LHP Report

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DISCLAIMER: This document only serves as an initial introduction on how to use the LHP model and should be used along with the companion documents [1],[2]. The idea is that with further use and contributions from team members this document can grow to be a comprehensive user documentation.

INTRODUCTION

The living heart project is in effect a simulation setup on Abaqus, with 2 components mainly a comprehensive Geometry of the Heart as well as a default 1 beat setup for the electrical followed by 3 beats in the mechanical simulation with associated boundary conditions, steps, meshes, assemblies, etc all using Standard/Explicit abaqus features.

What follows is a an overview of the underlying model components as and where how they are represented in Abaqus. Then finally, a discussion on the current state and future goals of the ahc team for the lhp project.

THEORY

Here I am referring to equations outlined in /cite, with their relevant parameters and their default values. I am avoiding the derivations and focusing on the final form which contains the parameters. [2]

Equations **(5)** describe the balance equations for the electrical potential and the balance of linear momentum for the deformation. Parameters: None

Electrical Model:

1. Equation **(6)** for the electrical flux proportional to the gradient of the electrical field multiplied by the Conductivity Tensor. Parameters: d_{iso} *(isotropic contribution of conductivity tensor),* d_{ani} *(anisotropic)*
2. Equation **(7)** is for the transmembrane current. Parameters: c, α *(controlling fast upstroke potential),* r *(recovery variable that controls the slow repolarization).*
3. Equation **(8)** considers the evolution of the recovery variable r. Parameters: $\gamma, \beta, u1, u2$ *(control the restitution behaviour).*

Mechanical Model*:*

1. Equations **(9),(10)** describe the passive and active tissue stress contribution of the heart muscles. Parameters: $k\ (bulk\ modulus),\ a, b, a_{ff}, b_{ff}, a_{fs}.b_{fs}$ *(parameters of the orthotropic holzapfel model),* v_{ff}, v_{fs} *(weighing factors for active stress generation).*
2. Equation **(11)** describes the behaviour of active muscle traction as a function of changes in the **electric potential** and this is where the coupling between the electrical and mechanical is formulated. Parameters: $k_T,\ \phi_r$ *(control the maximum active force and the resting potential),* $\varepsilon(\phi)$ *(the activation function that ensures a smooth activation of the active muscle traction)*

Fluid Model:

The blood fluid dynamics is modeled as a fluid exchange relation in Abaqus with a linear relation between pressure and volume and the valvular resistance is modeled as a constant resistance to flow which controls the flow rate as follows.

$$q_{c \to c+1} = \frac{p_c - p_{c+1}}{R_{c \to c+1}},$$

$$\dot{V}_c = q_{c-1 \to c} - q_{c \to c+1}$$

Where q_c is the flow rate between two chambers is composed of p_c the pressure difference between the chambers scaled by R_c is the Windkessel type resistance from the valves or external circulation systems and $\dot{V}c$ is the corresponding change volume in the chambers is defined the difference between the influx and outflux rates.

LITERATURE PARAMETERS

Category	Name	Value
Electrical Conduction	d_{iso}	$2\ mm^2/ms$
	d_{ani}	$6\ mm^2/ms$
Electrical Excitation	α	0.01
	γ	0.002
	β	0.15
	c	8
	$u1$	0.2
	$u2$	0.3
Mechanical Passive Stress Contribution	k	$1000\ kPa$
	a	$0.496\ kPa$
	b	$7.209\ kPa$
	a_{ff}	$15.193\ kPa$
	b_{ff}	$20.417\ kPa$

	a_{ss}	$3.283\ kPa$
	b_{ss}	$11.176\ kPa$
	a_{fs}	$0.662\ kPa$
	b_{fs}	$9.466\ kPa$
Mechanical Active Stress Contribution	v_{ff}	1.0
	v_{ss}	0.4
	k_T	$0.49\ kPa/mV$
	ϕ_r	$-80\ mV$
Active Traction Coupling	ε_0	$0.1/mV$
	ε_∞	$1.0/mV$
	ε	$1/mV$
	ϕ	$0\ mV$
Blood Flow (Blood)	ρ	$1.025 \cdot 10^{-6}\ kg/mm^3$
Blood Flow (Valves)	R^{tv}	$0.0010\ kPa\ ms/mm^3$
	R^{mv}	$0.0061\ kPa\ ms/mm^3$
	R^{av}	$0.0027\ kPa\ ms/mm^3$
Blood Flow (External Circulation)	R^{pc}	$0.0104\ kPa\ ms/mm^3$

	R^{sc}	$0.0850\ kPa\ ms/mm^3$

ABAQUS MODEL

GEOMETRY:

The geometry of the heart modeled from medical imaging data at 70% ventricular diastole is composed of abaqus parts which are either meshed and included in the simulation, meshed only, or not meshed and not included in the simulation. Following is a table that shows examples of how the different parts are treated in the software. [1]

Part Name	Dimensionality	Simulation Usage
Aortic_Arch	**Surface** (Shell Element Type)	Mechanical
Aortic_Valve	**Solid**	Not Used
Chordae_Tendineae	**Line** (Truss Element Type)	Not Used (Meshed)
L_Atrium	**Solid** (To Model Wall Deformation), **Surface** (To Model Fluid Exchange Properties)	Mechanical, Electrical
Compliance	**Surface** (Models Fluid Exchange Properties of arterial, venous and pulmonary systems respectively as a single entity)	Mechanical

