MATHEMATICAL AND NUMERICAL MODELING OF CARDIAC ELECTROMECHANICS IN VENTRICLES WITH ISCHEMIC CARDIOMYOPATHY

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Among the cellular-to-organ level physical phenomena contributing to the cardiac function, an important role is played by the coupling between the electrical activity of the heart and its mechanical contraction. For this reason, numerical simulations of ventricular electromechanics play nowadays a crucial role in computational cardiology and precision medicine. Indeed, it is of outmost importance to analyze and better address pathological conditions by means of anatomically accurate and biophysically detailed individualized computational models that embrace electrophysiology, mechanics and hemodynamics.

With this aim, we develop a novel electromechanical model for the human ventricles of patients affected by ischemic cardiomyopathy. This is made possible thanks to the introduction of a spatially heterogeneous coefficient that accounts for the presence of scars, grey zones and non-remodeled regions of the myocardium. We couple this 3D electromechanical model with 0D circulation models by an approach that is energy preserving. Our mathematical framework keeps into account the effects of mechano-electric feedbacks, which model how mechanical stimuli are transduced into electrical signals. Moreover, it permits to classify the hemodynamic nature of tachycardias. These aspects are very important for the clinical exploitation of our electromechanical model.

We propose two segregated-intergrid-staggered (SIS) numerical schemes to solve this 3D-0D coupled problem. Specifically, we consider two partitioned strategies for which different space-time resolutions are employed according to the specific core model. In particular, numerical models for cardiac electrophysiology require a finer representation of the computational domain and a smaller time step than those used for cardiac mechanics. For the first numerical scheme (SIS1), we introduce intergrid transfer operators based on Rescaled Localized Radial Basis Functions to accurately and efficiently exchange information among the several Partial Differential Equations (PDEs) of the electromechanical model. Different (potentially non-nested) meshes and first-order Finite Elements can be used for the space discretization of the PDEs. The second numerical scheme (SIS2) that we propose employs another flexible and scalable intergrid transfer operator, which allows to interpolate Finite Element functions between nested meshes and, possibly, among arbitrary Finite Element spaces for the different core models.

We also design a Machine Learning method to perform real-time numerical simulations of cardiac electromechanics. Our method allows to derive a reduced-order model (ROM), written as a system of Ordinary Differential Equations, in which the right-hand side is represented by an Artificial Neural Network (ANN), that possibly depends on a set of parameters associated with the model to be surrogated. This method is non-intrusive, as it only requires a collection of pressure and volume transients obtained from the full-order model (FOM). Once trained, the ANN-based ROM can be coupled with hemodynamic models for the blood circulation external to the heart, in the same manner as the original electromechanical model, but at a dramatically reduced computational cost. We demonstrate the effectiveness of the proposed strategy on two relevant contexts in cardiac modeling. We employ the ANN-based ROM to perform a global sensitivity analysis on both the electromechanical and the hemodynamic models. Then, we perform a Bayesian estimation of a couple of parameters starting from noisy measurements of two scalar outputs.

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