Interactive Electromechanical Model of the Heart for Patient-Specific Therapy Planning and Training using SOFA

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Hugo Talbot[a,b], Stéphanie Marchesseau[b], Christian Duriez[a], Hadrien Courtecuisse[a], Jatin Relan[b], Maxime Sermesant[b], Stéphane Cotin[a], Hervé Delingette[b]

[a]*Shacra Team, Inria Lille - North Europe, France*
[b]*Asclepios Team, Inria Sophia Antipolis - Méditerranée, France*

1. Introduction

Simulating and personalizing electromechanical models of the heart can help in the training of cardiologists, as well as in planning the therapies and understanding the pathologies. We present here an interactive implementation of an organ-scale model of the heart with two applications: training for catheter ablation of cardiac arrhythmia and planning of cardiac resynchronisation therapy.

Cardiac arrhythmia is a very frequent pathology that comes from an abnormal electrical activity in the myocardium. Catheter thermo-ablation is a minimally invasive technique preventing such arrhythmias by removing the substrate or the trigger responsible for the cardiac dysfunction. Because of the ageing population, the number of patients suffering from arrhythmias is steadily increasing. Moreover this procedure requires highly skilled and experienced cardiologists. Therefore, the development of new training tools is required, and computer-based simulators can provide a good environment for this. To develop such a simulator, one important missing step is the ability to simulate the electrophysiology and the mechanical behaviour of the heart in real-time.

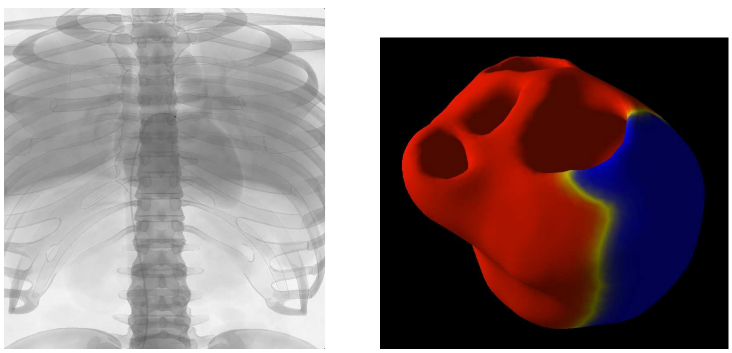
On the other hand, Cardiac Resynchronization Therapy (CRT) relieves Heart Failure (HF) symptoms with the implantation of a pacemaker that reduces heart dyssynchrony. However 30% of patients are non-responders to the therapy due the difficulties in configuring the pacemaker and selecting the patient. Many research groups (see for instance [1]) are investigating model-based solutions to tackle this significant issue for the clinical community. The hypothesis is that we can combine the anatomical and functional data to build patient-specific cardiac models that would have the potential to predict the therapy effects.

The contributions of this work are twofold. First, we developed an electrophysiological training simulator in SOFA which tackles the interactive issue in the context of cardiac arrhythmias. Coupled with this electrophysiology, we developed a mechanical model of the heart that can be personalized from MRI datasets.

Our simulations are based on the SOFA platform[1]. SOFA is an open-source framework targeted at real-time simulation with an emphasis on medical simulation, mainly developed at Inria. A large choice of efficient solvers, hyperelastic or viscous material laws are already implemented in SOFA. Moreover, it enables interactivity during the simulation (pacing, surgery planning, ...) and gives a good trade-off between accuracy and computational efficiency.

2. Interactive Simulation of Cardiac Electrophysiology

We focus here on the training of cardiologists for the catheter-based ablation of cardiac tissues in the context of cardiac arrhythmias (see Fig. 1b). Our cardiac computations are based on the finite-element method. SOFA already enables the simulation of catheter navigation. In our simulation, we compute the navigation of a catheter inside the venous system from the femoral vein to the right atrium.



(a) Simulated catheter navigation with synthetic X-Ray rendering.

