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Multiscale Simulation of Biomechanical Systems

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Abstract

Predictive computational models are a significant tool in the study of biomechanical structures. In general, biomechanics is defined as the mechanical discipline that investigates the effects of physiological forces acting on and within the biological structures. As in many other biological phenomena, many length scales are crossed by biomechanics research: intracellular, multicellular, and extracellular matrices; and tissue, organ and multiorgan systems. It is well established that the effect of forces at higher scales influence the behavior at lower scales and that lower-scale properties influence the higher-scale response. However, computational methods that incorporate these interactions in biomechanics are relatively rare.

In this research, a hierarchical multiscale approach is employed to investigate how mechanical stimuli in the organ scale are transmitted to microstructure in the cell scale. As an important biomechanical structure, the aortic heart valve, as a soft tissue, constructs a complex fiber-reinforced composite structure that the mechanical communication from the larger scales affects its active biomechanical processes. For instance, any organ-scale motion deforms the tissue, which in turn deforms the interstitial cells (ICs). In order to study this communication, a simple one-way coupling is utilized to relate different scale simulations by passing data from the largest scale to the smallest one. First, the organ-level simulation is performed. The results of element deformations at the organ-level simulation are applied, as boundary conditions, to a representative volume element (RVE) of tissue. Then, deformations from the tissue-level simulation are passed similarly to the cell-level simulation and the cell aspect ratio will be extracted. The aortic valve leaflets undergo large displacements through the blood pressure and due to anisotropic hyperelastic material constituents. Accordingly, a general code has been developed in C++, Matlab and Java to predict the highly nonlinear and transversely isotropic material behaviors based on the total lagrangian procedure of large deformation theory within a multilevel finite element method.

While the models represent a simplified version of the native aortic valve, a good agreement with the experimental data can be observed. Therefore, the proposed multiscale finite element approach can be used in the study of the mechanical behavior of heart valves. Such a procedure may also be regarded as a predictive multiscale modeling in computational biomechanics. The developed code can also be employed not only for analysis of native biomechanical systems but also in the design of tissue engineered constructs, such as tissue-engineered heart valves.

Keywords: *Multiscale, Biomechanical Simulations, Finite element, Large deformations, Hyperelasticity, Soft tissue, Aortic heart valve*