TOWARDS INTEGRATED NONINVASIVE PERSONALIZATION OF CARDIAC ELECTROMECHANICS

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ABSTRACT

Personalization of cardiac functions and properties from subject-specific noninvasive clinical observations has been an active area with increasing clinical significance. The personalized cardiac information can quantitatively reflect the pathophysiology of an individual heart and further be used to assist heart diagnosis and treatment planning. Due to the electromechanically integrated nature of the heart, it is important to use an integrative approach to elucidate cardiac functions and properties of a specific individual. In this paper, we first introduce our earlier works on noninvasive recovery of cardiac electrophysiology and cardiac mechanics from body surface potential maps (BSPMs) and medical image sequences, respectively. Recognizing BSPMs complements medical image sequences in providing insights into an individual heart, we present works on mechanics-guided personalization of cardiac electrophysiology and electrophysiology-driven personalization of cardiac mechanics. Furthermore, working towards using an integrative approach to elucidate a subject-specific cardiac system, we propose an integrated framework for noninvasive personalization of cardiac electromechanics by combining an integrated cardiac physiome model and multi-modality observations (BSPMs and medical image sequences).

Index Terms— Integrated cardiac physiome model, cardiac electromechanics, cardiac electrophysiology recovery, cardiac deformation recovery

1. INTRODUCTION

The heart is an electromechanically integrated organ that requires first to be electrically activated in order to contract. At the same time, cardiac electrophysiology experiences feedback from mechanical contraction [1]. This inter-dependent relationship determines that neither cardiac electrical function nor mechanical function alone can represent the whole heart behavior. In clinical practice, cardiac electrical and mechanical functions are typically evaluated separately. Cardiac electrical function is generally assessed by noninvasive body surface mapping (e.g. electrocardiogram (ECG) or BSPMs), which, as remote and integrative measurements of the entire electrical activity of the heart, lack the ability to provide quantitative information about the regional cardiac electrical activity. On the other hand, cardiac mechanical function is usually evaluated by medical imaging techniques, such as MRI, ultrasound, or CT. However, the imaging data is typically collected under sophisticated physical mechanisms, and thus they are usually noisy, incomplete and sparse. Furthermore, the data can not quantitatively reflect transmural myocardium mechanical activity.

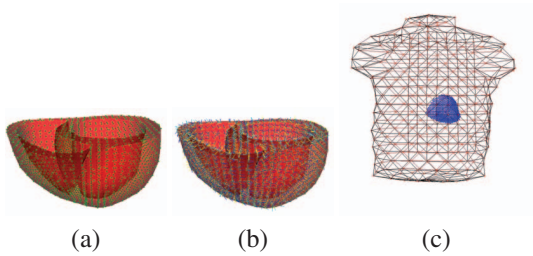
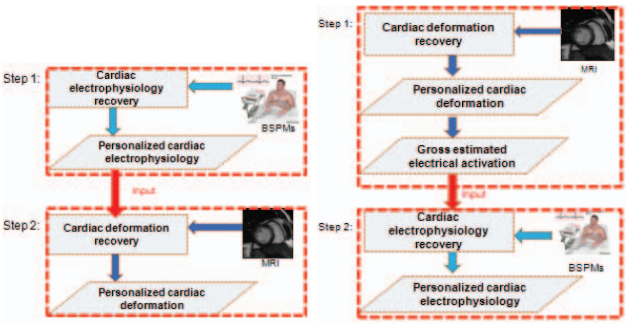


Fig. 1. (a) Heart geometry represented by nodes (green) bounded by heart surfaces (red). (b) Fibrous-sheet structure. (c) Coupled heart-torso structure.

Personalization of cardiac functions and properties from noninvasive clinical observations provides a way for quantitatively understanding the pathophysiology of an individual heart, which has been great of interest within cardiac research community [2, 3, 4, 5]. At the early stage, personalization of cardiac electrophysiology and cardiac mechanics are typically done separately. Model-constrained strategies for noninvasive volumetric imaging TMP dynamics from individual BSPMs have been introduced for studying cardiac electrical activity [2, 5]. On the other hand, model-constrained frameworks for noninvasive cardiac deformation recovery from subject-specific medical image sequences have also been proposed for studying cardiac mechanical behavior [6, 7, 8]. Although these noninvasive personalization techniques show promising results with experiments on clinical data [2, 6], they only consider either cardiac electrical function or mechanical function by ignoring the other.



(a) (b)

Fig. 2. (a) Electrophysiology-driven personalization of cardiac mechanics. (b) Mechanics-guided personalization of cardiac electrophysiology.

