A Microstructure-Based Anisotropic, Nonlinear Viscoelastic Model for Fibrous Tissues: Applications to the Cornea

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ABSTRACT

Soft fiber-reinforced tissues such as the cornea, tendons, and blood vessels have a unique combination of mechanical properties that enables them to perform important structural, protective, and energy-absorbing applications. Because of their fiber-reinforced microstructure, these tissues are extraordinarily stiff and strong for their weight. They also possess a unique combination of flexibility and toughness that is exploited for energy-absorbing and protective applications. The toughness of these tissues arises from their ability to dissipate energy through a variety of mechanisms, such as poroelastic flow, fiber-fiber interactions through the soft matrix (e.g., collagen fibril-fibril glide), and viscoelastic deformation of the matrix and fibers. For this latter mechanism, a microstructure-based constitutive model has been developed for the anisotropic nonlinear viscoelasticity of fibrous soft tissues that incorporates fiber-level and matrix viscoelastic deformation mechanisms [1]. The model represents the tissue as a continuum mixture consisting of various fiber families embedded in an isotropic matrix. Both the fibers and matrix are required to deform affinely with the continuum deformation gradient, and a fiber stretch and viscous and elastic stretch components are defined from the continuum deformation tensor and associated viscous and elastic deformation tensor. The stress response of the tissue is developed from the sum of an isotropic component for the matrix and an anisotropic component that is the average of the fiber stress response weighted by a distribution function that describes the fiber architecture. Similarly, an anisotropic relation for the anisotropic viscous rate of deformation tensor of the fiber phase is developed from the weighted average of the viscous stretch rate relations for the fibers. A separated isotropic relation specified for the viscous rate of deformation of the matrix.

The model was implemented in a finite element program and applied to model the nonlinear tensile creep and stress-strain behavior of excised corneal strips measured in experiments [2, 3] and to the inflation response of the intact tissue [4]. The advantage of the model is that it decouples the parameters associated with viscoelasticity and anisotropy. For the cornea, the parameters associated with the material anisotropy were obtained by fitting to the X-ray scattering data for the distribution of collagen fibrils in the human cornea [5]. The viscoelastic parameters of the model were fitted to the stress-strain and creep response of the tensile strip tests. The agreement between the data and simulations were well
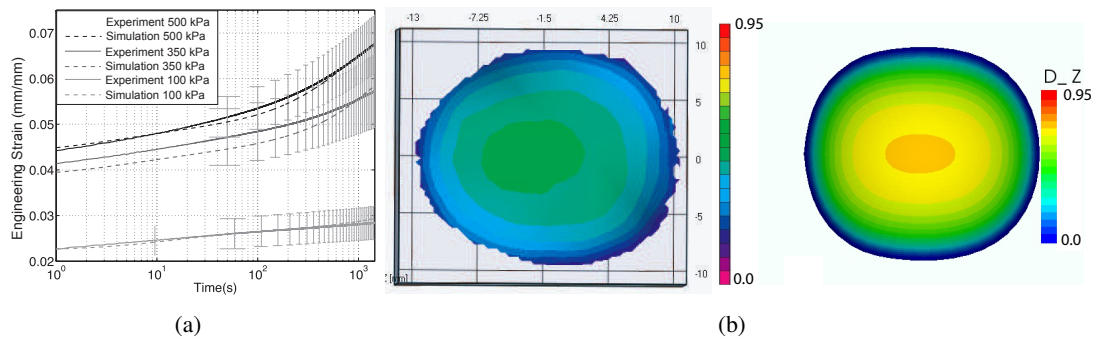
Figure 1: (a) Uniaxial creep strain curves showing a nonlinear dependence on the applied stress comparing experiments and simulations. (b) Contours of the out-of-plane displacement (mm) for the cornea in response to inflation, comparing experiments and simulation.

within the experimental error. For the creep test shown in Fig. 1(a), the model was able to reproduce the observed nonlinear stress-dependence of the strain-time curves in which the creep rate increased with the applied stress. For the cyclic tests, the model was able to predict the rate-dependence of the loading and unloading response. Currently, the model is being applied to finite element simulation of the bulge tests to examine the effects of the fibril distribution on the anisotropic viscoelastic response of the cornea under normal physiological loads (see for example Fig. 1(b)) and in response to a surgical incision.

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