Evaluation of Annulus FE Model Stresses in a Functional Spinal Unit Based on Uniaxial or Biaxial Experimental Data for Crack Prediction

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Introduction: Annular cracks in the intervertebral disc (IVD) may contribute to disc prolapse and/or subsequent low back pain. The role of mechanical loading in producing annulus cracks is not well documented. A finite element (FE) approach is most suitable for such an analysis, but requires appropriate modeling of the annulus. Several authors have used a composite mechanics approach involving collagen fibers and proteoglycan ground substance, while others have refined this approach by adding porosity and viscoelasticity effects [1, 2]. Another approach for modeling annulus is the hyperelastic anisotropic material model which is based on strain energy constitutive equations [3]. This approach is based on strain energy data obtained from testing strips of annulus under biaxial or uniaxial stress states. The objective of the present work is to compare stress distribution and failure location obtained from incorporating uniaxial and biaxial strip test data in hyperelastic anisotropic FE model of a ligamentous functional spinal unit (FSU). The results are then compared with the predicted biomechanical behavior based on the experimental approach and also with clinical observations. Such an analysis will help determine if uniaxial or biaxial stress data are better suited for predicting clinically observed crack initiation of IVD.

Methods: A modified version of an experimentally validated 3-D FE model of E-CORE [4] was used. The geometry of the developed model is based on CT images and is shown in Fig.1. All model simulation parameters such as fluid elements for the nucleus and contact elements for the articular facet joints were left unchanged, except annulus fibrosus (AF). For the material model of AF, hyperelastic anisotropic behavior based on Holzapfel model was used, instead of a composite mechanics approach where the effect of continuous collagen fibers are typically modeled with rebar elements. Due to the difference between the material constant values in the Holzapfel model as obtained from uniaxial versus biaxial strip test specimens of AF, two FE models were developed. One model is based on the properties obtained from uniaxial experiments [5], and another model is based on the properties obtained from biaxial experiments [6]. FE models were fixed at the inferior-most surface of L5, and subjected to three loading cases: 500 N compression, 500 N with a 7.5 Nm flexion, and 500 N with a 7.5 Nm extension.

Results: The range of motion (ROM) based on either the uniaxial or biaxial properties used for modeling the AF was within the standard deviation of reported in-vitro studies [7]. The intradiscal pressure (IDP) for the biaxial model was 30% lower than for the uniaxial model, resulting in closer values with the mean in-vitro reported data [8]. For the biaxial model, the maximum axial stress in the mid plane of the IVD for compression was found to be at posterior inner part of the annulus, and the magnitude of the stress was much closer to the in-situ data [9]. Figure 2(a) shows the difference in the magnitude of the axial stress between uniaxial and biaxial models located on midsagittal plane. This line was chosen because of availability of experimental data, which were reproducible to within 20% [9], for comparison. In the combined loading case of 500 N compression and 7.5 Nm extension, maximum axial stresses occurred in the inner part of posterior region of AF. The difference between magnitudes of the axial stress in biaxial and uniaxial models is shown in Fig. 2(b). Figure 3(a) shows stress distribution in the axial direction for the biaxial-based model, indicating the maximum stress to be within the posterior region of AF. Figure 3(b) shows von Mises stress distribution in the endplate annulus interface based on the biaxial model, indicating the maximum stress to be in the outer part of the endplate in the posterior region. This stress distribution and maximum stress locations were the same based on the uniaxial properties model, although the von Mises stress values were different as compared to the biaxial properties model.

Discussion: Common parameters such as ROM and IDP were within the standard deviation for both uniaxial and biaxial material properties models. However, the stress distribution of the annulus based on the biaxial model shows significantly higher stresses in the posterior inner region. This is clinically relevant as radial cracks propagate from the inner to the outer direction. The magnitudes of stresses based on the biaxial model were also closer to the experimental results. The presence of higher stresses at the endplate annulus interface indicates that stresses were higher at the periphery and lower in the inner region. This suggests that rim lesions will progress from the outer to the inner direction, in line with pedicle screw biomechanics single vs dual thread screws clinical observations.

Significance: Using biaxial material properties rather than commonly used uniaxial properties in stress analysis of AF results in more accurate prediction of crack initiation and damage progression in accordance with experimental results as well as clinical
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Figure 1: Different features of the functional spinal unit (FSU) FE model based on E-CORE geometry [4].
Figure 2: (a) Axial stress comparisons between uniaxial and biaxial-based models and as compared to experimental data [5] along mid-sagittal plane of AF under 500 N compression load and (b) Axial stress in the posterior region of AF mid-plane along a line passing through outermost part of AF to the junction of the AF and NP under 500 N compression with 7.3 mm extension load.
Figure 5 (a) Axial stress distribution at the mid-plane for the shell-based model and (b) von Mises stress distribution for the shell model at the epiphysis-aneurysm interface. Both results are for 300N compression load.

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