Implementation and validation of soft tissues hyperelastic constitutive laws : application to the human skin and artery

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INTRODUCTION

We aim to characterize the biomechanical behavior of soft tissues by comparing experimental data with simulation. In this work, we present applications of the implementation of different hyperelsatic models in FEniCS [1], an open-source FE code, on **human skin** and **artery**. For that purpose, uniaxial extension and inflation tests have been studied.

METHODS

The displacements $\boldsymbol{u}$ over nodes of a structure under constraints (loads or prescribed displacement) are the solutions of the variational problem (1). Even if the geometrical non-linearity is taken in account, we still need to implement a hyperelastic constitutive law to model the nonlinear behavior of the soft tissues.

$$F(\boldsymbol{u};\boldsymbol{v}) = \left.\frac{d\Pi(\boldsymbol{u}+\epsilon\boldsymbol{v})}{d\epsilon}\right|_{\epsilon=0} = 0 \quad \forall\, \boldsymbol{v} \in \boldsymbol{V}(trial\ space) \qquad (1)$$

with $\Pi = \int_\Omega \psi(\boldsymbol{u})\boldsymbol{dx} - \int_\Omega \boldsymbol{B}.\boldsymbol{dx} - \int_{\delta\Omega} \boldsymbol{T}.\boldsymbol{ds}$ and $\psi(\boldsymbol{u})$ the hyperelastic strain energy density.

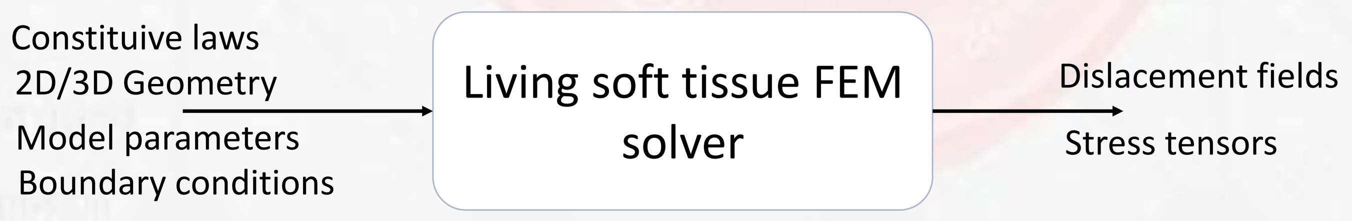

Figure 1. The framework process

APPLICATION ON HUMAN SKIN

The first application consists in simulating the mechanical response of a bi-material skin. The latter is composed of a healthy region and a benign tumor, called 'keloid' (figure 2). Previous studies showed that the keloid growth is linked to the mechanical properties of the skin [2].

Figure 2. Keloid scar

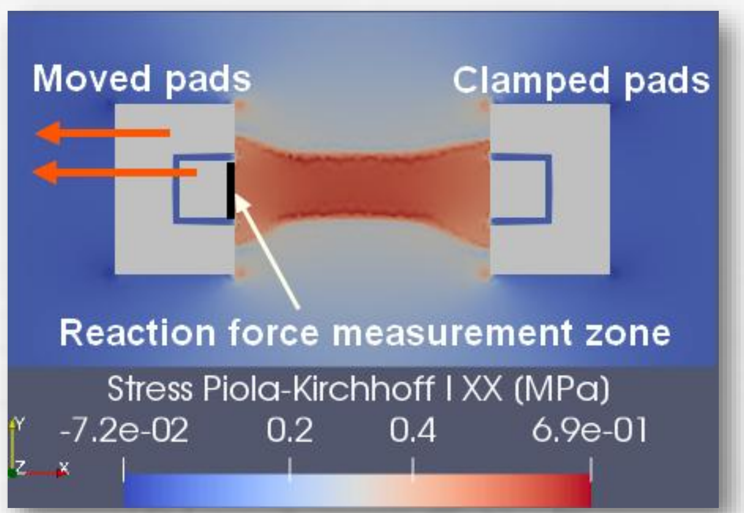

Figure 3. Mechanical stress field as an output of the framework

We simulate the uniaxial extension test to identify the stress field over the keloid medium, the healthy region and on their interface (figure 3). A challenging task must be done first : recognize the suitable hyperelastic model.

