

Modeling the mechanics of tissue-engineered human heart valve leaflets

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Modeling the mechanics of human tissue-engineered heart valve leaflets

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Introduction

Computational models provide valuable information to assess the mechanics of tissue-engineered (TE) constructs. In this study, a structurally based model for collagenous cardiovascular tissues [1] is applied to evaluate the mechanical behavior of TE heart valve leaflets [2]. A recently published model for arterial wall mechanics [3] is extended with a fiber volume fraction [4] to describe the relative amount of fibers present in each direction. In this way, structural information with respect to the tissue's fiber architecture can be incorporated.

Materials and methods

The tissues are modeled as incompressible fiber reinforced materials and the extra stress (τ) is written as:

$$\tau = \hat{\tau} + \sum_{i=1}^N \phi_f^i (\psi_f^i - \vec{e}_f^i \cdot \hat{\tau} \cdot \vec{e}_f^i) \vec{e}_f^i \vec{e}_f^i \quad (1)$$

with $\hat{\tau}$ the (isotropic) matrix stress, ϕ_f the fiber content, ψ_f the fiber stress, and \vec{e}_f the fiber direction [1]. The in-plane angular fiber distribution is described by a Gaussian function:

$$\phi_f^i(\gamma_i) = A \exp \left[\frac{-(\gamma_i - \mu)^2}{2\sigma^2} \right] \quad (2)$$

with A a scaling factor and μ the mean value and σ the standard deviation of the fiber distribution. γ_i denotes the in-plane angle of the fibers, where $\gamma_i = 0^\circ$ corresponds to the circumferential direction and, consequently, $\gamma_i = 90^\circ$ coincides with the radial direction of the leaflets. The fiber direction in the undeformed configuration is written as:

$$\vec{e}_{f_0}^i(\gamma_i) = \cos(\gamma_i) \vec{v}_1 + \sin(\gamma_i) \vec{v}_2 \quad (3)$$

with \vec{v}_1 and \vec{v}_2 the circumferential and radial direction, respectively.

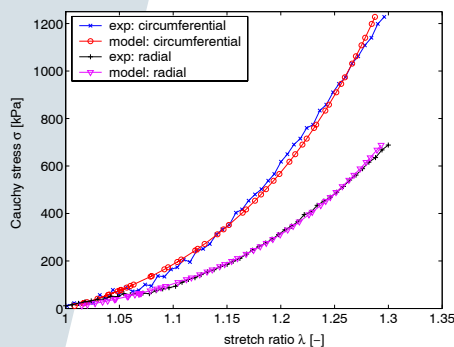


Fig. 1: Measured and predicted results from uniaxial tensile tests in the circumferential and radial direction of the TE leaflets.

The model parameters of the TE leaflets are estimated by fitting the model to the averaged results of uniaxial tensile tests in the circumferential and radial direction [Fig. 1]. A pressure of 12 kPa is applied to the leaflets to study their mechanical response. The balance equations are solved using the finite element (FE) method and the FE mesh is shown in Fig. 2.

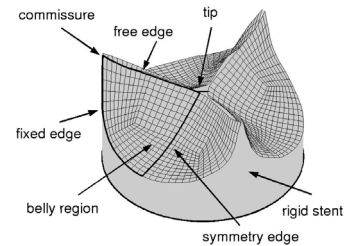


Fig. 2: Finite element mesh of a stented valve geometry.

Results

The simulated distributions of the major principal stretches and stresses in the TE heart valve leaflets after pressure application are shown in Fig. 3. Compared to native leaflets, the response of the TE leaflet is (a) less nonlinear, (b) less anisotropic, (c) stiffer, and (d) there is less coaptation due to the absence of large radial strains [5].

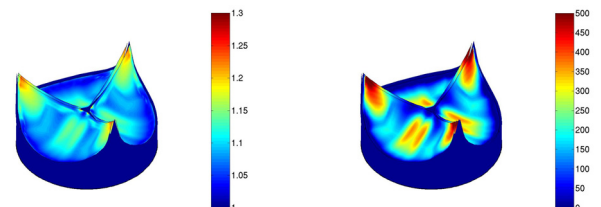


Fig. 3: Major principal stretch [-] (left) and stress [kPa] (right) distribution in the TE leaflets.

Discussion

- The constitutive model fits the experimental data very well.
- The presented computational framework enables us to estimate the required pressure levels in a bioreactor system to obtain the desired amount of strains in TE leaflets.
- The method offers possibilities to investigate the interrelation between mechanical conditioning and tissue remodeling [6].

References:

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