Physics-based modeling and machine learning integration towards automating cardiovascular material model discovery and analysis

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Abstract

Computational modeling of cardiovascular tissues forms a critical tool towards understanding the biomechanical factors underlying cardiovascular diseases, predicting disease progression, and designing personalized interventions. However, the selection of and proper use of appropriate material models for these simulations often requires specialized expertise and is prone to user bias, which can have detrimental consequences for patients.
Recent breakthroughs in constitutive artificial neural networks allow for the automatic discovery of optimal material models and parameters directly from experimental data, including uniaxial, biaxial and triaxial tissue testing protocols. The discovered models are interpretable, consisting of physically meaningful terms and parameters, and can be seamlessly integrated into finite element simulations through a newly developed, open-source available universal material subroutine (1). This subroutine seamlessly integrates trillions of potential constitutive material models that come out of the automated material model discovery pipeline, and automatically capture various traditional models as special cases. By replacing dozens of individual material subroutines with a single universal material subroutine, populated directly via automated model discovery, we can make finite element simulations more user-friendly, robust, and less vulnerable to human error.

Various examples demonstrate the effectiveness of this approach for systemic arteries (2), pulmonary arteries (3), and myocardial tissue (4) where finite element analysis simulations highlight the impact that improved accuracy has on large-scale organ mechanics under complex hemodynamic loading conditions. This integrated approach towards automated material model discovery and finite element analysis empowers a broader community of researchers to perform reliable biomechanical simulations, driving innovation and discovery in the field of cardiovascular tissue mechanics.

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