Fast parameter calibration of a cardiac electromechanical model from medical images based on the unscented transform

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Abstract Patient-specific cardiac modelling can help in understanding pathophysiology and predict therapy planning. However, it requires to personalize the model geometry, kinematics, electrophysiology and mechanics. Calibration aims at providing proper initial values of parameters before performing the personalization stage which involves solving an inverse problem. We propose a fast automatic calibration method of the mechanical parameters of a complete electromechanical model of the heart based on a sensitivity analysis and the Unscented Transform algorithm. A new implementation of the complete Bestel–Clement–Sorine (BCS) cardiac model is also proposed, in a modular and efficient framework. A complete sensitivity analysis is performed that reveals which observations on the volume evolution are significant to characterize the global behaviour of the myocardium. We show that the calibration method gives satisfying results by optimizing up to 5 parameters of the BCS model in only one iteration. This method was evaluated synthetically as well as on 7 volunteers with a mean relative error from the real data of 10%. This calibration is designed to replace manual parameter estimation as well as initialization steps that precede automatic personalization algorithms based on images.

Keywords Computer model · Cardiac mechanics · Parameter calibration · Medical images · Unscented transform

1 Introduction

The clinical understanding and treatment of cardiovascular diseases is highly complex and includes a wide range of therapies: from drug therapy to radiofrequency ablation (RFA) aiming at reducing ventricular tachycardia (VT) or atrial fibrillation (AF), also including cardiac resynchronization therapy (CRT) aiming at relieving heart failure (HF) symptoms with the implantation of pacemaker leads (Smith et al. 2011). Optimizing the leads configuration, selecting suitable patients and estimating regions to be ablated are difficulties that face the cardiologists for each patient. In order to provide additional guidance to cardiologists, many research groups are investigating the possibility to plan such therapies based on biophysical models of the heart (Kerckhoffs 2010). The hypothesis is that one may combine anatomical and functional data to build patient-specific cardiac models that could have the potential to predict the benefit of the therapies. Cardiac electromechanical simulations are based on computational models that can represent the heart geometry, motion and electrophysiology patterns during a cardiac cycle with sufficient accuracy. Integration of anatomical, mechanical and electrophysiological information for a given subject is essential to build such models.

Several approaches for the past 20 years have been developed to describe and simulate cardiac function, including cardiac mechanics and electrophysiology (Humphrey et al. 1990; Hunter et al. 1997; Nash 1998; Bestel et al. 2001; Sachse 2004). They differ in their choice of hyperelastic material, electrophysiological properties or electromechanical coupling. In this paper, the Bestel–Clement–Sorine (BCS) model (Bestel et al. 2001), further improved by Chapelle et al. (2012), is used for its consistency with thermodynamical requirements in its continuous as well as in its discrete form (Sainte-Marie et al. 2006). Moreover, it has demonstrated a
good predictive power under different pacing conditions in terms of haemodynamics (Sermesant et al. 2012).

The simulation becomes patient-specific after several levels of personalization: geometrical (a computational mesh is built from patient-specific anatomical images (see Fig. 1), kinematic (the motion of the cardiac structure is estimated from cine-MR images (McLeod et al. 2012; Sermesant et al. 2006), electrophysiological (the depolarization and repolarization times are extracted from electrocardiograms (Relan et al. 2011) and mechanical. The focus of this paper is on the latter personalization level, which consists in optimizing mechanical parameters of the model so that the simulation behaves in accordance with patient-specific data sets (images and other signals).

This inverse problem has been tackled by different authors. For instance, Xi et al. (2011) and Liu and Shi (2009) estimate the passive material stiffness with data assimilation methods, while (Wang et al. 2009) use sequential quadratic programming. Moireau and Chapelle (2011) as well as (Chabiniok et al. 2011) estimate the contractility parameters using Reduced Unscented Kalman Filtering. Sundar et al. (2009) and Delingette et al. (2012) rather use adjoint data assimilation methods.

All these methods are time consuming since they require an important number of simulations. Moreover, there is no guarantee that such algorithms converge toward a relevant solution due to their dependence on initial range of parameter values since it is often necessary to be close to the solution for the algorithm to converge toward the global minimum. The choice of the parameters to estimate and their initial calibration have, therefore, great impact for the personalization.

Our main contribution tackles this initialization issue: we propose a simple and efficient method to automatically calibrate the parameters from the ventricular volume evolution over the cardiac cycle. It has been applied successfully for the calibration of mechanical parameters from 7 healthy cases. Our proposed method is based on the Unscented Transform algorithm and requires only one iteration with multiple simulations performed in parallel for calibrating typically 4 or 5 parameters selected from a sensitivity analysis.

Our approach remains tractable (computational time around 20 min for a tetrahedral mesh of 80,000 elements) due to a novel and efficient implementation of the BCS model in the interactive framework SOFA\(^1\). It also includes the changes of cardiac phases through a valve model and takes into account the mechanical effect of the pericardial sac.

2 Materials and methods

2.1 Data acquisition

We demonstrate the application of the proposed method on cardiac MRI data, including both SSFP sequence for anatomical description and cine-MRI for motion tracking. Data were acquired at the Division of Imaging Sciences & Biomedical Engineering at King’s College London, UK, as part of studies that were ethically approved.

2.1.1 Volunteer study

This study includes an extensive multi-modality imaging of volunteers from which seven healthy cases were used. All data sets consist of sequences of 4D cine-MRI with a spatial resolution of approximately \(1.5 \times 1.5 \times 7 \text{ mm}^3\) and a temporal resolution of around 30 ms (30 images per cardiac cycle) that cover the ventricles entirely. Volunteers were aged 28 ± 5 years and supposed to be without clinical history of cardiac diseases. This data set was made available to the research community for the STACOM’2011 challenge, see Tobon-Gomez et al. (2011) for details regarding the data acquisition of this study.

2.1.2 Clinical data pre-processing

Three different steps are needed before any mechanical personalization can be performed: extraction of the myocardium geometry, estimation of the patient’s cardiac motion and personalization of the electrophysiological propagation.

Geometry personalization

To personalize the geometry from images, we used Philips automatic cardiac segmentation (Ecabert et al. 2011) in

\(^1\) SOFA is an Open Source medical simulation software available at www.sofa-framework.org.