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Statistical Approach for a Micromechanically Based Continuum Description of Damage Evolution in Collagenous Tissues

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Introduction

During clinical interventions biological tissues may be subjected to supra-physiological loading conditions. One example is the balloon angioplasty procedure, where an atherosclerotic artery is circumferentially overstretched by means of a catheter with the goal to increase the arterial lumen. This procedure is accompanied by a softening of the material, which is believed to result from microscopic damage, that is induced in the collagen fibers during overstretch. In order to improve such treatment methods, the modeling of the observed damage behavior and related computer simulations are subject of current research.

Material Modeling

We model arterial tissue as a fiber-reinforced material consisting of a ground-matrix material and two superimposed families of collagen fibers. In order to account for the specific contibutions of the components, we use a decoupled form of the strain-energy function. Hereby, damage is considered by incorporation of a one-dimensional damage variable $D_{(a)}$ into the transversely-isotropic parts of the strain-energy [1]

$$\Psi^{\text{ti}}_{(a)} := m(P_{(a)}(\boldsymbol{C}, D_{(a)})) \quad \text{with} \quad P_{(a)} = (1 - D_{(a)})\Psi^{\text{ti},0}_{(a)} - c.$$

Here, m is a monotonically increasing convex function, $\Psi^{\text{ti},0}$ is the effective (undamaged) transversely-isotropic function, and c is the value of the latter function in the reference configuration.

Statistical Framework

For the damage variable $D_{(a)}$ we derived a function that is based on collagen fiber properties on the microscale, see [2]. Due to trigonometric considerations we evaluate the stretch of an interfibrillar proteoglycan (PG) bridge as

$$\lambda_{\text{pg}} = \frac{L_{\text{pg}}}{L_{\text{pg},0}} = \sqrt{\{\cos\alpha - L(\lambda_{\text{fib}} - 1)\sin\alpha\}^2 + \frac{\sin^2\alpha}{\lambda_{\text{fib}}}}.$$

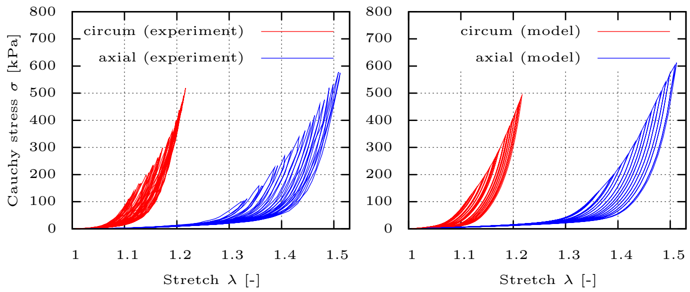
Herein, $L_{\text{pg},0}$ and L_{pg} denote the length of the PG bridge in the undeformed and deformed configuration, respectively. The considered deformation is due to a macroscopic fiber stretch λ_{fib}. Additionally, the microscopic parameters α and L are introduced, which describe the PG angle as well as the ratio of several internal lengths of the collagen fiber. Motivated by a sliding filament model [3], which states that PG bridges can store reversible strains in a certain domain, we introduce a maximum sustainable PG stretch $\lambda^{\text{sust}}_{\text{pg}}$. Considering the quantities λ_{pg}, α and L to be randomly distributed now allows to determine bounds y_l and y_u of a regime of failed PG bridges as solutions of the function $\lambda_{\text{pg}} - \lambda^{\text{sust}}_{\text{pg}} = 0$. Thus, a domain of active PG bridges is given by the inequality

$$\lambda_{\text{pg}} - \lambda^{\text{sust}}_{\text{pg}} \leq 0.$$

The damage variable $D_{(a)}$ is defined as the fraction of failed PG bridges and can thus be evaluated as the integral of the considered probability density function ϑ over the bounds

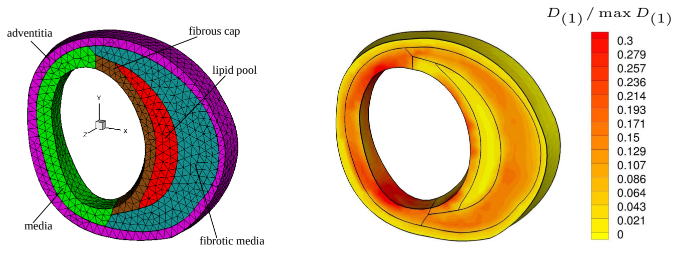
$$D_{(a)} = \int_{y_l}^{y_u} \vartheta(y)dy = \hat{\vartheta}(y_u) - \hat{\vartheta}(y_l) \quad \text{with} \quad \int_y \vartheta(y)dy = 1.$$

With adjusted parameters the derived material model is able to capture experimentally observed damage hysteresis of cyclically loaded arterial tissue specimen in circumferential and axial directon, see figure below.



Example

The material model with adjusted parameters is applied within a finite element example, whereby the overinflation of a simplified three-dimensional atherosclerotic artery is numerically simulated. Here, five different tissue types are taken into account (see figure below), whereas no damage is considered in the lipid pool. This example allows for the study of damage distribution after an overinflation as it occurs, for instance, during balloon angioplasty.



References

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