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Remodelling of continuously distributed collagen fibres in the aortic heart valve

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Introduction
To optimise the conditioning protocol for tissue-engineered (TE) aortic heart valves, a mathematical model is developed to relate tissue remodelling to the local mechanical condition within the construct. The model is applied to predict mechanically induced changes in collagen fibre content and orientation in the aortic valve.

Material and methods
The leaflet of the aortic valve is modelled as an incompressible fibre reinforced material [1]:

$$\sigma = -pI + (1 - \phi)\tau_m + \phi\delta k(F \cdot S_o \cdot F^T - Q \cdot S_o \cdot Q^T)$$

where \(\phi\) is the fibre volume fraction, \(\tau_m\) the isotropic matrix stress, \(k\) the fibre stiffness, \(F\) the deformation gradient tensor and \(Q\) the rotation tensor. \(S_o\) denotes the fibre orientation tensor in the undeformed configuration and is defined as \(S_o = \langle \vec{e}_o \vec{e}_o \rangle\), where \(\langle \ldots \rangle\) denotes the average over the distribution space of fibre directions in the undeformed configuration (\(\vec{e}_o\)).

\[\text{Figure 1: } \phi_{ss} \text{ as a function of } \Lambda.\]

The (steady-state value of the) fibre volume fraction (\(\phi_{ss}\)) as a function of the mean fibre stretch (\(\Lambda\)) is shown in fig. 1. The evolution of \(\phi\) is modelled by a first order rate equation:

$$\frac{d\phi}{dt} = \frac{1}{\tau_1}[\phi_{ss}(\Lambda^2) - \phi]$$

Fibre reorientation is modelled by a first order rate equation. The change in \(S\) is described by:

$$\nabla S = \frac{1}{\tau_2}(A - S)$$

with \((\ldots)\) the Truesdell derivative and \(A\) the stimulus for fibre reorientation. Assuming that anisotropy of the fibre orientation develops from the macroscopic deformation, \(A\) is chosen to be a function of the Finger strain tensor \(B\):

$$A = \frac{B^v}{tr(B^v)}$$

where \(v\) is used to control the degree of alignment.

Results
The tip displacements are monitored for different fibre stiffnesses (fig. 3). The volume fractions on the aortic side of the leaflet after the remodelling process are shown in fig. 4. The final computed principal fibre directions are displayed in fig. 5.

Discussion
- The model considers the interaction between 1) the mechanical loading condition within the leaflet and 2) changes in collagen fibre content and orientation.
- The first principal fibre directions resemble the preferred fibre orientation in a native aortic heart valve leaflet [2].
- The fibre stiffness is assumed constant, whereas collagen fibres are generally modelled by an exponential constitutive law [3].
- The evolution of the remodelling rules are not yet validated experimentally.

References:

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