Development and Validation of a Poroelastic Finite-Element Lumbar Disc Model for Impact Response Analysis

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Introduction: Lumbar spine mechanics have been quantified experimentally under impact loading conditions. These studies (Cassidy et al. 1990, Ranu 1990, Yingling et al. 1997) came to some common conclusions, showing an increase in compressive modulus, maximum stress, and intradiscal pressure with loading rate. Previous work by the authors (Jamison IV et al. 2013) has shown an increase in stiffness and decrease in energy dissipation in the disc as a function of faster impact events. These types of shocks may lead to internal damage, injury, and even discogenic pain, as seen in the literature. Additionally, several investigators (Lee and Kim 2000, Wang et al. 2000, El-Rich et al. 2009) have used finite element (FE) models to analyze impact loads on the lumbar spine. The chief limitation of these studies is that none used cadaver specimen subjected to impact events to validate their FE model; rather, they employed creep and quasistatic data as their benchmark. This may have limited the fidelity of these impact models. Therefore, there are two objectives to this study: to develop a finite element model of the lumbar intervertebral disc and validate it using experimental data from cadavers subjected to sub-traumatic impact shocks, and to characterize the internal mechanical response of the disc under impact shocks of varying durations.

Methods: An axisymmetric, poroelastic model of a vertebra-disc-vertebra motion segment was created based on an existing L3-L4 model for the analysis of changes in disc mechanics due to progressive degeneration (Massey et al. 2011) using ABAQUS software. The model geometry consisted of the nucleus pulposus (NP), annulus fibrosus (AF), annular fibers, adjacent bony and cartilaginous endplates (EB and EC, respectively), and trabecular and cortical portions of the corresponding vertebrae (Figure 1). All component materials were modeled as a linear elastic solid matrix with fluid filled pores. Linear elastic properties are defined by Young’s Modulus and Poisson’s ratio, while permeability is defined by an initial void ratio (e₀) and initial hydraulic permeability (k₀). The nucleus, annulus, and cartilaginous endplate additionally incorporated strain-dependent permeability. Material properties were determined from selected FE studies (Lee and Kim 2000, Wang et al. 2000, Ferguson et al. 2004, El-Rich et al. 2009, Massey et al. 2011) and selected such that the model response would provide a good fit to the validation data (Table 1). The bottom surface of the model inferior vertebra was rigidly fixed for all displacements and rotations. The internal nodes about the axis of symmetry had a fixed boundary condition to restrict movement in the radial direction. The top surface of the superior vertebra was subjected to a compressive pressure of 0.6 MPa to represent functional loading. The model was validated against experimental results from impact events imposed on individual human lumbar motion segments (n = 4, age = 30 ± 2.3 yrs., one of each level from L1-L2 through L4-L5). Each specimen was placed under a 400-N pre-load to simulate body weight (Kasra et al. 1992, Schmidt et al. 2010) and then subjected to a sequence of impact events (Δt = 80, 160, 320, 500, 1000 ms) in random order. Each impact event was represented as a triangular waveform with a 1-mm displacement. Loading and unloading portions of the model response curves were within the experimental corridor at both 80 and 160 ms. Beyond 160 ms, the loading and unloading portions begin to fall outside of this tolerance interval. With the sustained functional load, the model was then subjected to impact events as described above, with varying durations (Δt_imp = 40, 80, 120, 160, 200 ms). Time histories at each node for change in fluid volume (Vfluid), von Mises stress (S), and pore pressure (POR) were measured in each simulation.

Results: There were no significant differences in S or POR response among the range of impact events. Figure 2 shows the maximum von Mises stress averaged across all nodes in the NP, AF, and EC. Highest S_avg values were seen in the AF at nearly 1.5 MPa, followed closely by EC; the stress response in the NP was the lowest at ~0.25 MPa. The NP, with the highest initial fluid volume, predictably had the greatest change in average pore pressure at nearly 2.5 MPa. AF pore pressure was ~1.25 MPa. Fluid loss was negligible during all impact simulations. There were no cases in which the change in Vfluid was more than 0.015%.

Discussion: Unlike previous FE studies in the literature, the authors utilized experimental impact loading scenarios in order to validate the model. We allowed for the estimation of internal stresses and stress distributions throughout the functional spinal unit, which can be compared to local failure properties for the disc components. This analysis can ultimately contribute to expanding the understanding of IVD mechanics and injury mechanisms during transient shock loading. Our analysis of IVD internal mechanics shows that the average von Mises stress in the AF and EC are much higher than the NP, while the pore pressure in the NP is higher than that of the AF and EC. The use of a neo-Hookean or viscoplastic material law should be considered in future work. A rate-dependent material law will allow for the comparison of impact loads seen in this study to those that are longer in duration and allow for a wider application of the FE model.

Significance: We have successfully developed and validated a poro-elastic finite element model of the lumbar intervertebral disc for analysis of internal mechanical response during impact loading conditions. Unlike previous finite element studies in the
literature, the authors utilize experimental impact loading scenarios in order to validate the model.

Acknowledgments:

<table>
<thead>
<tr>
<th>Material</th>
<th>E (MPa)</th>
<th>v</th>
<th>e₀</th>
<th>k₀</th>
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<tr>
<td>Nucleus Pulposus</td>
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<td>4</td>
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<td>-</td>
<td>-</td>
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<td>0.05</td>
<td>6.43e-16</td>
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<tr>
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