As a first trial, we have implemented an alternative form of the compressible Neo-Hookean materials (2).

$$\psi(I_1) = \frac{\mu}{2}(I_1 - 3 - 2\ln J) + \frac{\lambda}{2}(\ln J)^2 \qquad (2)$$

were $\boldsymbol{\mu}$ and $\boldsymbol{\lambda}$ are Lamé parameters and J the jacobian of the deformation gradient. Additionally, the FEM solver has been integrated into a FEMU problem to find back the real parameters of an artifical data set (figure 4).

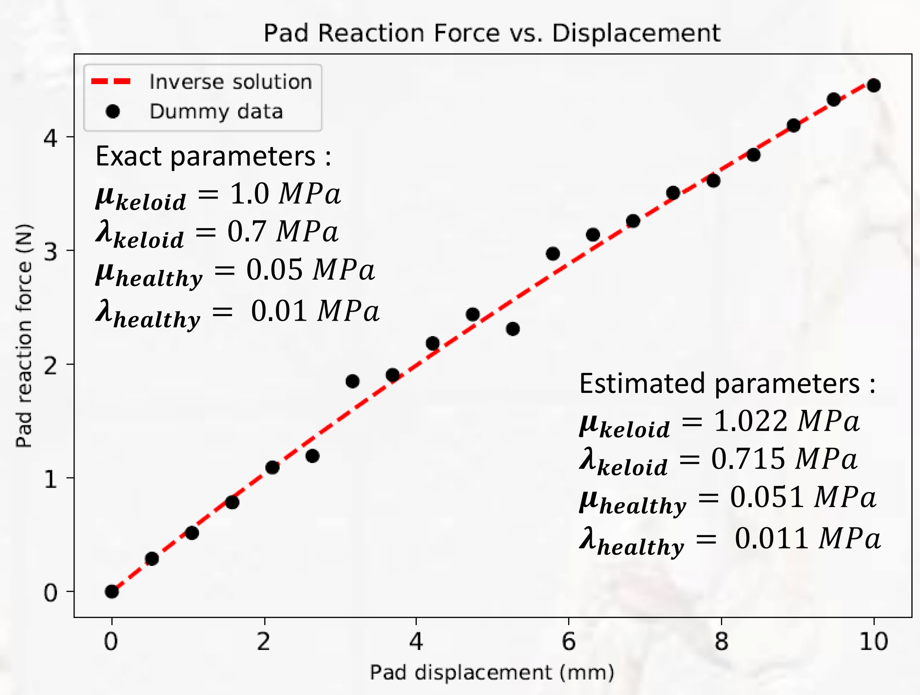

Figure 4. The estimated parameters of the Neo-Hookean model

APPLICATION ON ARTERY

The artery exhibits a hyperelastic, nearly incompressible and anisotropic behavior.

Anisotropy is due to the orientation and distribution of collagen fibers inside the arterial wall. and can be expressed using energy-strain equation introduced by Holzapfel [3] :

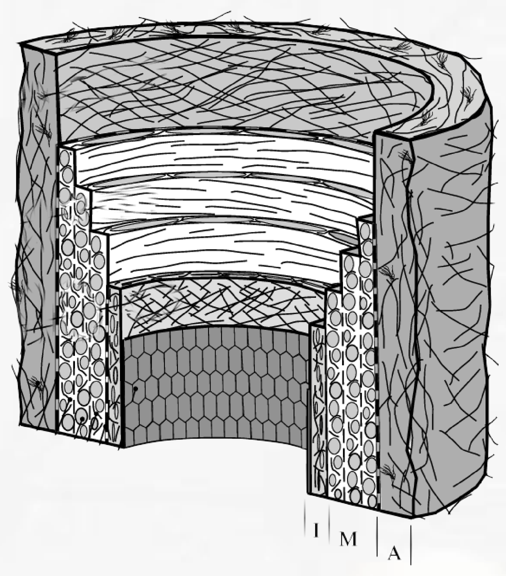

Figure 5. Artery layers [3]

$$\psi(I_1, I_4) = c_{10}(I_1 - 3) + \frac{k_1}{2k_2}\left(\exp\left[k_2(I_4^\alpha - 1)^2\right] - 1\right) \qquad (3)$$

where I_4 describes the orientation of collagen fibers, I_1 is a model invariant and c_{10}, k_1, k_2 are material parameters.

