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EWE: Toward electro-mechanical cardiac simulations with MOOSE

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We present the software framework EWE, which is designed for coupled electromechanical simulations in computational cardiology. EWE is build on the multi-physics framework MOOSE. Numerical simulations of coupled problems on an idealized geometry for a left ventricle are shown.

1 Introduction

In-silico modelling of cardiac activity has become an important tool for understanding and treating many different forms of heart disease. Multiple software packages exist that are focussed on numerical simulations of the heart, a recent review is given in [1]. In the framework of the *Center for Computational Medicine in Cardiology* [2], efforts are ongoing to develop an implementation named EWE, tailored to cardiac simulations within the general-purpose finite element framework MOOSE, see e.g. [3] and [4]. Here, a brief summary of the model EWE is given and some preliminary results are shown.

2 Model

In the current state, EWE features a) a model for the electric activity of the heart based on the mono-domain equation

$$\partial_t V = \frac{1}{\chi}\nabla\cdot(\mathbf{G}_{\text{mono}}\nabla V) - I_{\text{ion}}(s,V) + I_{\text{app}} \tag{1a}$$

$$\partial_t s = f(s,V) \tag{1b}$$

for the membrane potential V. Here, χ is the surface-to-volume ratio, $\mathbf{G}_{\text{mono}}$ the conductivity tensor and I_{app} some externally applied current. For the gating variables s, their temporal evolution given by f and the generated current I_{ion}, the model by Bernus et al. [5] is implemented. However, EWE features an abstract interface that allows to employ other cell models later on, if needed. Furthermore, EWE provides b) an implementation for a nonlinear incompressible elastic problem of the form

$$\rho_0\frac{\partial \mathbf{x}}{\partial t^2} = \nabla\cdot(\mathbf{FT}) \tag{2}$$

where $\mathbf{P} = \mathbf{FT}$ is the 1st Piola-Kirchhoff stress tensor, see e.g. [6] for a general introduction into the topic. Finally, there exists c) a coupling between the electrical and mechanical part based on the active-strain model by [7]. Here, an additional ODE

$$\frac{\partial T_\alpha}{\partial t} = \varepsilon\left(V(t)\right)\left(k_{T_\alpha}V(t) - T_\alpha\right) \tag{3}$$

with

$$\epsilon(V(t)) = \begin{cases} 0.01 & \text{for} \quad V(t) < 0.05, \\ 0.04 & \text{for} \quad V(t) \geq 0.05 \end{cases}, \qquad k_{T_a} = 47.9\,\text{kPa}$$

is solved at each mesh point to generate a strain T_α from the membrane potential V. Figure 1 shows a single cell simulation of two activation cycles of the Bernus model, the membrane potential (red) and the resulting tension T_α (blue). A graphical representation of the different components of EWE and their interaction is given in Figure 2.

All the functionality above is implemented by deriving from C++ base classes provided by the MOOSE framework. The diffusion term in (1a) e.g. is derived from a so-called *Kernel*, which represents a term in the equation to be solved. The ion channel model provides a forcing term, also derived from a *Kernel*, but the gating variables are stored in a class derived from *Material*. A detailed description will be made available in the documentation for EWE.

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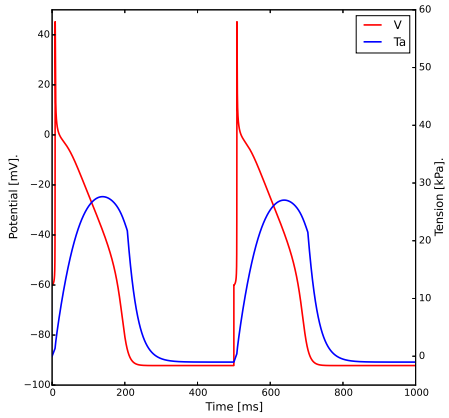

Fig. 1 Single cell simulation with the Bernus model. The red line is the membrane potential generated by the model, the blue line is the tension generated from the potential through.

