Mechanical Imaging of Dynamic Patient Stress Patterns

Henrik N. Finsberg[1,2], Gabriel Balaban[1,2], Joakim Sundnes[1,2], Hans Henrik Odland[3], Marie Rognes[1,2], and Samuel T. Wall[1]

[1]Simula Research Laboratory, Fornebu, Norway
[2]University of Oslo, Oslo, Norway
[3]Oslo University Hospital, Oslo, Norway

INTRODUCTION Abnormal stresses are hypothesized to be a key driver in remodelling processes associated with heart failure [7]. 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. We formulate this matching as a mathematical optimization problem in which the least squares difference between simulated and measured strains and volumes is minimized. This minimization is carried out using a gradient based optimization algorithm and an automatically derived adjoint equation. As a result, we obtain patient specific stress maps that can be used to improve the treatment of cardiac conditions in which stress plays a significant role.

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) [6] partitioning of the heart as shown in Figure 2. Left ventricular pressure data were obtained invasively by catheterization of each patient during later surgery. The pressure and volume data has been synchronized in order to produce a pressure volume loop for each patient.

Triangulated point clouds for the left ventricular endocardial and the epicardial surfaces were extracted from the echo images. An artficial right ventricle has been generated for each patient by using an in house algorithm. For each patient a computational mesh has been made using the space between the left and right ventricular surfaces [3], and rule-based fiber fields have been generated [1].

MECHANICS MODELLING In order to model the motion of the ventricle walls, we consider the passive elasticity and active contraction in the fibers as the main physical effects. For the passive elasticity we make use of an transversely isotropic version of an invariant based strain energy function [5]. This strain energy density 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.

In order to model the active contraction in the muscle fibers, we make use of an active strain decomposition. This decomposition is given by the relation

$$\mathbf{F} = \mathbf{F_a}\mathbf{F_e} \tag{2}$$

The first two authors contributed equally to this work.

where $\mathbf{F_a}$ and $\mathbf{F_e}$ represent the active and passive parts of the deformation gradient $\mathbf{F}$. We model the active strain as [4]

$$\mathbf{F}_a = (1-\gamma)\mathbf{f}\otimes\mathbf{f} + \frac{1}{\sqrt{1-\gamma}}(\mathbf{I}-\mathbf{f}\otimes\mathbf{f}). \tag{3}$$

In order to accurately represent systolic fiber shortening we allow different values of γ for each of the 17 ASE segments, and allow all of the γ's to vary independently in time throughout systole.

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

$$\min_{\mathbf{m},\gamma} I(\mathbf{u},\mathbf{m},\gamma,p_i,V_i,\varepsilon_i) \tag{4}$$

where

$$I = \sum_i \left[\sum_{j=1}^{17} \sum_{k\in c,l,r} \left(\varepsilon_i^{k,j} - \int_{\Omega_j} e_k^T \nabla\mathbf{u}\cdot e_k \, dx \right)^2 \right] + \alpha \left(\frac{1}{3} \int_{\partial\Omega_{\text{endo}}} (\mathrm{id}+\mathbf{u})\cdot JF^{-T} N \, dS - V_i \right)^2. \tag{5}$$

Here Ω_j is a 3-d segment of the computational mesh, $\mathbf{u}$ the displacement field, $\mathbf{m}$ the material parameters as before, 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. 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, (clr), used by the echo scanner. The complete optimization problem is solved iteratively by a gradient based algorithm, L-BFGS-B [8]. The necessary gradient information is provided by an automatically derived adjoint solver [2].

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, and patient specific diastolic pressure measurements. Current work is focused on incorporating optimized $\mathbf{m}$ and γ values in order to calculate stress.

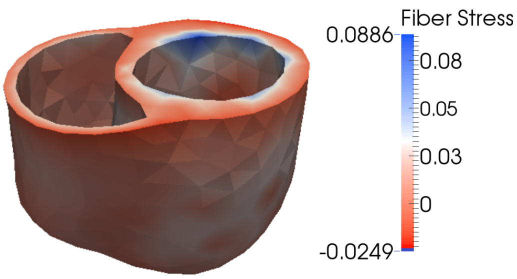

Figure 1: Simulated fiber stress in a patient specific bi-ventricular geometry.

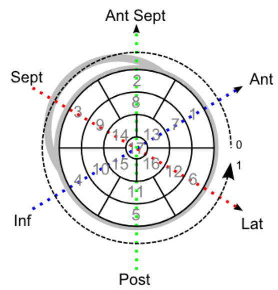

Figure 2: 17 segment division of the left ventricle according to the ASE standard.

ACKNOWLEDGEMENTS The authors gratefully acknowledge the support of the Research Council of Norway via grants given to the Center for Cardiological Innovation and Center of Biomedical Computing.

References

[1] JD Bayer, RC Blake, G Plank, and NA Trayanova. A novel rule-based algorithm for assigning myocardial fiber orientation to computational heart models. *Annals of biomedical engineering*, 40(10):2243–2254, 2012.

[2] Patrick E Farrell, David A Ham, Simon W Funke, and Marie E Rognes. Automated derivation of the adjoint of high-level transient finite element programs. *SIAM Journal on Scientific Computing*, 35(4):C369–C393, 2013.

[3] Christophe Geuzaine and Jean-François Remacle. Gmsh: A 3-d finite element mesh generator with built-in pre-and post-processing facilities. *International Journal for Numerical Methods in Engineering*, 79(11):1309–1331, 2009.

[4] Sjur Gjerald, Johan Hake, Simone Pezzuto, Joakim Sundnes, and Samuel T Wall. Patient–specific parameter estimation for a transversely isotropic active strain model of left ventricular mechanics. In *Statistical Atlases and Computational Models of the Heart-Imaging and Modelling Challenges*, pages 93–104. Springer, 2015.

[5] Gerhard a Holzapfel and Ray W Ogden. Constitutive modelling of passive myocardium: a structurally based framework for material characterization. *Philosophical transactions. Series A, Mathematical, physical, and engineering sciences*, 367(1902):3445–75, sep 2009.

[6] Roberto M Lang, Michelle Bierig, Richard B Devereux, Frank A Flachskampf, Elyse Foster, Patricia A Pellikka, Michael H Picard, Mary J Roman, James Seward, Jack S Shanewise, et al. Recommendations for chamber quantification: a report from the american society of echocardiography's guidelines and standards committee and the chamber quantification writing group, developed in conjunction with the european association of echocardiography, a branch of the european society of cardiology. *Journal of the American Society of Echocardiography*, 18(12):1440–1463, 2005.

[7] Cindy Ruwhof and Arnoud van der Laarse. Mechanical stress-induced cardiac hypertrophy: mechanisms and signal transduction pathways. *Cardiovascular research*, 47(1):23–37, 2000.

[8] Ciyou Zhu, Richard H Byrd, Peihuang Lu, and Jorge Nocedal. Algorithm 778: L-bfgs-b: Fortran subroutines for large-scale bound-constrained optimization. *ACM Transactions on Mathematical Software (TOMS)*, 23(4):550–560, 1997.