ON THE IMPORTANCE OF ANISOTROPY IN BIOLOGICAL MATERIALS: APPLICATION TO AORTIC TISSUES

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INTRODUCTION

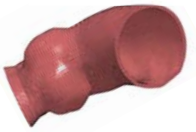
Accurate modelling the constitutive mechanical behaviour of the materials in FE simulations is crucial to capture the mechanical response of cardiovascular tissues. We have updated the **ANSYS LS-DYNA** list of materials with a user-defined material to model a **hyperelastic matrix with up to two families of embedded fibres**, whose directions can be set locally. The aim of this study is to compare different material laws with structural analyses on a tri-leaflet valve and an aortic root.

MATERIALS AND METHODS

A multi-step algorithm was implemented: (1) the geometry and mapped mesh with eight-node hexahedral solid elements were generated; (2) pre-simulations to obtain the principal stress directions with realistic boundary conditions; (3) implementation of local coordinate systems for each element of the mesh, according to the principal stress directions by means of a Matlab code [1]; (4) user-defined strain-energy function [2] characterized with data from the literature [3, 4]; (5) FE simulations with **linear elastic (E)**, **isotropic (Iso)** and **anisotropic (Aniso)** materials imposing physiological loads.

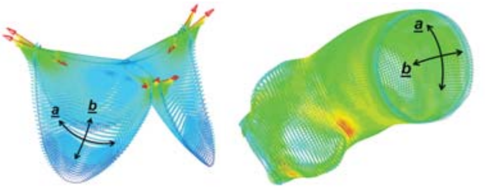
1. GEOMETRY & MESH

Tri-leaflet valve CAD model



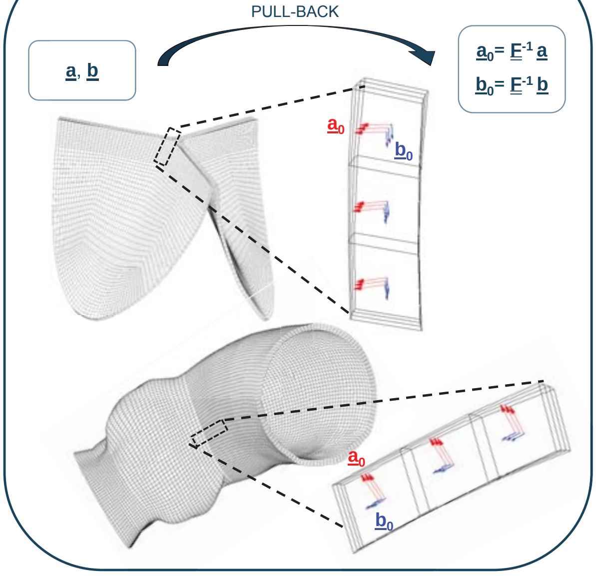
CT-reconstructed aortic root

2. PRE-SIMULATIONS



→ Principal stress directions **a** and **b**

3. LOCAL-COORDINATE SYSTEM



PULL-BACK

a, **b**

$\mathbf{a}_0 = \mathbf{F}^{-1}\mathbf{a}$

$\mathbf{b}_0 = \mathbf{F}^{-1}\mathbf{b}$

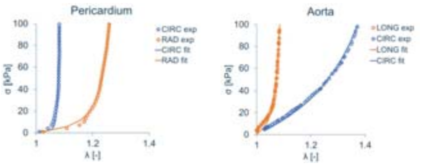
4. DATA FITTING AND CONSTITUTIVE LAW

$$\mathrm{W} = \bar{\mathrm{W}}_{\mathrm{iso}} + \mathrm{W}_{\mathrm{aniso}} + \mathrm{W}_{\mathrm{vol}}$$

$$\bar{W}_{\mathrm{iso}}(\bar{\mathbf{C}}) = C_{10}\,(\bar{I}_1 - 3) + D_1\left(e^{D_2(\bar{I}_1-3)} - 1\right)$$

$$W_{\mathrm{aniso}}(\mathbf{C}, \mathbf{a}_0, \mathbf{b}_0) = \frac{k_1}{2k_2}\left[e^{k_2(I_4-3)^2} - 1\right] + \frac{k_3}{2k_4}\left[e^{k_4(I_6-3)^2} - 1\right]$$