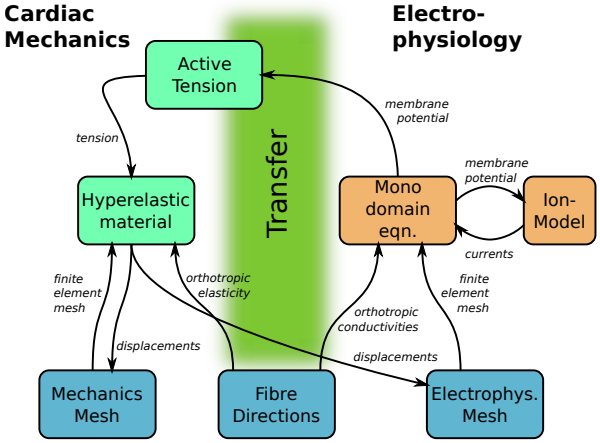

Fig. 2 Sketch of the different components in EWE and their interaction.

3 Results

In order to illustrate some of the current capacity of EWE, preliminary results for a short-term coupled electro-mechanical simulation on a highly idealized ventricle geometry are shown. At this stage, no effort is made to choose physiologically realistic parameters. In particular, the simulation does not feature a proper representation of fibre directions and employs a uniform conductivity tensor. An initial stimulus I_{app} is applied for 5ms in a small region at the upper boundary of the geometry (marked by the grey dot in Figure 3). The stimulus triggers an activation wave propagating around and down the "ventricle" (left). Through the coupling modeled by (3), the potential generates active tensions (right) that cause deformations of the domain – although here they are too small to be noticeable in the geometry in Figure 3.

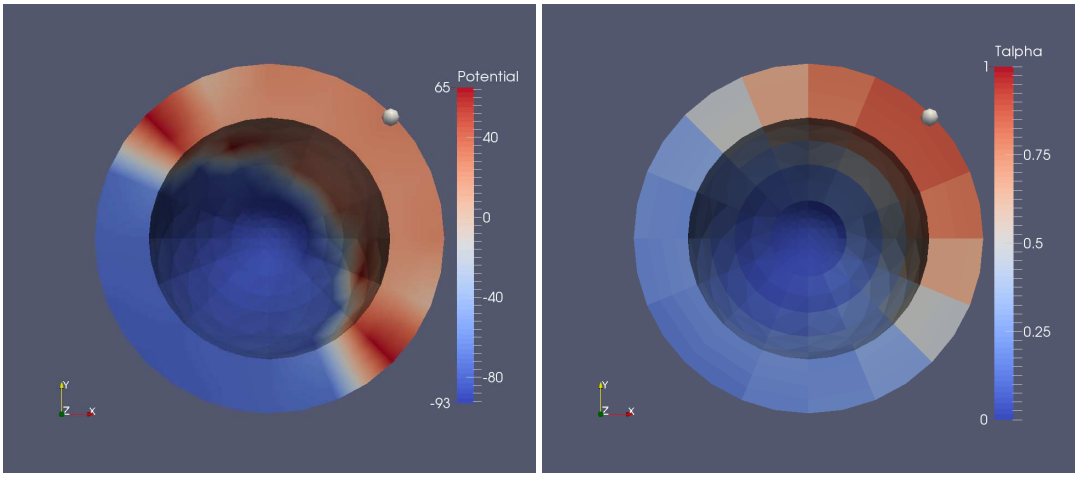

Fig. 3 Membrane potential (left) and generated active tension T_α (right) simulated with EWE on an idealized ventricle geometry. The point indicates the position of the initial stimulation triggering the activation.

References

[1] A. Lopez-Perez, S. Rafael, and J. M. Ferrero, BioMedical Engineering OnLine pp. 14–35 (2015).
[2] Center for computational medicine in cardiology, http://ccmc.usi.ch/, Accessed: 2015-05-14.
[3] D. Gaston, C. Newman, G. Hansen, and D. Lebrun-Grandié, Nuclear Engineering and Design **239**(10), 1768–1778 (2009).
[4] Moose, http://mooseframework.org/, Accessed: 2015-04-30.
[5] O. Bernus, R. Wilders, C. W. Zemlin, H. Verschelde, and A. V. Panfilov, American Journal of Physiology – Heart and Circulatory Physiology **282**(6), H2296–308 (2002).
[6] G. A. Holzapfel and R. W. Ogden, Philosophical transactions. Series A, Mathematical, Physical, and Engineering Sciences **367**(1902), 3445–75 (2009).
[7] M. P. Nash and P. J. Hunter, Journal of Elasticity and the Physical Science of Solids **61**(1-3), 113–141 (2000).