(b) Depolarization wave propagating inside the cardiac geometry.

Figure 1: Simulation of catheter navigation and cardiac electrophysiology in SOFA.

In our work, we chose the Mitchell Schaeffer (MS) model [2] to simulate electrophysiology since it provides a very good estimation of the transmembrane potential while computationally tractable for personalisation. We personalized the parameters of the MS model to fit patient-specific data [3].

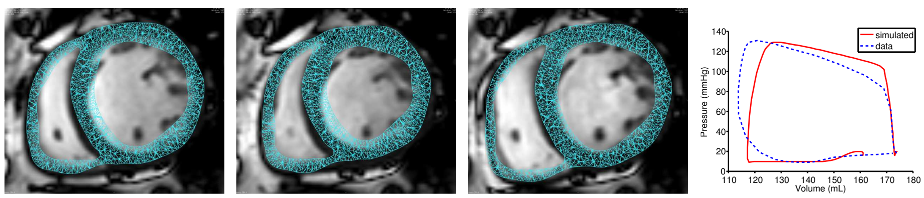
Targeting real-time computations is very challenging due to the stiffness of the equations involved. In order to use larger time steps, we first propose an adaptive parametrisation of the Mitchell-Schaeffer model to fit patient data. Second, a GPU implementation of the electrophysiology has been performed to decrease the computation time using recent methods [4]. These optimizations allowed us to reach computations less than 3 times slower than real-time, thus

[1]http://www.sofa-framework.org

making our simulation interactive. Same computations performed on CPU was at least 10 times slower than our GPU version.

Our simulation already enables the cardiology trainee to virtually stimulate any region of the heart. Such electrical stimulation are usually carried out to establish a definitive diagnosis before a thermo-ablation. Furthermore, the electrophysiological model can simulate thermo-ablation and the resulting electrophysiology. To do so, the factorized matrix of the system needs to be updated when ablating.

3. Patient-Specific Simulation of Cardiac Electromechanics



(a) t = 190 ms (b) t = 410 ms (c) t = 720 ms (d) PV loop

Figure 2: (Left) Short axis view of the simulated mesh overlaid on the MRI at different times of the cardiac cycle (heart period = 870 ms) on a pathological heart. (Right) Resulting Pressure-Volume loop.

The Bestel-Clément-Sorine [5] electromechanical model of the heart has been implemented in SOFA. It contains an hyperelastic component to account for the myocardium elasticity, implemented using optimized finite-element methods [6], as well as an active part that deals with the contraction of the sarcomere. This active part uses the electrical potentials described previously as inputs for the mechanical contraction force. The model includes also viscous and elastic components to better characterize the fibre isotony during the deformation. Finally, the blood flow that circulates in the ventricles is also modelled globally using a constraint formulation. Efficient and interactive simulations were made possible thanks to the adoption of the simulation platform SOFA. Real-time simulations could not yet be reached but the computation time (about 10 minutes for one cardiac cycle) being reasonably small, a large set of personalization algorithms can be used on this implementation.

The authors developed a first calibration algorithm that enables to match the volume and pressure curves while estimating 7 parameters out of the 14 parameters of the complete Bestel-Clément-Sorine model. An example of the resulting deformation overlapped with the MR images during a cardiac cycle is shown Fig. 2.

4. Conclusion

In this paper, we presented our simulation environment based on the open-source framework SOFA for an interactive electromechanical model of the heart.

Our new performance results computing the cardiac electrophysiology have been detailed. Thanks to model optimizations and an efficient GPU implementation, we reached an interactive simulation close to real-time based on 3D patient-specific data. This first result is very encouraging regarding the development of our training simulator. Furthermore, first electromechanical personalization results were presented and proved that the now available model can fit MRI data in the context of patient-specfic therapy planning.

Such frameworks can open new possibilities in using computer models in the training of physicians as well as in the planning of therapies.

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