$$W_{\mathrm{vol}}(J) = \frac{k}{2}(J-1)^2$$



5. FE SIMULATIONS

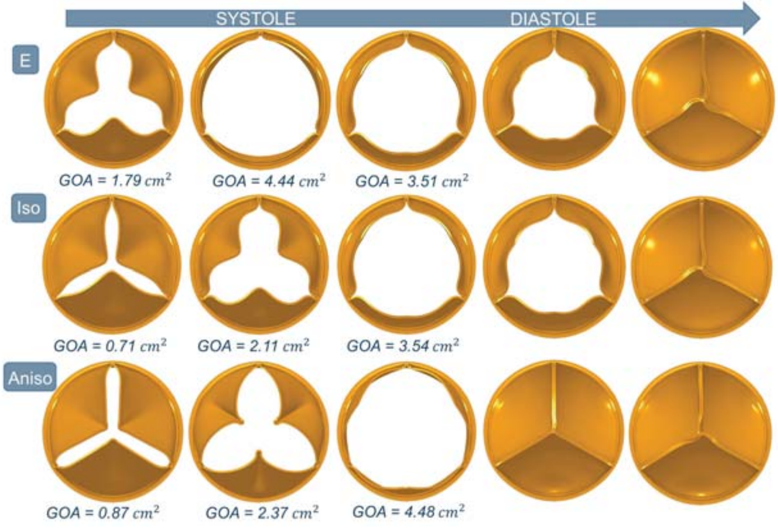
→ Physiological boundary conditions

→ Materials:

- ☐ **Linear Elastic (E)**
- ☐ **Isotropic (Iso)**
- ☐ **Anisotropic (Aniso)**

RESULTS

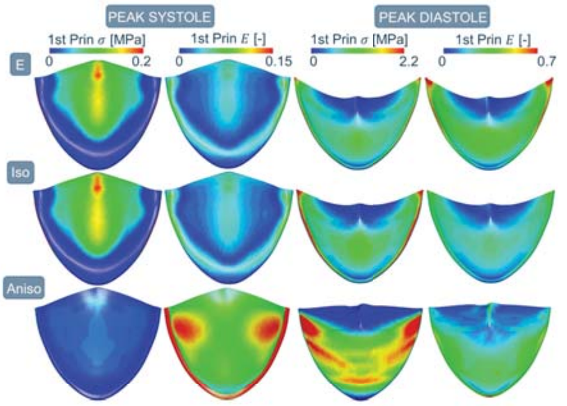
Valve kinematics in five steps during the physiological cardiac cycle for the three material models, linear elastic (E), isotropic (Iso) and anisotropic (Aniso). The Geometric Orifice Area (GOA) is also calculated.



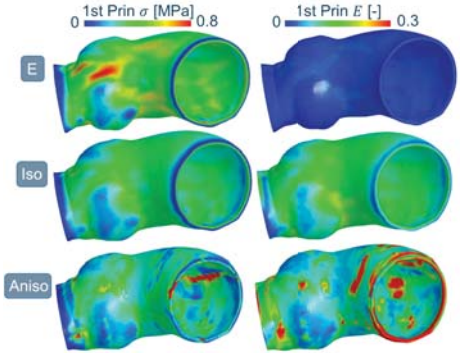
Material parameters and calculation time for one cycle for all the performed simulations with eight CPUs.

	Valve	Aorta	Valve	Aorta
E	$E = 8\,MPa; \upsilon = 0.49$	$E = 2\,MPa;\ \upsilon = 0.49$	3 *h* 46 *m*	0 *h* 20 *m*
Iso	$D_1 = 0.16\,kPa;\ D_2 = 14.88$ $\upsilon = 0.49$	$D_1 = 12.39\,kPa; D_2 = 2.57$ $\upsilon = 0.49$	30 *h* 9 *m*	5 *h* 7 *m*
Aniso	$C_{10} = 5\,kPa; \upsilon = 0.49$ $k_1 = 0.576\,kPa; k_2 = 230.67$ $k_3 = 9.487\,kPa; k_4 = 7.59$	$C_{10} = 5\,kPa; \upsilon = 0.49$ $k_1 = 50.31\,kPa; k_2 = 0.56$ $k_3 = 82.51\,kPa; k_4 = 57.53$	31 *h* 5 *m*	6 *h* 46 *m*

First principal stress and strain in the systolic and diastolic peaks for all the valve models.



First principal stress and strain in the systolic peak for all the aorta models.



CONCLUSIONS

The main relevance of this work is the implementation of a user-defined material, which allows to model in **ANSYS LS-DYNA** a hyperelastic matrix with two different families of embedded fibres, whose directions are locally defined. The comparison of the three different material models confirmed the importance of the choice of the constitutive law in modelling soft materials. The models showed different opening and closing timing – for the valve, different strain and stress distribution and different calculation time. More investigation is required to analyse the influence of the anisotropy with fluid-structure interaction simulations and how the orientation of the fibres influences the material behaviour, as well as to compare our simulations against experiments.

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References :
[1] Driessen et al., J Biomech Eng 127.2 (2005): 329-336.
[2] Nolan et al., J Mech Behav Biomed Mater 39 (2014): 48-60.
[3] Sacks et al., Ann Biomed Eng 25.4 (1997): 678-689,
[4] Kamenskiy et al., Biomech Model Mechanobiol 13 (2014): 1341-1359.