Mechanical Imaging of Dynamic Patient Stress Patterns

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INTRODUCTION Abnormal stresses are hypothesized to be a key driver in remodelling processes associated with heart failure [4]. However, it is currently impossible to measure stresses safely *in vivo* in a human heart. This necessitates the use of computational models in cardiac stress calculation.

A key step to making simulated stresses useful for clinical practice is patient specificity. This means that the simulated stresses should come from a computational model that has been calibrated to behave in the same way as a patient's heart. Doing this typically involves first creating a patient specific geometry, and then using available clinical data to personalize the mechanics of a computational model.

One source of mechanical data that is currently available is dynamic left ventricular strain, which can be obtained cheaply and efficiently using 4D echocardiography methods. In our study, we combine such strain data with left ventricular pressure and volume measurements in order to match simulated bi-ventricular mechanics to those observed in the ventricles of a patient.

DATA COLLECTION The data used in our study were collected at the Oslo University Hospital from 8 patients suffering from heart failure. 4-D ultrasound images were obtained for each patient. Based on these images left ventricular volumes and strains were estimated for each point in the cardiac cycle. The estimated strains were specified as segment averages, using the 17 segment American Society of Echocardiography (ASE) [3] partitioning of the heart as shown in Figure 2. Left ventricular pressure data were obtained invasively by catheterization of each patient during later surgery.

MECHANICS MODELLING In order to model the diastolic motion of the ventricle walls, we consider the passive elasticity as the main physical effect. We model this elasticity by using an invariant based strain energy function [2] which we embed in an incompressible finite element framework. This strain energy is given by

$$\psi(\overline{\mathbf{C}},\mathbf{m}) = \frac{a}{2b}\left(\exp\left[b(I_1(\overline{\mathbf{C}})-3)\right]-1\right) + \frac{a_f}{b_f}h(I_{4f})\left(\exp\left[b_f(I_{4f}(\overline{\mathbf{C}})-1)^2\right]-1\right) \tag{1}$$

Here $\overline{\mathbf{C}} = J^{-\frac{2}{3}}\mathbf{C}$ is a modified Cauchy-Green strain; I_1, I_{4f} are mechanical invariants; h a Heaviside step function, and $\mathbf{m} = (a, b, a_f, b_f)$ are patient specific material parameters that we are interested in estimating.

PARAMETER ESTIMATION In order to customize the mechanics of the mathematical model to a set of patient data, we consider the following optimization problem:

$$\min_{\mathbf{m},\gamma} I(\mathbf{u},\mathbf{m},p_i,V_i,\varepsilon_i) \tag{2}$$

where

$$I = \sum_i \left[\sum_{j=1}^{17}\sum_{k\in c,l,r}\left(\varepsilon_i^{k,j} - \int_{\Omega_j} e_k^T \nabla\mathbf{u}\cdot e_k \, dx\right)^2\right] + \alpha\left(\frac{1}{3}\int_{\partial\Omega_{\text{endo}}}(\text{id}+\mathbf{u})\cdot JF^{-T}N \, dS - V_i\right)^2. \tag{3}$$

Here Ω_j is a 3-d segment of the computational mesh, $\partial\Omega_{\text{endo}}$ the left ventriculat endocardial surface, $\mathbf{u}(m,p_i)$ the displacement field, p_i the measured endocardial pressure, V_i the measured cavity volume, $\varepsilon_i^{k,j}$ a measured strain, and α a parameter to control the weight given to the volume matching in the functional.

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Furthermore i denotes the index of a point in time in the cardiac cycle, and j denotes the index of one of the 17 ASE segments. Finally the index k refers to the circumferential, longitudinal the radial directions; $\{c, l, r\}$, used by the echo scanner. The complete optimization problem is solved iteratively by a gradient based algorithm, L-BFGS-B [5]. The necessary gradient information is provided by an automatically derived adjoint solver [1].

PRELIMINARY RESULTS In Figure 1, we show the fiber direction component of the Cauchy stress field in a patient specific geometry, generated using a chosen set of material parameter values (not yet optimized), and patient specific diastolic pressure measurements.

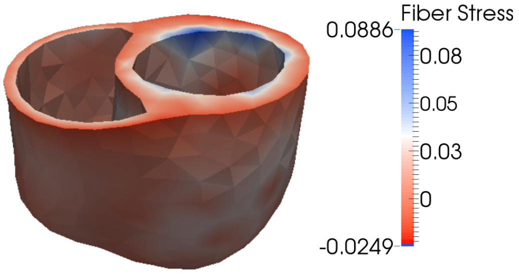

Figure 1: Simulated fiber stress in a patient specific bi-ventricular geometry.

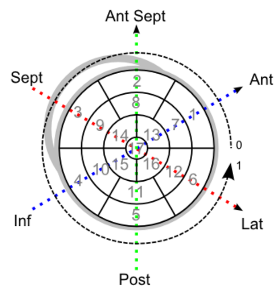

Figure 2: 17 segment division of the left ventricle according to the ASE standard.

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