AN ANISOTROPIC MICROMECHANICALLY BASED VISCOELASTIC MODEL FOR SOFT COLLAGENEOUS TISSUES

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1. Introduction

Soft biological tissues are characterized in general by time dependent and in particular viscoelastic properties. This becomes apparent in mechanical testing where these materials reveal e.g. stress relaxation when stretched to a constant level and rate dependent hysteresis in cyclic loading. These characteristics depend on the direction of loading and are thus of anisotropic nature. In the present contribution, we propose a micromechanically motivated approach. The constitutive equations are based on the multiplicative decomposition of the stretch in fiber direction into an elastic and a viscous part. Anisotropy is taken into account by a non-uniform spatial distribution of the fiber-matrix units. Finally, the model is generalized to the three-dimensional case by integration over a unit sphere [1, 2, 3, 4].

2. Fiber-matrix unit

The passive mechanical properties of soft biological tissues are to a large extent determined by the histological structure of the extracellular matrix. The latter one includes fibrous constituents, primarily different types of collagen and the ground substance which contains a large amount of water. The typical J-shaped stress-strain curve of soft tissues is usually divided into a toe and a linear region. The increasing stiffness in the toe region is attributed to the orientation and uncoiling of collagen fibers. However, this fiber transition from a crimped to a straightened state needs rearrangement of the nearby ground substance [2]. Since the latter one is a highly viscous material, fiber straightening turns out to be a viscoelastic process.

2.1. One-dimensional model

The stretch λ in a fiber direction is multiplicatively decomposed into an elastic and a viscous part as $\lambda = \lambda_e \lambda_v$. While λ_v is associated with uncoiling and straightening of the fibers, λ_e describes the stretch in the collagen itself. Accordingly, the rheological model for the fiber-matrix unit can be illustrated in the case of small deformations by the following scheme (Fig. 1). Therein, $\Psi_v(\lambda_v)$ is the

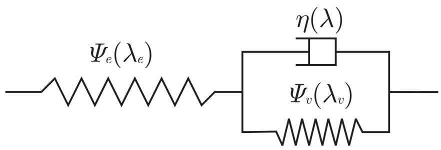

Figure 1. Rheological model for fiber-matrix unit.

strain-energy associated with fiber straightening and $\Psi_e(\lambda_e)$ is the collagen strain-energy which describes the linear region of the stress-strain curves. The dashpot element reflects the viscous properties of the ground substance and is characterized by a stretch dependent viscosity function $\eta(\lambda)$.

2.2. Anisotropic three-dimensional model

In order to obtain an anisotropic three-dimensional constitutive model, the free energy of the fiber-matrix unit is weighted by a directional distribution function and numerically integrated over a unit sphere (cf. [2, 3, 4]). While the stretches λ are assumed to be affine, the viscoelastic stretches λ_v in each integration point result from an evolution equation.

3. Application

We considered an incompressible biological tissue sample with fibers distributed around a preferred direction. Fiber dispersion was described by the von Mises distribution [5] where additionally a constant uniform ground distribution was added (cf. [1]). The strain-energy functions and the viscosity function were chosen according to

$$\Psi_v(\lambda_v) = \frac{k_1}{2k_2}\left\{\exp\left[k_2(\lambda_v^2-1)\right]-1\right\},\ \Psi_e(\lambda_e) = c_1(\lambda_e-1)^2,\ \eta(\lambda) = d_1\left\{\exp\left[d_2(\lambda_c-1)^2\right]\right\},$$

where k_1, k_2, c_1, d_1 and d_2 denote material parameters. As proposed in [6], Ψ_v contributes only if $\lambda_v > 1$. For numerical integration over the unit sphere, a 61 integration points scheme [3] was utilized.

4. Conclusions

In this paper a viscoelastic model for the anisotropic behavior of soft tissues has been proposed. The model is based on the generalization of a one-dimensional model for the fiber-matrix interaction to the three-dimensional case. Anisotropy caused by non-uniform fiber distributions is easily included by a distribution function. The results suggest that many features of soft tissues are qualitatively well captured. For example, the strong increase in the hysteresis ratio with frequency compared to a moderate change in the storage modulus reported for some tissue types [7] can be obtained by the model.

5. References

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