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 a2nSeveral 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 ihurens a (s)1md a resg8rcoce. T-patbetween crawling wave pattern bands is equal to one-half of the shear wavelength , analysis of spatial features allows estimation of the governing shear wave speed distribution as follows

$$c_S = 2 f_S \quad . \tag{1}$$

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 $\hat{u}(m,n)$

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

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

$$\langle \; {}_{s} \rangle = \left| \frac{2 \; (2 \; {}_{s} + \overset{S}{f_{s}})T}{\tan^{-1}\left\{ \frac{-\mathrm{Im}[r(1,0)]}{\mathrm{Re}[r(1,0)]} \right\}} \right|$$

fibers. Notice that shear wave speed estimates are higher for shear waves propagating parallel to muscle fibers as compared

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