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Modeling Whole Heart Muscle Fibers in Cardiac Computational Models

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Abstract: A crucial issue in simulating the heart function is accounting and modeling the arrangement of myocardial fibers that characterizes the cardiac tissue. Aggregations of myofibers, namely the results of cardiomyocytes orientation, plays a key role in the electric signal propagation and in the myocardial contraction. This motivates the need to accurately include muscular fibers in cardiac computational models (CCM). Rule-Based-Methods (RBMs), which provide a surrogate of myocardial fibers field, are one of the most used strategy to prescribe fiber orientation in CCM. In this work, we present a Laplace-Dirichlet-Rule-Based-Method (LDRBM), a particular class of RBMs, for generating myocardial whole heart fibers directly on full heart computational geometries. The methodology is straightforward and can be easily applied to any four-chambers models. The heart LDRBM includes a detailed myocardial fiber architecture and is able to quantitatively reproduce almost all the features of the different four-chambers, particularly those of the right ventricle and the atrial bundles.

Keywords: Cardiac fiber architecture, Fiber reconstruction, Finite element method, Laplace-Dirichlet-Rule-Based-Methods, Whole heart modeling.

1. INTRODUCTION

In cardiac computational models (CCM), a major issue consists in modeling the complex arrangement of myocardial fibers that characterizes the cardiac tissue. Aggregations of myofibers determine how the electric potential propagates within the muscle and also the mechanical contraction [Punske et al. (2005); Gil et al. (2019)]. This motivates the need to accurately include fiber orientations in order to obtain physically meaningful results.

Due to the difficulties of reconstructing cardiac muscle fibers from medical imaging [Toussaint et al. (2013)], a widely used strategy, for generating myofiber orientations in CCM, relies on the so-called *Rule-Based Methods* (RBMs) [Potse et al. (2006)].

Laplace-Dirichlet-Rule-Based Methods (LDRBMs) are the most used RBMs for prescribing ventricular fibers in CCM. LDRBMs, which rely on the solution of Laplace boundary-value problems, have been recently reviewed and analysed under a communal mathematical description [Piersanti et al. (2021)].

Regarding the atria, several RBMs have been developed, using either semi-automatic rule-based approaches [Fastl et al. (2018)], atlas-based methods [Roney et al. (2020)] or manually prescribing the atrial fiber orientations [Krueger et al. (2010)]. All the former procedures require manual intervention and often are designed for specific morphologies. Only recently, a LDRBM has been proposed for the atria [Piersanti et al. (2021)].

Prescribing the myofibers architecture is significantly more challenging in full heart geometries. Many of the existing four-chambers heart models embed only the ventricular fibers [Strocchi et al. (2020)], include simplified architecture for the atria [Land and Niederer (2018)] or adopt different RBMs for the ventricles and the atria [Gerach et al. (2021)]. To the best of our knowledge, none of whole heart computational studies makes use of a unique RBM to directly embed reliable and detailed cardiac myofiber architecture that takes into account different fiber orientations specific of the four chambers.

In this work we present a LDRBM for the generation of full heart myofibers architecture, that is able to reproduce all the important characteristic features of the four chambers, needed to provide a realistic cardiac musculature. Our newly developed method is built upon the combination of the ventricular and atrial LDRBMs presented in [Piersanti et al. (2021)] and on a novel definition of several inter-heart distances by means of Laplace problems.

2. METHODOLOGY

To properly represent the cardiac fiber architecture, throughout the whole heart computational domain, the heart LDRBM defines several inter-heart and intra-heart

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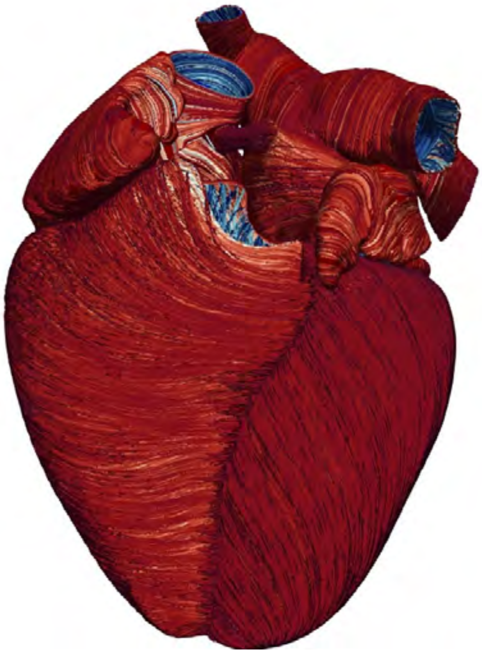

Fig. 1. Fiber generation, employing the full heart LDRBM, applied to the realistic Zygote Heart model.

distances, obtained by solving Laplace problems with specific Dirichlet boundary conditions on the heart boundaries. The inter-heart distances are used to define a transmural distance (from the endocardium to the epicardium), to discriminate the left from the right heart and the atria from the ventricles. Meanwhile, the intra-heart distances are computed to represent different atrial and ventricular distances, characteristic of the four chambers.

Afterwards, the heart LDRBM first sorts the atria from the ventricles. Then, it suitably combines the gradients of the inter-heart and intra-heart distances with the aim of defining an orthonormal local coordinate axial system in each nodal point of the heart computational domain. Finally, the reference frame is rotated with the purpose of defining the myofiber orientations.

3. RESULTS

The heart LDRBM has been applied to prescribe the whole heart muscular fiber architecture on the realistic 3D Zygote heart (see Figure 1), a CAD-model representing an average healthy human heart reconstructed from high-resolution Computed Tomography scan [Inc. (2014)]. As it is a very detailed geometry of the human heart, it demonstrates the applicability of the proposed methodology to arbitrary patient-specific scenarios.

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