Power Pitch Session 2

Developing an Open-Source Framework for the Simulation of MR Elastography Experiments

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Introduction: Magnetic Resonance Elastography (MRE) is a non-invasive quantitative medical imaging technique used to estimate tissue stiffness. The technique allows for the detailed assessment of tissue mechanical properties, providing valuable insights into liver disease, breast cancer, and neurological disorders such as Alzheimer's disease, multiple sclerosis, and traumatic brain injury [1]. Utilizing computational models and personalised simulations in MRE can offer valuable insights into the biomechanical properties of biological tissues in health and disease. Previous studies have shown that finite element (FE) modelling can be effectively utilized to develop and evaluate MRE, investigating the effects of material properties, excitation frequency, and boundary conditions on shear wave propagations [2, 3, 4]. In this work, we aim to develop an open-source approach for FE simulations of the tissue biomechanics that lead to the MRE contrast, allowing ourselves and others to test and compare different acquisition strategies as well as stiffness estimation techniques.

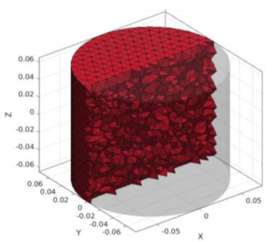

Fig. 1. Mesh view of 3D Cylindrical MRE phantom FE model.

Methods: For our initial simulation we investigated an elastic, homogeneous, nearly incompressible, and isotropic cylindrical model to create a simplified representation of tissue mechanics and to compare with real MRE data collected on a cylindrical phantom (CIRS Inc, VA, USA). The FE analysis for this study was conducted using the open-source package 'FEBio' [5], and using the GIBBON (Geometric Image-Based Bioengineering Network) toolbox in MATLAB to generate the mesh. In our FE analysis, we used tetrahedral (tet10) elements, which have 10-nodes and quadratic shape functions. The material properties of the phantom were characterized by a Young's modulus of 9kPa, a Poisson's ratio of 0.49 to ensure nearly incompressible behavior, and a density of 1000 kg/m³. Sinusoidal motions in the z-direction at 60.1 Hz with amplitude of 150 µm were applied to the nodes in the entire outer surface of the model to simulate the vibration used in MRE. The outer nodes were also fixed along X and Y, assuming the container to be rigid. A high-quality mesh is essential to achieve both high accuracy and computational efficiency in FE modelling. To determine the appropriate mesh resolution necessary for obtaining accurate results, we conducted a mesh sensitivity study.For the experimental part of the study, the phantom underwent MRE acquisitions on a 3T MR scanner (Siemens Healthineers, Erlangen, Germany). We utilized a Resoundant MRE system (Resoundant Inc., USA) that generated mechanical vibrations at a frequency of 60.1 Hz, synchronized with the MRE sequence. The phantom was positioned within the MR head coil, with the passive driver placed on its top surface to transmit mechanical vibrations produced by the pneumatic active driver.

Results: The displacement data show observable deformation patterns throughout the model. We plotted the resulting displacement values against different mesh sizes (Fig.2) to observe the effect of mesh refinement on the accuracy of the model. Our findings indicate that the mesh size converges at approximately 48,000 Solid Elements. At this convergence point, the displacement values stabilize, and further reductions in mesh size yield nearly negligible changes in the displacement values. The MRE wave images from both the FE simulation and experimental results at four phases of driving frequency, all conducted at 60.1 Hz, show good visual agreement in their depiction of the propagation of shear waves within the phantom (Fig.3).

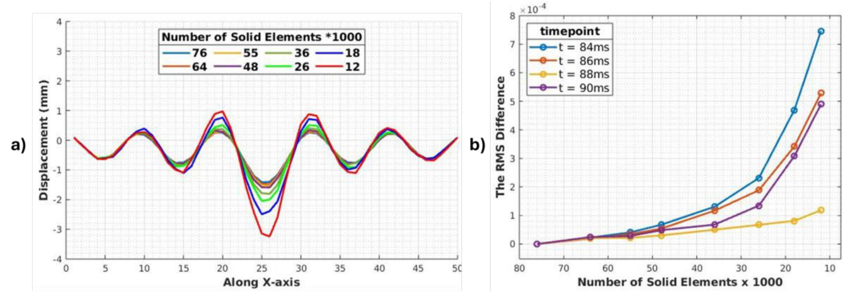

Fig. 2. Overview of mesh sensitivity study; **(a)** 1D Displacement profiles of simulated phantom for varying mesh sizes at timepoint *t* = 86ms . **(b)** The RMS difference (compared to reference mesh) of simulated displacement profiles each mesh.

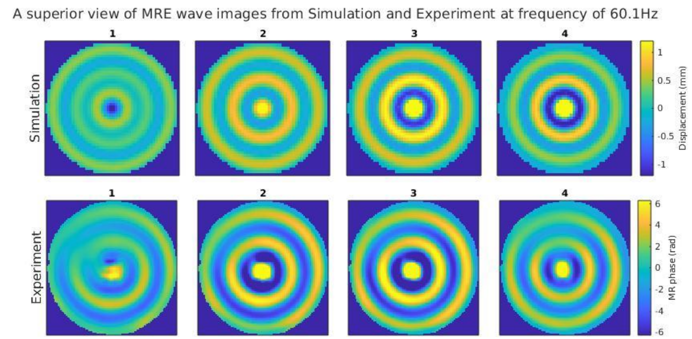

Fig. 3. Wave image comparison between experimental study and simulation results for four phases of driving frequency at 60.1Hz driving frequency.

Discussion: In this study, we examined the displacement data and frequency response of the MRE phantom under dynamic loading conditions using FEBio. Our mesh convergence analysis found that a mesh-size of ~48k elements should be sufficient for our simulations – and simulating 100 ms of transient behaviour took ~12 minutes on a 64-CPU compute node. The simulation model we have used so far is purely elastic and we would not expect this to accurately represent the viscoelastic behavior observed in biological tissues. The next step for our future work is to investigate how to incorporate realistic viscoelastic properties into our simulations.

Conclusions: Our preliminary results demonstrate the capabilities of open-source software implementations to simulate a simple MR elastography experiment in a cylindrical phantom. We aim to develop this approach to allow deeper investigation into the optimisation of brain MRE in human subjects.

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References

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