The 8th European Congress on Computational Methods in Applied Sciences and Engineering
ECCOMAS Congress 2022
5-9 June 2022, Oslo, Norway

Modeling the electromechanics of the whole heart in detailed image-based geometries.

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Keywords: *Multiphyisics problems, Finite Elements, Cardiac Electromechanics, Artificial Neural Network, Whole Heart Modeling*

The literature lacks electromechanical models of the heart that take into account both atrial and ventricular contraction in detailed four-chamber geometries. More generally, while ventricular electromechanics (EM) in 3D image-based geometries is extensively studied in both physiological and pathological conditions, studies in four-chamber geometries have only begun in recent years and, moreover, often neglect the contraction of the atria. Even in the few studies in which atrial contraction is considered, it is difficult to achieve physiological results, for example in terms of atrial pressure-volume loop.

These difficulties are mainly due to the complexity of the atrial geometry and to the fact that, due to its lower muscle strength, the atrial deformation is also strongly influenced by ventricular contraction and relaxation. Consequently, physiological results can be obtained in the atria only considering biophysically detailed models of all cardiac districts.

In this work we propose a mathematical model of the whole-heart EM, considering biophysically detailed "core models" of the electrophysiology (EP), of the passive mechanics, and of the ventricular and atrial active contraction. More specifically, the model is characterized by: i) an accurate myocardial fibers architecture using a novel whole-heart rule based method that take into account all the fibers' bundles of the atria; ii) the usage in the EP model of the state-of-the-art ionic models for the ventricles and the atria; iii) an Artificial Neural Network based model of active force generation, that surrogates a biophysically detailed but computationally demanding microscale model; iv) a 0D closed-loop model of the circulatory system fully-coupled with the mechanical model to determine pressure and volume load of the heart chambers; v) the modeling of the pericardium and of the epicardial fat using specific boundary conditions acting in the epicardial normal direction as parallel spring and dashpot.

From the numerical point of view, we approximate using the Finite Element (FE) method each core model and we adopt appropriate partitioned schemes to couple the different models in this multiphysics setting. Moreover, we employ a flexible and scalable intergrid transfer operator which allows to use a relatively coarse mesh for the passive and active mechanics and a finer nested mesh for the EP, optimizing the computational cost.

The model described is applied to the solid 3D Human heart model, an image-based whole heart geometry that includes many anatomical details such as, for instance, the atrial appendages. Thanks to our biophysically detailed EM model and to the detailed cardiac geometry adopted, we are able to simulate all the phases of the cardiac cycle in all the four chambers, reproducing physiological results both for the atrial and the ventricles. In particular, we are able to reproduce the eight-shaped pressure-volume loop in the atria and to model the so-called atrial kick in late ventricular diastole.

By comparing the results with a simulation where the atrial contraction is neglected, we demonstrate its determinant role in the development of anatomically and physiologically detailed electromechanical models.

Acknowledgements. This project has received funding from the European Research Council (ERC) under the European Unions Horizon 2020 research and innovation programme (grant No 740132).

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