Recognizing BSPMs and medical image sequences can provide complementary information of an individual heart, we recently presented two frameworks for personalization of cardiac electrophysiology and mechanics: mechanics-guided personalization of cardiac electrophysiology (MGPCE) [9] and electrophysiology-guided personalization of cardiac mechanics (EGPCM) [3]. In MGPCE, gross cardiac electrical activation is estimated from personalized cardiac deformation and then be treated as a guide for cardiac electrophysiology personalization. In EGPCM, cardiac mechanics personalization is driven by personalized cardiac electrophysiology obtained from BSPMs. In these two frameworks, clinical observations of the heart from both BSPMs and medical image sequences are used, thus they can better characterize cardiac functions and properties. Delivering encouraging initial results, these two frameworks also limit in treating cardiac electrical and mechanical functions separately.

To overcome the limitations of our earlier works, currently, we are working towards an integrated framework for personalization of cardiac electromechanics from BSPMs and medical image sequences. In the framework, an integrated cardiac physiome model is utilized to provide *a priori* macroscopic description of the electromechanically integrated behavior of the heart, and also used as the central link between BSPMs and cardiac motion extracted from medical image sequences. A Bayesian *maximum a posteriori* estimation strategy is developed for estimation cardiac electromechanics from BSPMs and medical image sequences.

2. INTEGRATED PERSONALIZATION OF CARDIAC ELECTROMECHANICS

To personalize cardiac functions and properties of a specific individual, we need two major information sources available. On one side, noninvasive clinical observations of each individual provide subject-specific information about the functions of the heart for that particular individual. Because these observations are usually created under sophisticated physical mechanisms, and moreover are usually noisy, incomplete or sparse, understanding of them is likely to fall short of physiological plausibility without appropriate guidance or constraints. On the other side, physiological models from scientists and cardiologists can provide a general description of the mechanisms behind heart behaviors. Thus, cardiac information recovery strategies of combining a physiological model and various clinical observations has been widely used with cardiac research community [6, 5, 4, 2].

2.1. Integrated cardiac physiome model

Due to the electromechanically coupled nature of the heart, an integrated cardiac physiome model should comprise four components: cardiac electrophysiological model, electromechanical coupling, cardiac mechanical model and mechanoelectrical feedback [10]. Cardiac electrophysiology model details the spatiotemporal dynamics of cardiac electrical wave propagation. Electromechanical coupling determines active contraction stresses resulting in electrical activation. Cardiac mechanical model describes properties of the myocardium and the deformation related to the active contraction stresses. Cardiac mechanoelectrical feedback depicts the effect of mechanical activity on cardiac electrophysiology. Although models of different complexities are available [11, 12, 13, 4, 10], as our goal is to simulate macroscopic cardiac dynamics and connect to noninvasive clinical measurements, the models chosen should be detailed enough to include the macroscopic cardiac properties, but should not be too complicated that many parameters can not be determined using available knowledge or measurements. Following this spirit, we recently proposed an integrated cardiac physiome model in [14].

2.2. Representation of heart and torso structure

To perform individual cardiac analysis, a subject-specific heart and torso representation is required. Medical images like MRI can provide the boundaries of the heart and torso by using various image segmentation approaches [15, 16], based on which surfaces can be generated. A cloud of meshfree nodes is then placed within the heart surface to represent the 3D myocardium as in Fig.1(a). To describe myocardial conductive anisotropy, detailed ventricular fibrous-sheet structure are mapped from a mathematical model established in [17], which is depicted in Fig.1(b). Because the inhomogeneity of the torso has little impact on BSPMs pattern [2], we use boundary element method to represent the torso for the sake of computational efficiency. A coupled heart-torso structure is shown in Fig.1(c).

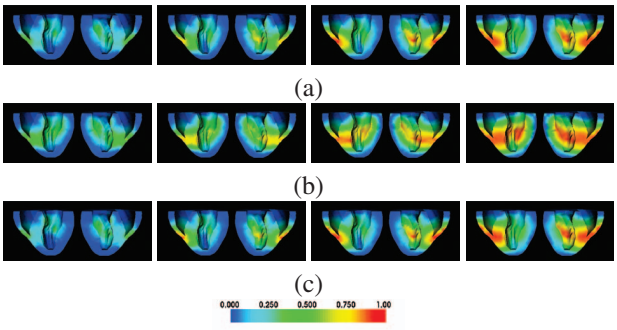


Fig. 3. Volumetric TMP activation in focal-arrhythmia caused by premature excitation. Left to right: depolarization at 7ms, 14ms, 21ms, 28ms. (a) True arrhythmic patterns. (b) Estimation using BSPMs alone [2]. (c) Estimation from mechanics-guided framework [9].

