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Coupled computational modeling of cardiac electrophysiology, mechanics and fluid dynamics [⋆]

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Abstract: We propose a computational model of a human heart including three-dimensional descriptions for electrophysiology, solid mechanics and fluid dynamics of the blood, aiming at reproducing the feedback mechanisms that occur within the heart. The model is obtained combining standalone physical models used in the cardiac modeling literature, introducing coupling terms, resulting in a multi-way coupled integrated model. We numerically solve the model with a staggered scheme. Fluid dynamics and solid mechanics are coupled implicitly with a monolithic scheme. The staggered scheme allows to select different timesteps for the different core models, leveraging the multiscale and multiphysics nature of the model. Simulations results on a realistic human heart model are consistent with the behavior shown by healthy hearts.

Keywords: Cardiovascular modeling, Heart, Multiphysics, Electrophysiology, Cardiac electromechanics, Fluid-structure interaction, Hemodynamics, Finite element analysis

1. INTRODUCTION

We aim at a multi-way coupled computational model that integrates three dimensional descriptions of cardiac electrophysiology (EP), active and passive mechanics and blood dynamics (individually referred to as core models). Such a model has the capability of capturing the feedback mechanisms between the different components of the heart. We refer to the model as electro-mechanics-fluid dynamics (EMF)

Due to the large size of an EMF model, fully coupled computational models of this kind are seldom considered in literature, e.g. in Hosoi et al. (2010), Santiago et al. (2018). Nonetheless, the core models have been studied in detail either in a standalone way or with reduced coupling to other models (see e.g. Augustin et al. (2016), Gurev et al. (2011), Regazzoni et al. (2022), Nordsletten et al. (2011), This et al. (2020), Zingaro et al. (2022)).

We leverage previously developed core models, introducing couplings between them. We solve the EMF model with a staggered scheme in time, exploiting its multiphysics and multiscale nature, and relying on finite elements for the space discretization. Numerical results, obtained on a realistic human heart, showcase the ability of the computational model to reconstruct physiological behavior.

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2. MODELS AND NUMERICAL METHODS

The EMF model has four major components: EP, activation, solid mechanics and fluid dynamics. For EP, we use the monodomain equation (Colli Franzone et al. (2014)) coupled with the ionic model of Ten Tusscher and Panfilov (2006). Active force generation, in the active stress framework, is obtained with the model presented in Regazzoni et al. (2018). The muscle displacement is modeled using elastodynamics equations, as described e.g. in Regazzoni et al. (2022), fed with the activation state computed by the activation model to compute the active stress contribution. We use Guccione and Neo-Hooke constitutive models for passive mechanics. Fluid dynamics of the blood are described by ALE incompressible Navier-Stokes equations (see e.g. Zingaro et al. (2022)). Valves are included with the Resistive Immersed Implicit Surface method (Fedele et al. (2017)), choosing the opening and closing times based on computed pressures. Fluid and solid are coupled by imposing continuity of velocity and stresses at the interface, see Bazilevs et al. (2013), resulting in a fluid-structure interaction (FSI) problem.

We discretize the EMF model in time with a staggered scheme. We solve the EP equations for a few small timesteps. We then solve the activation model, and the FSI equations. All couplings are treated explicitly, except for the FSI coupling, due to stability concerns. We discretize in space with finite elements on a hexahedral grid, with a finer grid for EP, nested into the one for mechanics, and with a conforming fluid-solid interface. The FSI problem is discretized monolithically and solved with Newton method and GMRES, with a block-triangular preconditioner using

SIMPLE (Deparis et al. (2014)) and AMG to approximate fluid and mechanics blocks.

3. NUMERICAL SIMULATIONS

We consider a human cardiac model, under physiological conditions. We generate fibers with rule-based algorithms (Piersanti et al. (2021)). We use boundary conditions mimicking the presence of the pericardial sac for the outer wall of the myocardium (Regazzoni et al. (2022)), and simplified boundary conditions of Neumann and resistive type for fluid inlets and outlet. The results are qualitatively consistent with the deformations observed in medical images. Moreover, major biomarkers such as ventricular volume and pressure are captured effectively by the model. The model shows the potential of reproducing effectively the behavior of the human heart under physiological conditions.

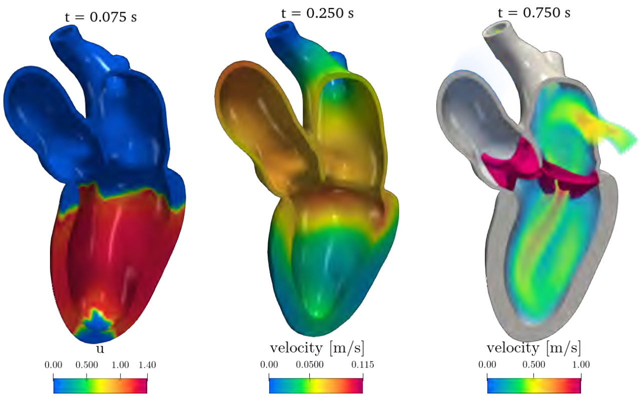

Fig. 1. Three snapshots of a numerical EMF simulation: EP (left), solid velocity (center), fluid velocity (right).

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