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

Mehmet N. YILDIRIM[1], Samuel Evans[2], Daniel Gallichan[1]

1. CUBRIC / School of Engineering, Cardiff University, Cardiff, UK
2. School of Engineering, Cardiff University, Cardiff, UK
YildirimMN@cardiff.ac.uk

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].
- 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.

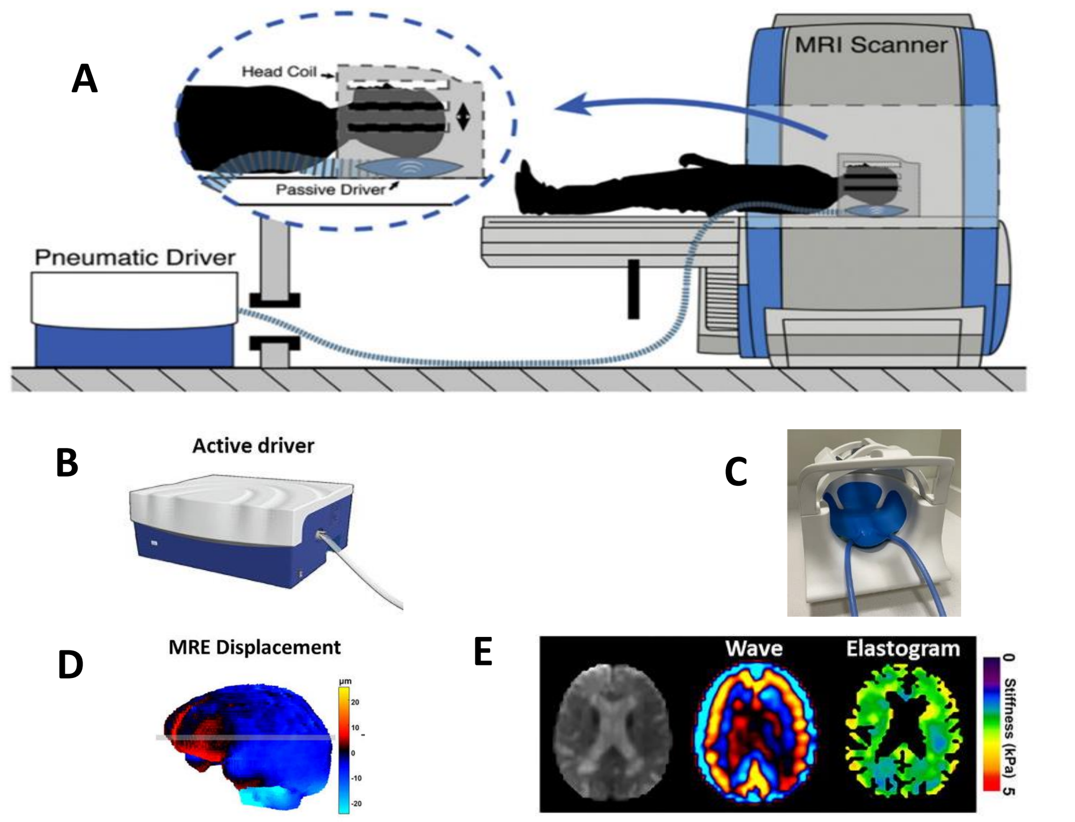


Figure 1. *Brain MRE setup (**A**), pneumatic active driver (**B**), pillow-like passive driver (**C**), MRE Displacement image (**D**), MRE magnitude, wave image, and stiffness map (**E**).*

Experimental Design

Simulation

Our model was:

- Elastic
- Homogeneous
- Nearly incompressible
- Isotropic

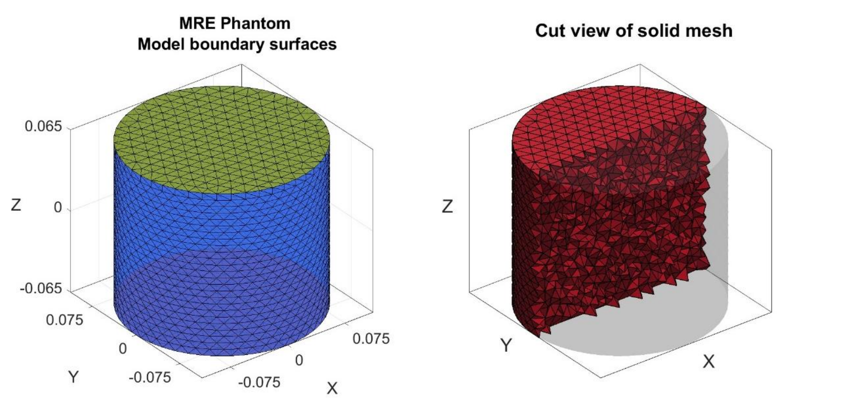


Figure 2. *MR Elastography phantom model boundary surfaces and cut view of solid mesh.*

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.

- We used tetrahedral (tet10) elements, which have 10-nodes and quadratic shape functions.
- Young's Modulus (E) = 9 kPa, Poisson's ratio = 0.49 and Density= 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.

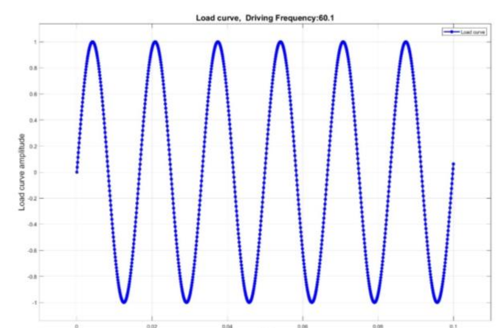


Figure 3*. Sinusoidal load at 60.1 Hz frequency*

Experiment

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.

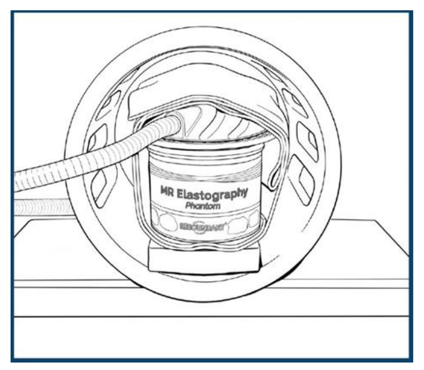


Figure 4*. Experimental setup of MR Elastography phantom*

Results

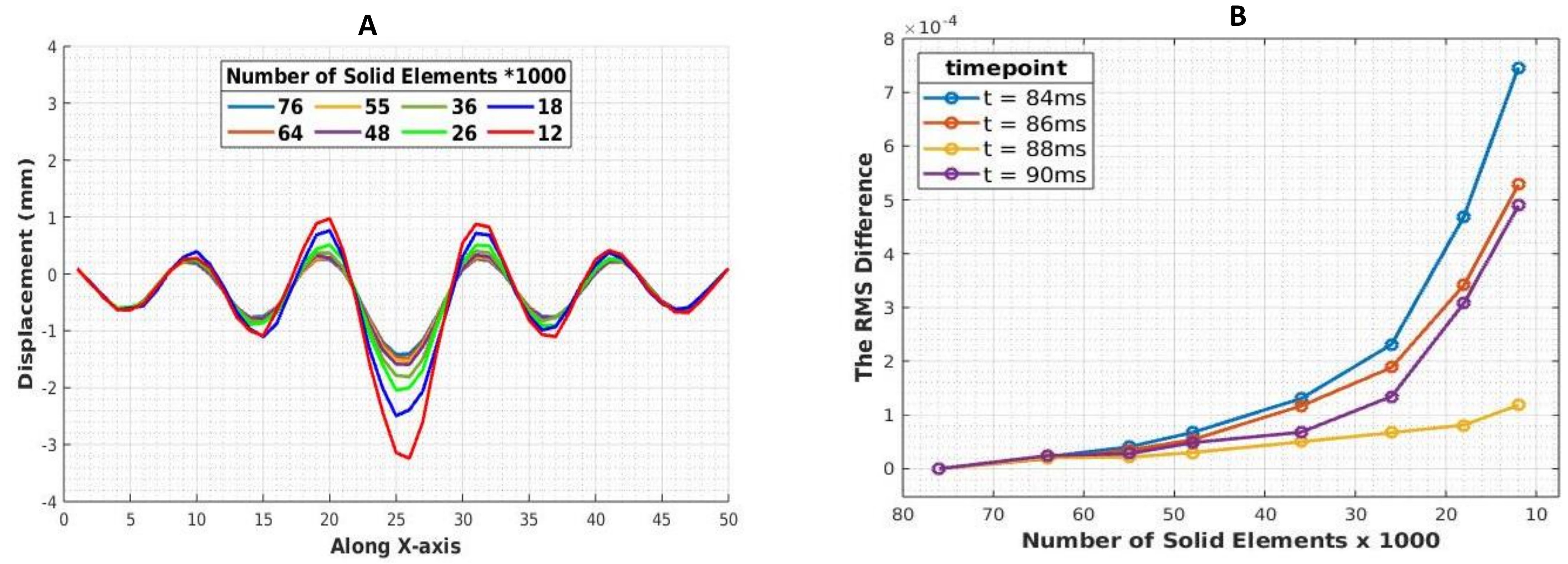


Figure 5. *Mesh convergence experiment. The displacement data show observable deformation patterns throughout the model. We plotted the resulting displacement values against different mesh sizes (**A**) to observe the effect of mesh refinement on the accuracy of the model. Our findings indicate that the mesh size converges at approximately 48,000 Solid Elements (**B**). At this convergence point, the displacement values stabilize, and further reductions in mesh size yield nearly negligible changes in the displacement values.*

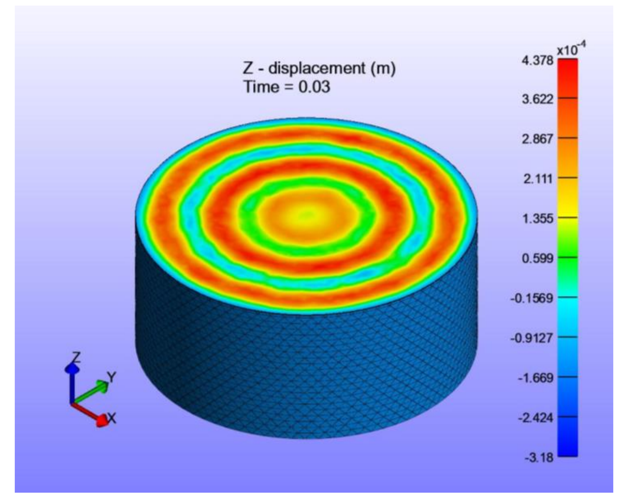


Figure 6. *Shows the propagation of the shear waves, presented as a plane-cut view at the centre of MRE phantom model.*

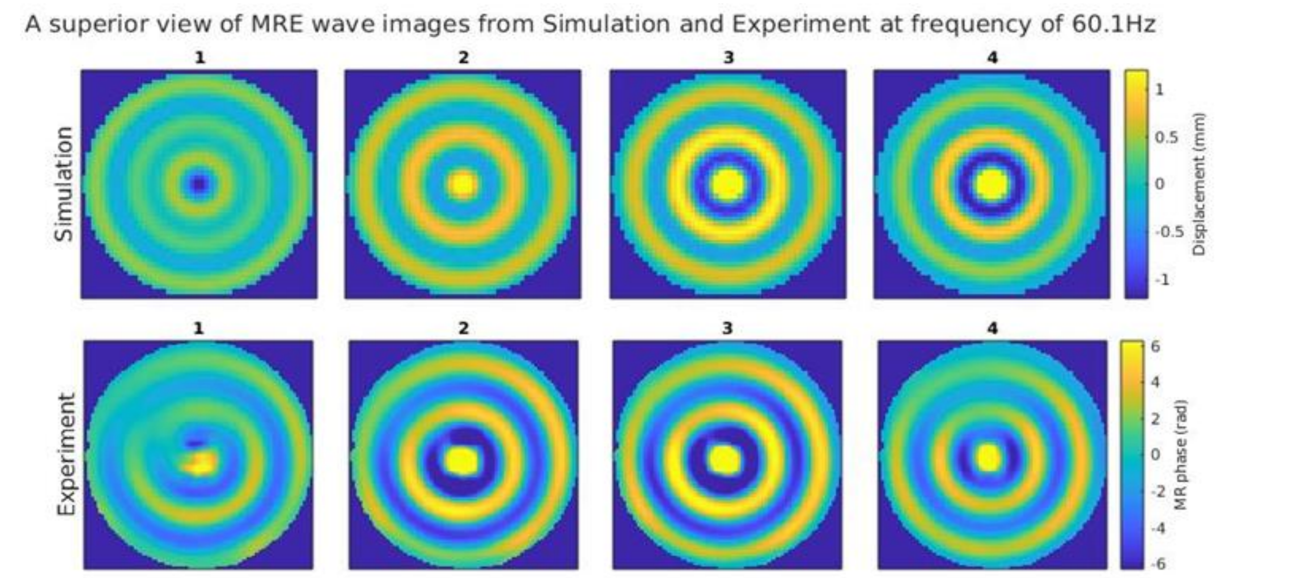
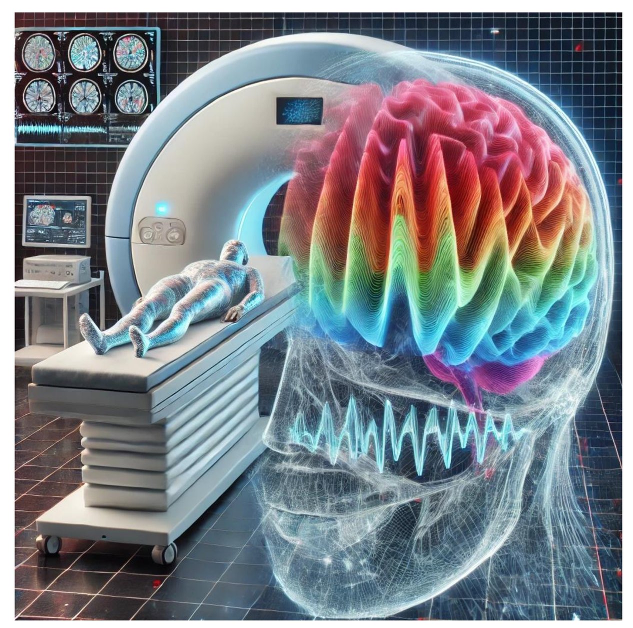


Figure 7. *The MRE wave images from both the FE simulation and experimental results at four phases of driving frequency, all conducted at 60.1 Hz, show good visual agreement in their depiction of the propagation of shear waves within the phantom.*

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.



Conclusion

- 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.

References & Acknowledgement

References:

[1] L. V. Hiscox et al., Phys. Med. Biol., vol. 61, no. 24, Art. no. 24, 2016, doi: 10.1088/0031-9155/61/24/R401.
[2] Q. Chen, S. I. Ringleb, A. Manduca, R. L. Ehman, and K.-N. An, J. Biomech., vol. 38, no. 11, pp. 2198–2203, Nov. 2005, doi: 10.1016/j.jbiomech.2004.09.029.
[3] S. Tomita et al., J. Vis., vol. 21, no. 1, Art. no. 1, 2018, doi: 10.1007/s12650-017-0436-4.
[4] M. McGarry et al., Phys. Med. Biol., vol. 66, no. 5, p. 055029, Mar. 2021, doi: 10.1088/1361-6560/ab9a84.
[5] FEBio, 'FEBio Software Suite'. Accessed: Jun. 28, 2024. [Online]. Available: https://febio.org/

Acknowledgement: I would like to give special thanks to Busra Sahin Yildirim and Esmahan Durmaz, Guarantors of Brain for travel grant and the generous scholarship granted by The Ministry of National Education of Turkey.