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Research paper

Modeling shear behavior of the annulus fibrosus

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ABSTRACT

Modeling the mechanical properties of the annulus fibrosus has two distinct challenges: the complex loading state experienced in vivo and the anisotropic, nonlinear nature of the tissue. Previous efforts to model the annulus fibrosus have not considered shear data in the analysis, yet the shear response may be critical to understanding tissue behavior and damage. In this study, we compared four hyperelastic constitutive models fitted to uniaxial and biaxial tension, confined compression, and shear experiments from the literature. Models were either directly based on Spencer's formulation for a fiber-reinforced composite material with two equivalent fiber families or represented the annulus as two transversely isotropic materials. Each model was composed of additive strain energy terms that represent specific constituents of the annulus fibrosus (proteoglycan matrix, collagen fibers, and collagen crosslinks). Additionally, we investigated the effect of restricting the fibers such that they supported tensile loads only. Best fit coefficients for these models were calculated both including and excluding shear data from the regression. All of the models fit the data well when shear data was excluded from the regression; when shear data was included in the regression, two models that were based on Spencer's formulation performed better than the others. None of the models could consistently predict data that was not included in the regression. Restricting the fibers to support only tensile loads had only a modest effect on the fit of the models, but did alter which constituent carried the majority of the strain energy in shear deformations. Our study suggests that a single hyperelastic model may capture the anisotropic behavior of the annulus fibrosus for multiple loading cases, including shear. However, care must be taken when extrapolating these models to additional deformations outside of the training dataset.

1. Introduction

The annulus fibrous (AF) is an anisotropic tissue of the intervertebral disc composed of a proteoglycan-rich ground substance reinforced with type I collagen fibers. These fibers are arranged in concentric lamellae with two alternating fiber directions ($\pm\phi$ from the anatomic axial direction, Fig. 1). During everyday activities, the AF is loaded in complex stress states due to bending, twisting, and axial loading of the spine.

To model the nonlinear, anisotropic material behavior of the AF, strain energy functions have been developed (Eberlein et al., 2001; Guerin and Elliott, 2007; Peng et al., 2006; Wagner and Lotz, 2004; Wagner et al., 2006; Wu and Yao, 1976)

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