Validation of Waveguide Magnetic Resonance Elastography Using Finite Element Model Simulation

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Target Audience: Biomedical engineers, researchers and biomechanical engineers.

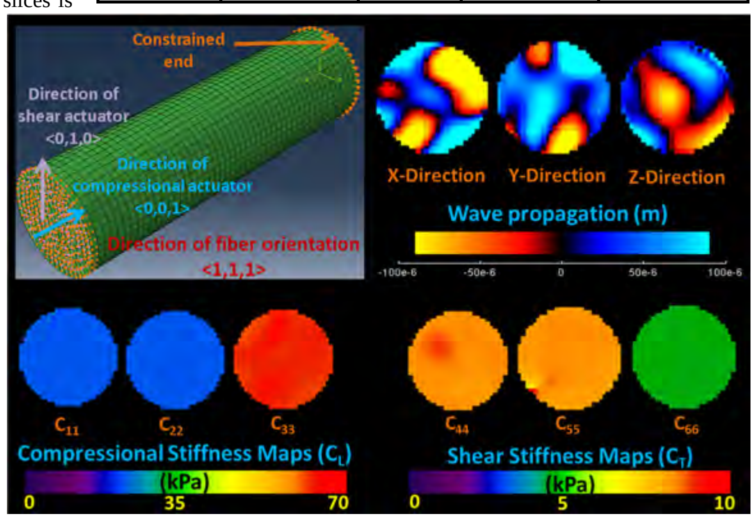
Purpose: Several biological tissues (e.g. - skeletal muscles, white matter tracts in the brain, and myocardium) have anisotropic mechanical properties due to the presence of fibers. Furthermore, many pathological states (e.g. - amyotrophic lateral sceloris[1], traumatic brain injury[2], myocardial infarction[3]) exhibit directional dependencies in stiffness. That is, the disease progression is manifested with an increase in anisotropic stiffness of the tissue. Therefore, non-invasive investigation of anisotropic stiffness properties of biological tissues is expected to be critical both for diagnostic and therapeutic purposes. Recently, with the advent of a technique called waveguide elastography[4-6] the estimation of anisotropic stiffness in biological tissues has become feasible. Waveguide elastography uses magnetic resonance elastography (MRE), a phase-contrast MR imaging technique, in conjunction with fiber orientation information (usually obtained using diffusion tensor imaging) to estimate anisotropic tissue stiffness. In this study, we use finite element modeling (FEM) to simulate wave propagation in fibers contained in a cylindrical rod to validate the feasibility of measuring anisotropic stiffness in an orthotropic material (transversely isotropic) using the technique of waveguide elastography.