SIMULATION SETUP

1. Preprocess the geometric parts (cut, partition, etc), assign sets, surfaces, features
2. Assign sections to parts (eg. surface,solids, lines). Note: For cavities eg. L_Atrium, Aortic_Arch, etc 2 sections are assigned one responsible for the wall (mechanical deformation) and a fluid cavity for modeling the fluid exchange system.
3. Assign Materials to the sections (here is where the equations are modeled with associated parameters). Note: In the LHP model the material properties (constants) were at first set to values found in literature (see above). However, several of these values were modified to match physiologically observed behavior. Furthermore, the materials used in the LHP are defined via user subroutines and are even encrypted.
4. Create instances of the parts and assemble. Note: Compliance part is instanced 3 times to account for pulmonary, arterial and venous circulations. Also, the ventricles have a modified valvular roots (aortic, pulmonary, tricuspid and mitral) using planar surfaces to model boundaries.
5. Specify the sequence of steps with associated boundary conditions. [1]

Step	Boundary Conditions	Description
All Steps (Heart)	**Fixed BCS at the cut planes of the aortic arch, pulmonary trunk and superior vena cava**	The cut planes are allowed to move relative to a fixed reference using distributed coupling with an elastic stiffness
All Steps (Compliances)	**Unidirectional Spring BC (COMPLIANCE-AXIAL), Fixed (COMPLIANCE-FIXED)**	To account for the dependance of the volumes in the cavities to pressure one of six faces is attached to a spring in the x direction while all the other faces are fixed in place
All Steps (Heart Cavities)	**Fixed Displacement (COMPLIANCE-FIXED)**	The inner cavity nodes are fully constrained

PRE-LOAD	**Pressures at 70% Diastole**	The pressures within the cavities are ramped from zero to to values cited to be normal at 70%
BEATn	**Pressure BCs in PRE-LOAD are removed, Excitation BCs on every node applied from electric potential history in elec_sim**	Removing Pressure BCs impose a constant overall blood volume for the remaining of the analysis.
RECOVERYn	**All Nodes set to resting potential at -80mV**	Also, the resting potential is applied to the main vessels so they display an appropriate passive response.

EXPECTED RESULTS

1. Key model results as in LV ejection fraction, Min-Max Pressure ranges for the cavities, Max Apex-Base shortening and Angle of Apical Twist. [1]
2. Visualise the evolution of (electric potential, mechanical displacement, muscle fiber strain) with time across cardiac cycle. [2]
3. Pressure Volume graphs. [2]
4. Long axis shortening of ventricles with time. [1],[2]
5. As we are running the simulation on 20 cores we also aim to assess computational performance (processor utilization, ram usage and run times compared to those specified in the documentation for the coarse mesh). Especially given a concern about using non power of 2 no. of cores. [1]

QUESTIONS AND ANSWERS

Including Coronary Arteries and Veins in the simulation ?

Ans: ***refer to section 4.3 [1]***

Including Heart Valves in the simulation ?

Ans: *replace the planar surfaces with the geometric valve parts included in the model, mesh using a suitable technique and connect them to ventricles using tie constraints or shell to solid couplings.* ***refer to section 4.4 [1]***

Including the Chordae Tendineae in the simulation ?

Ans: *Couple to ventricular papillary muscles and valves using* ***Distributed Coupling*** *constraints.* ***refer to section 4.5 [1]***

Changing Material Properties of the sections ?

Ans: *As the material types are defined via encrypted user subroutines. We can either replace the entire material via abaqus built in constitutive laws or our own material types via user def subroutines.* ***refer to section 5 [1]***

PROJECT STATE

1. Analysing the LHP model database (input files) we examined the main features of the abaqus lhp **mechanical** model and compared it to the literature to identify how for example (the fluid exchange model works, where is it defined, where the electrical coupling takes place, what is included in the default assembly and what is not, boundary conditions, primary and historical output fields as specified in the default model). ***Done***
2. As the first run of my mechanical simulation is probably faulty due to issues

with the electrical simulation. We will **run both simulations again** using the coarse mesh in order to do the same analysis on the output database. ***Pending***. We expect to determine key model results and visualize the output fields as mention in EXPECTED RESULTS

PROJECT GOALS

Further on we identify 2 main goals with the project.

1. Integrate a structural deformation simulation of the mitral valve within the LHP. Idea: (Using the **existing model part**, **the pressures of the cavities from the fluid exchange model** as a mechanical load and finally modifying the simplistic constant valvular resistance with a **time varying resistance as a function of the geometric orifice of the valve.**) Adapting ideas from [3] and [2].
2. Modifying Geometrical Parts of the heart and including them in the simulation.

REFERENCES

1. “SIMULIA Living Heart Human Model Documentation”, Abaqus 6.14
2. “The Living Heart Project: A robust and integrative simulator for human heart function”, Brian Baillargeon a, Nuno Rebelo a, David D. Fox b, Robert L. Taylor c, Ellen Kuhl d, 2014
3. “Mitral valve dynamics in structural and fluid–structure interaction models”, K.D. Laua,c,∗, V. Diazc, P. Scambler b, G. Burriesci c, 2010