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Patient-specific modeling for left ventricular mechanics using data-driven boundary energies

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Highlights

- Development of boundary conditions using patient-specific data.
- A systematic analysis of cardiac mechanics boundary conditions.
- Demonstration of efficacy for 6 patient-specific models.
- Novel quantitative comparison with non-invasive imaging data.

Abstract

Supported by the wide range of available medical data available, cardiac biomechanical modeling has exhibited significant potential to improve our understanding of heart function and to assisting in patient diagnosis and treatment. A critical step towards the development of accurate patient-specific models is the deployment of boundary conditions capable of integrating data into the model to enhance model fidelity. This step is often hindered by sparse or noisy data that, if applied directly, can introduce non-physiological forces and artifacts into the model. To address these issues, in this paper we propose novel boundary conditions which aim to balance the accurate use of data with physiological boundary forces and model outcomes through the use of data-derived boundary energies. The introduced techniques employ Lagrange multipliers, penalty methods and moment-based constraints to achieve robustness to data of varying quality and quantity. The proposed methods are compared with commonly used boundary conditions over an idealized left ventricle as well as over *in vivo* models, exhibiting significant improvement in model accuracy. The boundary conditions are also employed in *in vivo* full-cycle models of healthy and diseased hearts, demonstrating the ability of

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the proposed approaches to reproduce data-derived deformation and physiological boundary forces over a varied range of cardiac function.

Keywords: Cardiac mechanic; Patient-specific modeling; Patient-specific boundary conditions; Finite element method; Medical imaging

1. Introduction

Diagnostic medicine, medical imaging and novel therapies have rapidly improved patient outcomes across a wide range of heart conditions. While this has led to substantial progress, challenges in understanding (patho)physiology, improving patient diagnosis and therapy planning and designing the next generation of devices remain. Cardiac biomechanics provides a powerful tool for evaluating and predicting the complex behaviors of the heart and is increasingly playing an important role in translating physiologically based models towards strategies for understanding and treating heart failure [1–3]. A critical step in this effort is the ability to devise high fidelity computational biomechanical models that are capable of replicating cardiac function on a patient-by-patient basis.

Bolstered by continual improvements in cardiac biorheology, medical imaging and computational techniques, it is now possible to create high fidelity biophysical heart models [4–10]. Early studies in animal heart muscle [11–13] and more recent studies of human tissue [14] have enabled development of constitutive laws characterizing the anisotropic material behavior of the myocardium. Moving these excised tissue results into computational models was facilitated by descriptions of the laminar muscle structure, first determined from anatomical dissections [15] and more recently by diffusion tensor imaging [16,17]. Utilizing biomechanical models in the human heart has been enabled by medical imaging, capable of describing *in vivo* anatomy [18], detailed motion [19], blood flow [20] and even non-invasive estimates of pressure [21–23]. Exploitation of these patient data sources has been achieved through novel advancements in data assimilation [24,25,5] and parameter estimation techniques [10,26].

An important step towards translating biophysical heart models on a patient-by-patient basis is the personalization of cardiac function based on available data. A key challenge in this effort is the determination and handling of boundary conditions. Despite the importance of these conditions for correctly simulating the biomechanics of the heart, these effects are often less well-studied. Typical imaging – such as CINE or tagged MRI – can provide some guidance on motion [27,28]; however, this characterization can be incomplete or corrupted by noise. Use of this type of data also requires segmentation and image processing techniques that, in themselves, can introduce inaccuracies. Exploiting this data to drive computational biomechanical models in a manner which maintains model fidelity and minimizes modeling errors remains an open and important challenge.

Here we propose to address this issue by augmenting the traditional elastic energy potential minimization problem (commonly applied for cardiac biomechanics simulation) with a series of novel data-driven boundary energy terms. In this paper we focus on the isolated left ventricle (LV) (see Fig. 1)—commonly used in studies of cardiac biomechanics [29–32]. While lacking connection to other cardiac chambers, isolated LV models are often more straightforward to segment and characterize from medical imaging data, particularly MRI and ECHO. In addition, the LV is often the focus of heart failure studies due to the functional significance of its failure. Addressing boundary conditions on the LV, we develop tailored energy terms for each boundary component, focusing on the use of data available from non-invasive medical imaging. Through use of Lagrange multipliers, penalty variables and moment-based constraints, we devise terms which balance the use of real data with the energy required to force data-derived motion onto the computational model. These introduced techniques are then systematically compared with other common boundary conditions, highlighting their influence on simulation results as well as the benefits of the proposed approaches. Comparisons were carried out using an idealized LV mechanics model as well as patient-specific LV mechanics models based on data from 3 patients with dilated cardiomyopathy (DCM) as well as 3 volunteers. Efficacy of the proposed approach is demonstrated through direct quantitative comparisons between 3D displacement fields extracted from medical imaging data and simulation results.

The remainder of this paper is outlined as follows. A brief review of the LV cardiac mechanics model used is provided in Section 2. A summary of the elastic energy potential minimization approach is then presented in Section 3, followed by a description of the novel boundary energy potentials. An overview of the finite element implementation is