A structural constitutive model for collagenous cardiovascular tissues

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Introduction

Accurate constitutive models are required to gain further insight into the mechanical behavior of cardiovascular tissues. In this study, a structural constitutive framework is introduced that accounts for the angular distribution of collagen fibers. To demonstrate its capabilities, the model is applied to study the biaxial behavior of the arterial wall and the aortic valve.

Materials and methods

The tissues are modeled as incompressible fiber reinforced materials and the Cauchy stress ($\sigma$) is written as [1]:

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

(1)

with $p$ the hydrostatic pressure, $\hat{\tau}$ the isotropic matrix stress, $\phi_f$ the fiber volume fraction, $\psi_f$ the fiber stress, and $\hat{e}_f$ the fiber direction in the deformed configuration. Equation (1) gives the opportunity to incorporate experimentally measured fiber distributions by defining an appropriate set of fiber directions and volume fractions. The fiber direction in the undeformed configuration is defined in a local coordinate system:

$$\hat{e}_f^i = \cos(\gamma_i) \hat{v}_1 + \sin(\gamma_i) \hat{v}_2$$

(2)

For the fiber volume fractions, a (discretized) normal probability distribution function is used:

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

(3)

with $A$ a scaling factor and $\mu$ and $\sigma$ the mean value and standard deviation of the fiber distribution, respectively. Data from literature [2-5] is used to determine the model parameters. The modeled fiber architectures for the arterial wall and aortic valve [6] are schematically shown in Fig. 1 and 2.

Results

The evolution of the inner radius during inflation of the arterial wall at a constant axial pre-stretch is shown in Fig. 3. The highly nonlinear and anisotropic behavior of the leaflet tissue is evident in Fig. 4. The distribution of the major principal stretch and stress in the leaflet is represented in Fig. 5.

Discussion

- Incorporating the fiber distribution is required for a complete and accurate description of the tissue’s biaxial response [5].
- The nonlinear and anisotropic biaxial behavior of the cardiovascular tissues can be analyzed with the proposed model.

References: