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Determining Anisotropic Myocardial Stiffness from Magnetic Resonance Elastography

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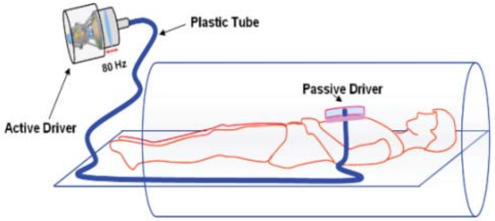
Background

Magnetic resonance elastography (MRE) is a recent, non-invasive technique for measuring myocardial stiffness. MRE process:

- Waves generated by external actuators
- Waves are visualised using a phase-contrast gradient echo MRI sequence
- Displacement information is converted into stiffness maps using an inversion algorithm.



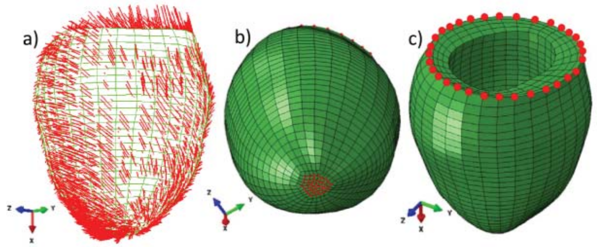
MRE setup (image courtesy of Dr. Kolipaka)

An aim of the project is to develop a new inversion algorithm which can successfully resolve anisotropic material properties of cardiac tissue by combining MRE and FEA methods.

Methods

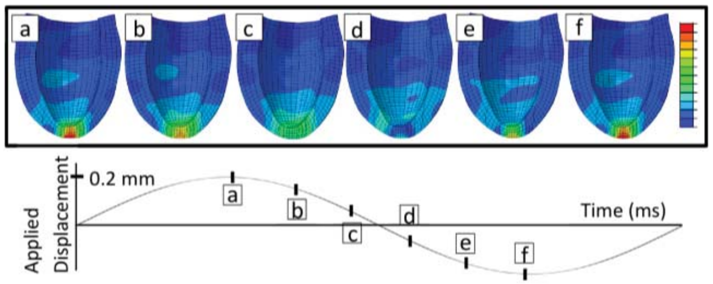
A left ventricle FE model were used to simulate shear wave propagation as it occurs in MRE. The material was modelled as linearly elastic and transversely isotropic. A four dimensional parameter sweep was carried out in which damping (s), E1 (transverse stiffness), E3 (fibre stiffness) and v (Poisson's ratio) were varied. The RMSE between each displacement field and the reference displacement field was plotted as a percentage of the RMS reference displacement. Three criterion based on the Hessian [det(H), cond(H_{norm}) and det($\widetilde{H}$)] were calculated in order to assess the determinability of the four parameters.

In order to evaluate the effect of noise, Gaussian noise was added to the epicardial surface boundary data and a material parameter optimisation (fmin_cobyla, Scipy) was run 30 times with noise regenerated before each optimisation.

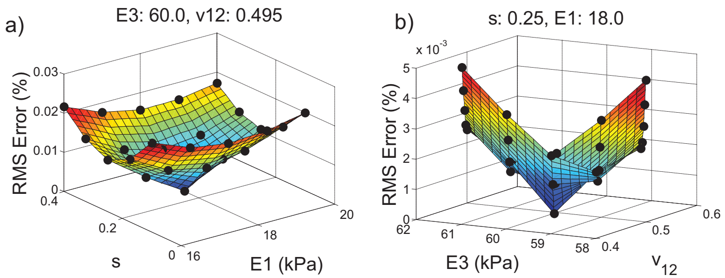


a) LV fibers; b) apical nodes in red which were displaced 0.2 mm/60 Hz; c) epicardial basal nodes in red that were fixed (no-displacement) in reference model

Results



Displacement maps at six points during one harmonic cycle in the reference FE LV model. The figure is a 2D view passing through the long axis of the LV and represents magnitude of displacement ($\sqrt{x^2+y^2+z^2}$); red: +0.2 mm, blue: 0 mm.



Percent RMSE for a) s and E1 and b) E3 and v_{12}. Plots are shown with additional interpolated data points; black spheres indicate points where error values were calculated.

Determinability Criteria	Value
det(H)	0.032
cond(H_{norm})	9.61
det($\widetilde{H}$)	0.94

Determinability criteria based on the Hessian (H) of objective function at the local minimum

Material Parameter	Reference Value	Optimised Value
s	0.25	0.252 ± 0.00665
E1	18 kPa	18.024 ± 0.148 kPa
E3	60 kPa	60.064 ± 0.488 kPa
v	0.495	0.494 ± 0.00234

Mean and standard deviation of material parameters from 30 optimisations with noise added to epicardial displacement boundary conditions

Conclusions

- Anisotropic material parameters are determinable from the simulated MRE displacement field
- Addition of noise did not affect the determinability of parameters

Acknowledgements

This research was supported by an award from the National Heart Foundation of NZ. Members from Ohio State University and the Ohio Supercomputing Centre have contributed to this project. Simulations were run on the NeSI high performance computing facilities.