Effects of Fiber Curvature on Anisotropic Inversions in Waveguide Elastography

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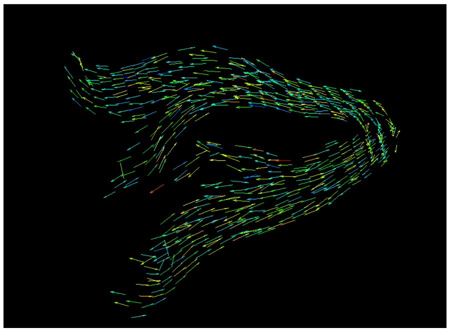
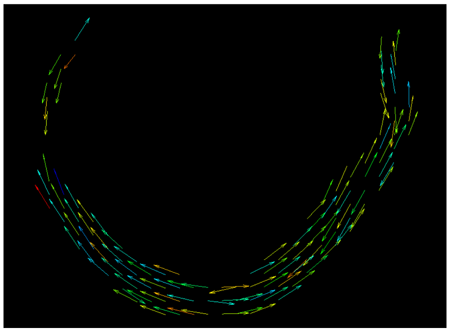
Background: Previously, we introduced a method called Waveguide Elastography (WGE) [1] which attempts to evaluate the material parameters of fibrous structures such as white matter tracts. These structures differ from gray matter in that they are composed of myelinated axons which can act as anisotropic waveguides. We applied this method in the Corticospinal Tracts of both healthy volunteers as well as patients suffering from Amyotrophic Lateral Sclerosis [2]. In these previous studies, we inverted the Orthotropic equations of motion along the local tangent vectors of the fiber tracts. Here, we invert along the principal direction of fiber tracts while including the effects of curvature. It was observed that the effects of curvature in the calculation of the Laplacians bias the "inherent" stiffness in a similar fashion as wave velocities are altered by an index of refraction in ray theory [4], which can be evaluated by the Eikonal equation [3]. Here, we demonstrate the effects of curvature on anisotropic inversions in the Forceps Major and compare our method with ray theory.

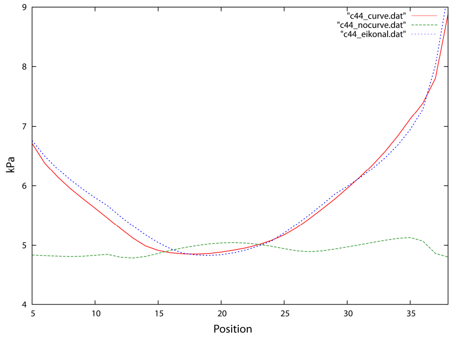
Methods: Waveguide Elastography requires a knowledge of the pathways along which elastic waves may travel, as well as a measurement of the dynamic displacements within the volume surrounding the pathways. With a knowledge of the position vectors of the pathways, a spatial-spectral filter is applied to the measured displacements to identify only those waves which are traveling at particular angles to, and along the fibers at every point. At this time as well, a Helmholtz decomposition is implemented which separates the total field into its longitudinal and transverse components. An Orthotropic inversion is then performed along the fibers to evaluate the stiffness values. By filtering along six specific directions within the local reference frame of the fibers, the equations of motion decouple allowing for each of the nine elastic coefficients to be solved for independently of one another. This approach allows for lower order anisotropic models (such as Hexagonal or Cubic, for example) to be exposed as valid by exposing redundancies in the Orthotropic coefficients. By differentiating the spatial-spectral filter twice with respect to arclength, the Laplacians can be evaluated which contain the effects of curvature along the pathways.

For the MRE measurement, the experiment was run on a standard 1.5T clinical MRI scanner (Siemens, Erlangen, Germany). A head-cradle extended-piston driver was used for 60Hz harmonic head stimulation. A single-shot spin-echo EPI sequence was used for acquiring three Cartesian components of the wave field in 70 adjacent transversal slices and eight time steps over the vibration period. Further sequence parameters: 2x2x2 mm^3 isotropic image resolution, 2 averages, motion encoding gradient: 60 Hz, 3 cycles with trapezoidal shape and first gradient moment nulling. Total acquisition time was three minutes.

For the fiber position measurement, Diffusion Tensor Imaging (DTI) data was acquired using a single-shot EPI sequence (TR/TE-8500/96 ms) with 12 non-colinear directions and one B_0 volume (b-value=1000 s/mm^2, 6 averages). Tensor calculation and tractography along the white matter pathways was performed using the tools from the FMRIB Software Library (FSL), i.e. dtifit and probtrackx. Total acquisition time was twelve minutes.







Results: In the figure above we show on the left the DTI mapping of the Forceps Major, while in the middle, we show a slice in the mid-plane of the structure. On the right, we show the results from our analysis along a central pathway for the shear coefficient, C_{44}. The red line is the result of performing the inversion using a Laplacian which includes the curvature, while the green line is the same coefficient using a Laplacian along the local tangent only with no curvature. As can be seen, the inversion which includes curvature varies as a function of position with values ranging from around 6.5 kPa on the left, around 4.8 kPa in the middle, and around 9 kPa on the right. The inversion with no curvature has a fairly constant value of around 4.8 kPa. When this latter value is used in the expression from the Eikonal equation as C_{44_0}, the expression for the local value of $C_{44_{local}}(r'(\tau))$ appears as $C_{44_{local}}(r'(\tau)) = C_{44_0} / \left| dr'(\tau)/d\tau \cdot dr'(\tau)/d\tau \right|$, (where $r'(\tau)$ is the local position vector along the pathway and the denominator is the square of the index of refraction), and we obtain the blue dotted line in the right most image which lies almost directly upon the red curve. This demonstrates that the effect of including curvature in the Laplacians is virtually identical to the effects of curvature obtained from the Eikonal equation, implying that within this frequency regime, WGE provides results in good agreement with ray theory. Therefore, the effects of curvature play a significant role in the evaluation of the anisotropic stiffnesses of white matter and, if an "inherent" material parameter is chosen as the desired metric, the Laplacian should be calculated along the local tangent only.

This work supported by the Office of Naval Research.

References:

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