2020-2021 Grand Challenge Award Final Report

Awardee: **Michael Sacks, Professor**
Biomedical Engineering

Research Award Title: **Simulation of the 3D Hyperelastic Behavior of Ventricular Myocardium using a Finite-Element Based Neural-Network Approach**

Research Summary

High-fidelity cardiac models using attribute-rich finite element based models have been developed to a very mature stage. However, such finite-element based approaches remain time consuming, which have limited their clinical use. There remains a need for alternative methods for novel cardiac simulation methods of capable of high fidelity simulations in clinically relevant time frames. Surrogate models are one approach, which traditionally use a data-driven approach for training, requiring the generation of a sufficiently large number of simulation results as the training dataset. Alternatively, a physics-informed neural network can be trained by minimizing the PDE residuals or energy potentials. However, this approach does not provide for a general method to easily account for complex geometries and boundary conditions. To address these challenges, we developed a hybrid approach that seamlessly bridged a neural network surrogate model with a differentiable finite element domain representation (NNFE). Given its importance in cardiac simulations, we applied this approach to simulations of the hyperelastic mechanical behavior of ventricular myocardium from recent 3D kinematic constitutive model (J Mech Behav Biomed Mater, 2020 doi: 10.1016/j.jmbbm.2019.103508). We utilized cuboidal domain and conducted numerical studies of individual myocardium specimens discretized by a finite element mesh and assigned with experimentally obtained myofiber architectures. Both parameterized Dirichlet and Neumann boundary conditions were studied. We developed a second-order Newton optimization method, instead of using stochastic gradient descent method, to train the neural network efficiently. The resulting trained neural network surrogate model demonstrated excellent agreement with the corresponding 'ground truth' finite element solutions over the entire physiological deformation range. More importantly, the NNFE approach provided a significantly decreased computational time for a range of finite element mesh sizes. For example, as the finite element mesh sized increased from 2744 to 175615 elements the NNFE computational time increased from 0.1108 s to 0.1393 s, while the 'ground truth' FE model increased from 4.541 s to 719.9 s. These results suggests that NNFE run times can be significantly reduced compared with the traditional large-deformation based finite element solution methods. The trade off is to train the NNFE off-line within a range of anticipated physiological responses. However, training time would only have to be performed once before any number of application uses. Moreover, since the NNFE is an analytical function its computational performance will be amplified when the corresponding problem becomes more complex.

Publications

1. "Simulation of the 3D Hyperelastic Behavior of Ventricular Myocardium using a Finite-Element Based Neural-Network Approach," Wenbo Zhang, David S. Li, Tan

Bui-Thanh, Michael S. Sacks, CMAME, in-revision.

2. "A Contact Algorithm for using a Finite-Element Based Neural-Network Approach," Christian Goodbrake and Michael S. Sacks, IJNME, submitted.

3. "Moving from Artisanal to Industrial: Scaling Digital Twins," Niederer S.A., Sacks M.S., Girolami M., and Willcox K., Nature Computational Science, Nature Computational Science volume 1, pages 313–320 (2021).

4. "Isogeometric finite element-based simulation of the aortic heart valve: Integration of neural network structural material model and structural tensor fiber architecture representations," Zhang,W., Rossini, G., Kamensky, D., Bui-Thanh, T., and Sacks, M. S., International Journal for Numerical Methods in Biomedical Engineering (2021).

Invited Lectures

1. "Neural Network Finite Element Modeling of the Heart Mechanics: A new look at an old problem," Department of Biomedical Engineering and Computer Science, Michigan Technical University, February 7, 2022.

2. "Neural Network Finite Element Modeling of the Heart Mechanics: A new look at an old problem," Department of Biomedical Engineering, The Pennsylvania State University, January 13, 2022.

3. "Neural Network-based Surrogate Computational Modeling of Myocardium: A new look at an old problem," KTH Solid Mechanics Keynote seminar, Thursday, June 24, 2021.

4. "Modeling the 3D myocardium mechanical behaviors using a neural network approach," Department of Civil Engineering, Duke University, March 16, 2021.

Presentations Made

1. "High Speed Simulation of the 3D Behavior of Myocardium using a Neural Network PDE Appraoch," Wenbo Zhang, Michael Sacks, and Tan Bui, USNCCM16, July 22, 2021.

2. "High Speed Simulation of the 3D Behavior of Myocardium using a Neural Network PDE Appraoch," Wenbo Zhang, David S. Li, Tan Bui-Thanh, Michael S. Sacks, Summer Biomechanics, Bioengineering, and Biotransport Virtual Conference, June 14-18, 2021.

3. "Direct Solution of 3D Soft Tissue Mechanical Behavior Using a Neural Network Energy Based PDE Solution Approach," W. Zhang, T. Bui-thanh, M. Sacks, 14th WCCM-ECCOMAS Congress 2020 (Virtual), 11-15 January, 2021.