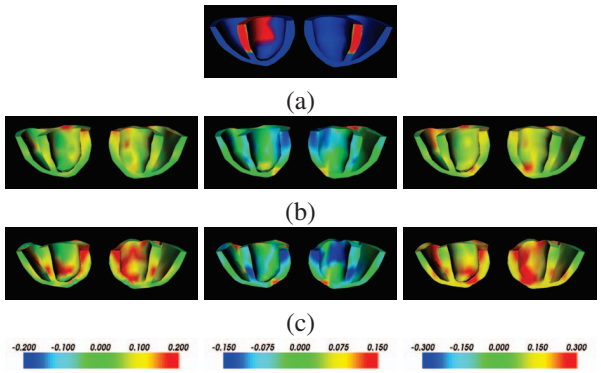


Fig. 4. Patient data. Strain maps at the end of systole (300ms), with red, blue, and green representing extension, contraction and no deformation respectively. Left to right: radial strain, circumferential strain, and first principal strain. (a) Gold standard. (b) Estimation using medical image sequence alone [6]. (d) Electrophysiology-driven [3].

2.3. Personalization of cardiac electrophysiology

To recover personalized cardiac electrophysiology, we presented an electrophysiological-model-constrained general Bayesian framework to noninvasively and directly map the spatiotemporal evolution of volumetric TMPs from BSPMs in [2], given heart-torso structure from tomographic images as in Fig.1 (c). Within this framework, the underlying cardiac electrophysiological system is carefully modeled and coupled to patient specific heart-torso model. The latent system dynamics is described as the spatiotemporal evolution of TMPs via Fitzhugh-Nagumo-like (FHN) reaction diffusion equations and related to body surface observations following the TMP-BSP projection model [2]. TMP mapping from initial phantom experiments on focal-arrhythmias are shown in Fig.3 (b). However, this work limits by ignoring cardiac mechanical activity.

2.4. Personalization of cardiac mechanics

Another direction of our past efforts is to recover cardiac deformation from subject-specific medical image sequences. To recover physiologically plausible subject-specific cardiac deformation from medical image sequences, we proposed a framework by coupling a cardiac physiome model with the motions of the cardiac boundaries extracted from the images [6]. This allows the *a priori* model and the observations to complement with each other under a multi-frame state space filtering framework. Fig.4 (b) show strain maps recovered from medical image sequences. The key shortcoming of this work is the electrical function of the heart is ignored.

2.5. Mechanics-guided personalization of cardiac electrophysiology

To enhance the reliability and subject specificity of the recovery results, different observation sources should be fused together. BSPMs provide integrative-projective electrical measurements on the body surface but not within the myocardium. Medical image sequences provide volumetric cardiac motion measurements, revealing the interactions between active contraction and passive mechanics, but these components are undistinguishable without extra electrical information. Furthermore, different from medical image sequences, BSPMs are spatially sparse but temporally dense. Therefore, BSPMs and medical image sequences provide partial but complementary measurements of the same electromechanical cardiac dynamics, thus their fusion is necessary for a more complete characterization of the subject-specific cardiac physiology and pathology.

Following this spirit, we presented a mechanics-guided cardiac electrophysiology personalization framework in [9]. In this framework, gross cardiac electrical activation is estimated from medical image sequences through empirical correlation between electrical activation and onsets of mechanical contraction, and then it is used as a guide for personalized cardiac electrophysiology recovery. The structure of the framework is shown as Fig.2 (b). Initial experiments on volumetric TMP imaging (Fig. 3 (c)) show encouraging results and significant improvements over previous efforts (Fig. 3(b)).

2.6. Electrophysiology-driven personalization of cardiac mechanics

We also presented a framework for cardiac deformation recovery by fusing subject-specific BSPMs and medical image sequences in [3]. In this framework, personalized TMPs is first estimated from BSPMs as in 2.3 and then used as an input to drive cardiac deformation recovery from medical image sequences as in 2.4. The structure of this framework is shown in Fig.2 (a). Compared to the framework in 2.4 by using sin-

gle clinical observation, the recovery results have significant improved as shown in Fig. 4 (c).

2.7. Integrated personalization of cardiac electromechanics

Although the frameworks in 2.5 and 2.6 have fused the information from BSPMs and medical image sequences which can better characterize an individual heart system than the frameworks using single information source, cardiac electrical and mechanical functions are still treated separately. Currently, we are working towards an integrated framework for noninvasive personalization of cardiac electromechanics. To realize it, an integrated cardiac physiome model proposed in [14] is utilized to provide *a priori* macroscopic description of the cardiac system. Based on this model, the relationship between volumetric TMP and BSPMs as well as the relationship between heart displacements and cardiac motion extracted from medical image sequences can be established. In other words, the integrated cardiac physiome model acts as a central link between multi-modality clinical measurements. To take both model and measurement uncertainties into account, the cardiac system is reformulated into a state space formulation. We have adopted a Bayesian *maximum a posteriori* estimation approach for recovering subject-specific cardiac electromechanics and clinical interested model parameters, such as excitability and elasticity, from multi-modality measurements (BSPMs and medical image sequences).

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