Determination of Anisotropic Velocity Profiles in Muscle Using Wave-Guide Constrained Magnetic Resonance Elastography

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Introduction: The determination of the elastic properties of biological materials such as muscle is of great importance as a diagnostic metric. These materials, however, consist of a complicated structure of fibers which often vary in both their orientation as well as their thickness. As a result of these structural complications, inversion methods for the determination of the elastic moduli from displacement data often yield inconsistent results due to the rotations, spatially varying degrees of anisotropy, and boundary conditions. In this paper, we implement a previously introduced measurement and analysis approach labeled Wave-Guide Constrained Magnetic Resonance Elastography [1], which was developed for analyzing waves in guided structures such as muscle, white matter tracts, and neuronal fiber pathways, and which does not assume any a priori anisotropic model. We analyze the waves propagating along particular muscle fiber pathways utilizing space-wavenumber analysis and determine the zero-order anisotropic wave-guide velocities as functions of position. The approach will be demonstrated using a 3-D MRE *in vivo* measurement of a human calf muscle excited acoustically at 90 Hz.

Theoretical and Experimental Development: Analysis was performed on the right calf of a healthy 24 year old female volunteer in 10^o dorsiflex, and all data were taken at the Mayo Clinic on a 1.5-T GE Signa. In Fig. (1) we show the midplane of a MRI scan consisting of 40 axial slices (of 5 mm thickness) where the location of the acoustic actuator is indicated by the arrow. 3-D MRE was performed with a field of view of 20cm $\times$ 20cm (256 $\times$ 256 pixels), over 32 saggital slices of 1.5 mm thickness. The calf was excited at 90 Hz using a longitudinal, pneumatic driver, and four time offsets were taken for each of the three sensitizations (x, y, z). Temporal Fourier transforms were performed on the displacement data to extract the first harmonic. Additionally, a Helmlholtz decomposition was performed on the data separating the u_x, u_y, and u_z displacement components into their longitudinal and transverse terms, which we show in Fig. (2). A Facia tracing algorithm was implemented which determined the exterior surface of the Tibialis Anterior as well as three characteristic fibers within this muscle as shown in Fig. (3). The paths of these individual fibers as well as their particular rotating Frenet reference frames were calculated, and application of a spatial-spectral filter provided the zero-order waveguide modes of the three fiber pathways. A sliding window spatial Fourier transform was then performed on this filtered and projected data with a window width of 10 cm. This provided space-wavenumber images for the forwardly propagating waves as shown in Fig. (4). The maxima of these decompositions provided the velocity profiles along the fibers (e.g., ω/k_{max}) which are shown for the transverse components in Fig. (5).

Analysis of Results: Along each of the three fibers, the longitudinal component is very fast and appears to propagate with a compressional velocity essentially that of water (1481 m/s). The transverse waves, however, vary in the range from 25 m/s to 10 m/s for the u_y displacement components, and from 35 m/s to 12 m/s for the u_z displacement components. Additionally, these are spatially dependent changing both velocity and polarization as functions of position.

Conclusions: It has been demonstrated that the combination of MRI with MRE enables the tracking and analysis of waves along arbitrarily oriented muscle fibers, establishing a method for *in vivo* Wave-Guide Constrained MRE. Future work will involve the use of Structural Intensity (SI) [2] and Diffusion Tensor Imaging (DTI) [3] in the determination of particular pathways of more complex orientation, and the evaluation of elastic moduli and attenuation from the spatially varying velocity profiles.

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References:

[1] A. J. Romano, P. B. Abraham, P. J. Rossman, J. A. Bucaro, and R. L. Ehman, Determination and Analysis of Guided Wave Propagation Using Magnetic Resonance Elastography, Magn Reson Med 2005;54:893-900.

[2] A. J. Romano, P. B. Abraham, E. G. Williams, A Poynting Vector Formlation for Thin Shells and Plates, and its Application to Structural Intensity Analysis and Source Localization. Part I: Theory. J Acoust Soc Am 1990;87:1166-1175.

[3] S.S. Blemker, A. J. Sherbondy, D. L. Akers, R. Bammer, S. L. Delp, and G. E. Gold, Characterization of Skeletal Muscle Fascicle Arrangements Using Diffusion Tensor Tractography, Proc Intl Soc Mag Reson Med 13, 2005; 2019.

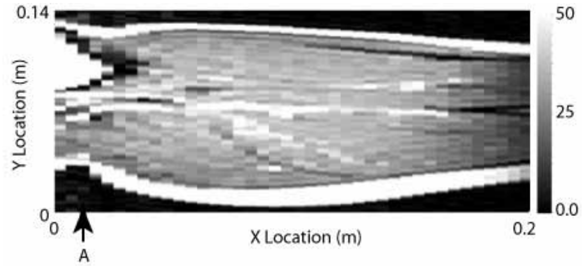

Fig. 1 - MRI image of right calf of volunteer showing location of actuator

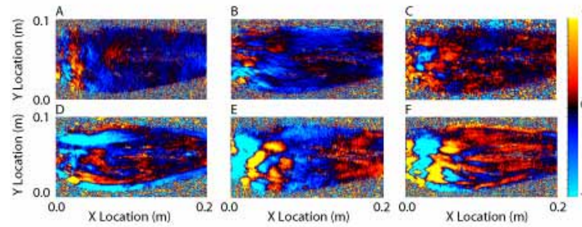

Fig. 2 - Helmholtz decomposition of the displacements within the central plane of data: A), B), C) longitudinal u_x, u_y, and u_z components; D), E), F) transverse u_x, u_y, and u_z components.

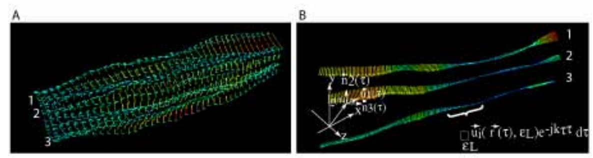

Fig 3 - A) surface of Tibialis Anterior and B) three fiber paths within this muscle identified using fascia tracking algorithm.

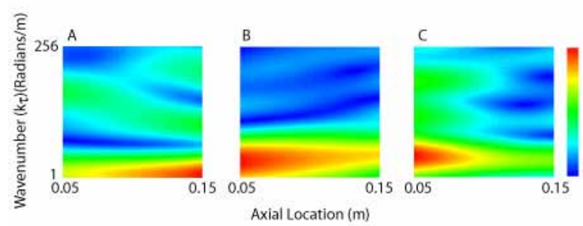

Fig. 4 - Magnitude of the space-wavenumber profiles for fiber 3. A) Longitudinal u_x, B) Transverse u_y, and C) Transverse u_z components.

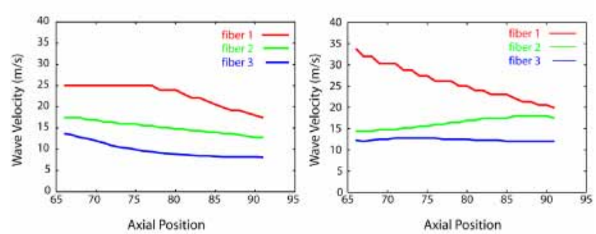

Fig. 5 - Wave velocities as determined from space-wavenumber images for a) u_y transverse components for fibers one, two, and three as indicated, and b) u_z transverse components for the same fibers.