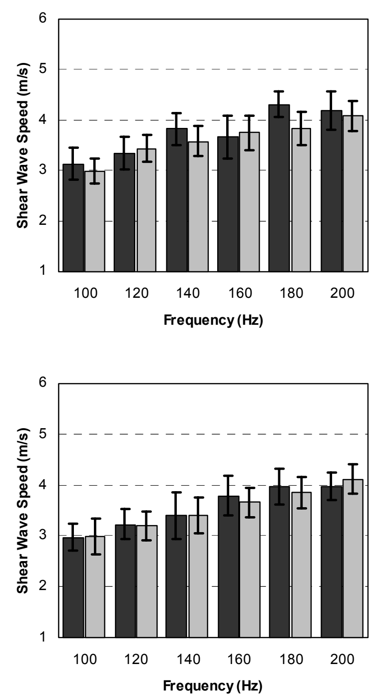

Figure 4. Summary of *in vivo* shear wave speed estimates from relaxed rectus femoris muscles. Results from two different healthy male subjects, top and bottom, respectively, are depicted as a function of frequency for the right (black) and left (gray) rectus femoris muscle. Note shear wave propagation was parallel to muscles fibers.

V. Conclusions

A quantitative sonoelastographic technique for skeletal muscle tissue characterization was introduced and analyzed. Results on *ex vivo* skeletal muscle samples demonstrated shear wave anisotropy and existence of fast and slow shear waves corresponding to propagation parallel and perpendicular to muscle fibers, respectively. Furthermore, comparison of relative frequency-dependent changes between shear wave speed estimates for both shear wave propagation parallel and perpendicular to muscle fibers suggests increased viscoelastic effects for the former. Preliminary sonoelastographic data from healthy human subjects was acquired in the relaxed rectus femoris muscles. Results demonstrate that quantitative elasticity data can be reproducibly acquired *in vivo*. Overall, preliminary results are encouraging and quantitative sonoelastography may prove clinically feasible for the *in vivo* characterization of skeletal muscle in health and disease.

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