Validation of Finite Element Models of Cardiac Structure and Kinematics via CINE, Displacement-Encoded, and Diffusion MRI.

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Introduction: Prompted by the high morbidity and mortality rates associated with heart disease, finite element (FE) modeling of the left ventricle (LV) has provided both descriptive and predictive insights on the structural remodeling, functional behavior, and material properties of the myocardium, and become an important part of biomedical device design, monitoring strategy development, and surgical planning. The outcome of these simulations is highly sensitive to input information particularly material assumptions in terms of constitutive equations, coefficients, and material symmetry. Methods for coefficient identification using imaging data have been demonstrated, and the outcome of FE simulations has been shown to also depend on fiber distribution assumptions [1-2]. However, experimental validation of the predicted deformation across the cardiac cycle as has been lacking mainly due to practical difficulties, including (a) the challenge in assessing fiber structural information of living tissue non-destructively and (b) the analysis a given same sample at different cardiac states. Recent studies in perfused heart preparations show that it is possible to overcome these experimental issues using Diffusion Tensor MRI (DT-MRI), which also holds promise for *in vivo* implementation [3]. The current work details the development and application of an experimental-computational platform aimed to optimize material assumptions for kinematic and structural predictions against direct experimental observations.

Materials and Methods:
Imaging Protocols. CINE, displacement-encoded (DENSE), and DT-MRI (respectively, 8/4/1 slices, 6/9/1 frames, FOV 40x40 mm, 96x96 pixels) were preformed on healthy rats (n=6) using a Bruker Biospec 7T instrument. Subsequently, intraventricular pressure was measured before the heart was excised, inserted with a small latex balloon, and perfused with cardioplegic solutions in an MRI-compatible Langendorff apparatus to obtain DT-MRI at various cardiac states. Early diastole (EAD) and end diastole (ED) were emulated by K^{+2} arrest with the balloon deflated and inflated, respectively, whereas end systole (ES) was attained by Li^{+2}-induced contracture with deflated balloon. A recovery period of ~ 10 min, or until electrical activity was restored, was allowed in between each state. FE Modeling. Subject-specific LV models to predict ED and ES were constructed from CINE imagery and DT-MRI at EAD, which was assumed to be unloaded and stress-free. The models were inspected for mesh quality and convergence prior to subsequent analysis. The boundary conditions consisted of pressure waveforms prescribed in the LV cavity, and image-based forces via Hyperelastic Warping [4]. Material Modeling. While holding all other variables constant, different simulated solutions were generated under various material assumptions, including (a) Exponential transversely isotropic Neo-Hookean and Fung-type constitutive models, and (b) ±20% variations of Fung-type material coefficients and strain-based material identification detailed in [2]. All simulations were run on the FEBio2 Software suite [5].

Results and Discussion: Figure 1 shows the LV model, CINE images of perfused heart at ED and ES, and fiber structural helix angle maps obtained and ED and ES via DT-MRI from a representative animal. LV models converged at approximately 3520 elements. Our preliminary results indicate that, although transversely isotropic and Fung-type models are similarly able to represent deformation, the later is capable of better capturing torsional kinematics and structural changes, particularly at ES. This is likely due to the inherent limitation of transversely isotropic material symmetry; although both cases were enhanced by a systematic characterization of off-fiber active contraction by means of a modified parameter scheme, which takes into account *in vivo* displacement-encoded MRI.

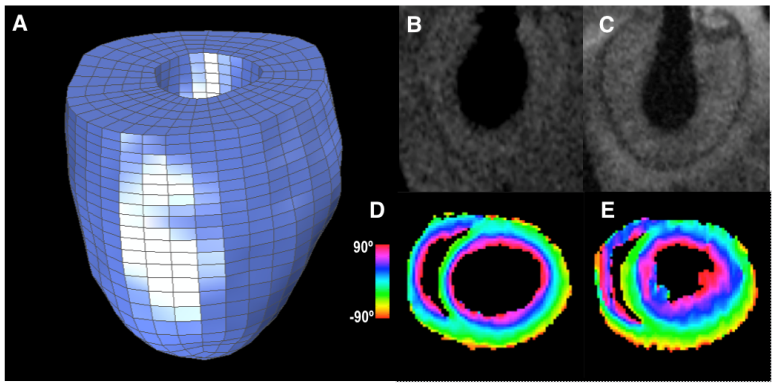

Figure 1. Representative onverged patient-specific FE model (A), CINE magnitude images at ED (B) and ES (C), and DT-MRI fiber helix angle orientation maps at ES (D) and ED (E) obtained from the same left ventricle.

Conclusion: A computational and experimental pipeline for the validation of FE simulations using imaging data was introduced. Future work includes detailed statistical analysis, and the analysis of effects of assumptions in input data sources like atlases on the outcome of simulations.

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