An inflation test of the artery was simulated using different hyperelastic laws. As shown in figure 5, the Yeoh model is the best to reproduce the experimental data.

$$\psi_Y(I_1) = c_{10}(I_1 - 3) + c_{20}(I_1 - 3)^2 \qquad (4)$$

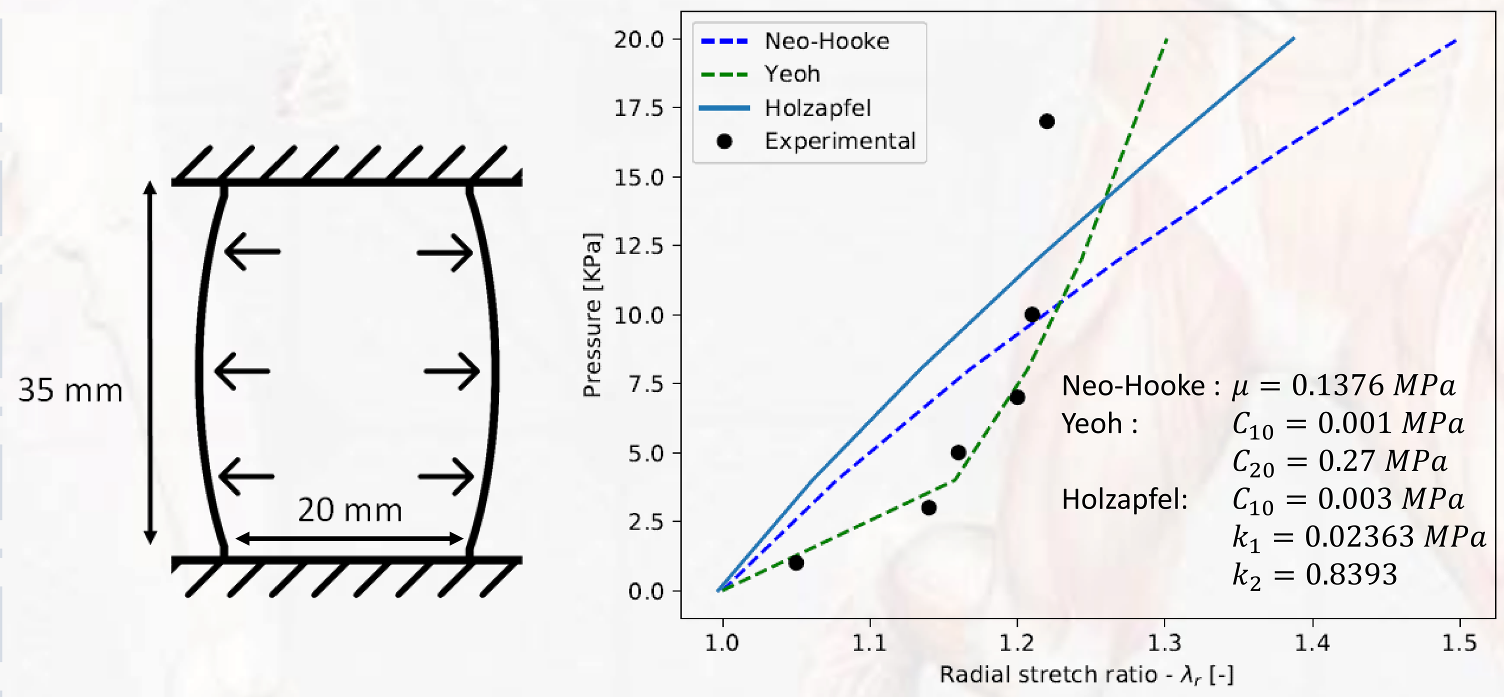

Figure 6. Arterial wall inflation modelled using different hyperelastic laws implemented in FEniCS (Experimental data and pameters values taken from [4]).

CONCLUSIONS & PERSPECTIVES

- Inverse identification of a bi-material human skin's parameters under uniaxial extension test.
- Benchmark validation of arterial walls response to an inflation test.
- An FE open-source framework to simulate the hyperelastic behavior of soft tissues.

- Understanding the intimal hyperplasia process induced by hand-arm vibrations.
- Development of prevention system against keloid growth.

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