Methods: ***Simulation:*** Frequency response analysis was performed on a 3D cylindrical rod with a diameter of 40 mm and a length of 200 mm in Abaqus 6.13 (Dassault Systèmes Simulia Corp., Providence, RI, USA). The simulation parameters included: Mesh elements: 12699; Degrees of freedom: 98794; Mesh type: hexahedral elastic elements. Fibers in the rod were arranged at an angle with fiber direction coordinates <1, 1, 1>. The material properties of the rod were as follows: Young's modulus in the fiber direction (E_{33}) was 60 kPa, Young's modulus in the transverse directions is isotropic (E_{11} and E_{22}) with 18 kPa each, shear modulus in each direction i.e. G_{12}, G_{23} and G_{31} were 6.04 kPa, 7.85 kPa and 7.85 kPa, respectively. The Poisson's ratio in ν_{12}, ν_{23} and ν_{31} was 0.49, 0.147 and 0.147, respectively. The material had a density of 1000 kgm^{-3} and a damping factor of 0.05. The face of the cylinder on the far end was constrained. Compressional (in <0, 0, 1> direction) and shear (in <0, 1, 0> direction) actuation with a frequency of 100Hz was applied to the near face of the cylinder to generate complex wave propagation as shown in the figure below. The cylindrical rod of fibers is selected because it replicates the structure of muscle fiber bundles which act like waveguides for anisotropic wave propagation. The shape and size of the waveguide (rod) induce an effective wave velocity that is indirectly dependent on the intrinsic property of the material[7]. For a thin rod approximation, effective velocity is $\sqrt{(E/\rho)}$, where E is the Young's modulus and ρ is the density of the material. Based on these effective velocity estimates of the expected longitudinal and transverse wavenumbers (k) were calculated. Finally, the effective wavenumbers were used to estimate the expected effective compressional and shear stiffness coefficients and these values have been provided in Table 1. ***Analysis:*** The displacement fields generated in FEM were re-constructed using MATLAB (Mathworks, Natick, MA) at an isotropic imaging resolution of 2x2x2 mm^3 (FOV: 256x256x256 mm^3, imaging matrix : 128x128x128). The fiber orientation was used to generate a local coordinate system (n1, n2, n3) for each imaging voxel, where n3 corresponded to the fiber axis (<1,1,1>) on the local coordinate system and n1 and n2 corresponded to the other two directions orthogonal to n3. A spatial-spectral filter based on the fiber direction was defined and applied on the first harmonic displacement data to identify displacements in particular directions defined by the local coordinate system. Simultaneously, Helmholtz decomposition was performed to separate the total field into its longitudinal and transverse components. Finally, an orthotropic inversion[4] was implemented to evaluate the compressional (C_{11}, C_{22}, C_{33}) and shear (C_{44}, C_{55}, C_{66}) complex stiffness values along the three different directions defined by the fibers of the cylindrical rod.

Results: The FEM generated thin-rod model, as well as the corresponding wave propagation and stiffness measurements using waveguide elastography are shown in the figure below. The wave propagation images demonstrate the complex wave pattern generated in the x, y and z directions when excited with a shear and compressional source at a frequency of 100 Hz. Wavenumbers in each direction obtained from the corresponding wave images are shown in Table 1. Based on this initial observation, a spatial spectral filter with a bandwidth of ± 20 centered on the observed wavenumber was designed and implemented to estimate the stiffness coefficients. The mean and standard deviation of the stiffness measurements observed in the compressional (C_{11}, C_{22}, C_{33}) and transverse (C_{44}, C_{55}, C_{66}) directions along the three different axes defined by the fibers of the cylindrical rod are provided in Table 1, and an example of stiffness maps from one of the slices is shown in the figure.

Table 1

Stiffness Coefficients	Expected Wavenumber m^{-1}	Expected Stiffness kPa	Observed Wavenumber m^{-1}	Observed Mean Stiffness and Standard Deviation kPa
C_{11}	148	18.02	138	21.66 ± 0.34
C_{22}	148	18.02	128	21.58 ± 0.17
C_{33}	81	60.2	87	62.18 ± 4.66
C_{44}	226	7.73	250	8.115 ± 0.9
C_{55}	226	7.73	204	8.115 ± 1.1
C_{66}	257	5.98	255	5.83 ± 0.06



Conclusion: Our FEM simulation results validate that waveguide elastography can successfully estimate anisotropic stiffness in an orthotropic model (transversely isotropic). However, for these simulations to have any translational value, further investigation is necessary to study the stiffness pattern in healthy and diseased conditions.

References:

1. Chin, A.B. et al. Muscle Nerve 2008; 37(5):560–565.
2. Giordano, C. et al. J. of Biomechanics 2014; 47(5), p. 1052-1059.
3. Gupta K, et al, Circulation, 2009; 1994; 89:2315-2326.
4. Romano, A.J. et al., MRM 2012; 68:1410-1422.
5. Romano, A.J. et al., In: Proc 21st ISMRM, 2013 (p. 2431).
6. Mazumder, R. et al., In: Proc 22nd ISMRM, 2014 (p. 2423).
7. Achenbach, J.D. Wave Propagation in Elastic Solids.Vol 16 (p. 250-252).