Finite Element Poroelastic Analysis of Vertebral Endplate Changes Effect on Disc Height

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INTRODUCTION:
The intervertebral disc undergoes extensive age related degenerative changes. The mechanism for disc degeneration is multifactorial and many studies have proposed that decreased nutrition to the disc is a major contributor to the degeneration process. Because the adult disc nucleus is avascular, the only sources of nutrition are diffusion from the blood vessels of the annulus and vertebral endplate and convective flow. During aging, permeability and porosity of the cartilage endplate decrease, reducing the ability for fluid to transport nutrients into the disc. Recent studies have reported endplate permeability spanning three orders of magnitude during the aging process. With this large range of reported permeabilities, it is especially important to understand how endplate permeability affects the convective flow of nutrients in and out of the disc. To accomplish this, theoretical and mathematical models have been utilized in limited capacity. The purpose of this study was to investigate the effect of changing the permeability and porosity of the cartilage endplate to simulate aging using the finite element poroelastic method.

METHODS:
The L3/L4 disc segment (Fig. 1B) was extracted from a validated three-dimensional, nonlinear, T11-Sacrum finite element (FE) model (Fig. 1A). The posterior elements and superior half of L3 and inferior half of L4 were removed for simplification of the L3/L4 model. Material properties were assigned from normal values in the literature. Poroelasticity was included and permeability and porosity were defined for all anterior column spinal structures. Deformation dependent permeability was applied to the soft tissues including the cartilage endplate and disc components. FE model range of motion was validated with experimental data and disc pressures were compared to cadaveric intradiscal pressure. Poroelasticity results were indirectly validated with literature.

![Figure 1: A) T11-Sacrum finite element model. B) L3/L4 disc segment cross-sectional view.](image)

Table 1: Range of permeability and porosity used for the aging cartilage endplate.

<table>
<thead>
<tr>
<th>Permeability (mm²/Ns)</th>
<th>Porosity</th>
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<tbody>
<tr>
<td>0.0075</td>
<td>0.8</td>
</tr>
<tr>
<td>0.0014</td>
<td>0.6</td>
</tr>
<tr>
<td>0.0001</td>
<td>0.42</td>
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</tbody>
</table>

The range of permeability and porosity values applied to the L3/L4 cartilage endplates are shown in Table 1. The largest permeability and porosity represent the healthiest model while the lowest values represent the most aged or degenerated model. The outer annular boundary was open to fluid flow.

A 24-hour period was evaluated to understand both short-term and long-term disc behavior. To evaluate the effect of short-term loading, a 1000 N axial compression load was applied consisting of a 60 second linear ramp from zero to maximum load. The long-term disc creep response was studied over the diurnal loading cycle consisting of 16 hours of constant axial compression of 1000 N followed by an 8-hour resting period with no force. The superior most nodes of L3 were applied the compressive load with the inferior most nodes of L4 fixed in all directions.

RESULTS:
During short-term loading decreasing permeability resulted in 95% less fluid expression from the disc segment. During long-term compression, decreasing permeability had little effect on fluid flow or nuclear pore pressure. Over time, the lowest porosity resulted in 87% less fluid expression.

The total disc segment height decreased 1.84 mm within 60 seconds of compression loading for all permeabilities and porosities considered. The greatest disc height of 2.7 mm was lost with the largest permeability and porosity. However, this height was regained during 8 hours of rest for the healthiest model (Fig. 2). The lowest endplate permeability and porosity model predicted a net total disc height loss of 0.4 mm (Fig. 2).

![Figure 2: Total disc height loss (mm) after 8 hours of recovery from 16 hours of sustained 1000 N compression load for varying properties.](image)

DISCUSSION:
Cartilage endplate aging and degeneration were investigated during the diurnal cycle by changing the permeability and porosity of the endplate in a three-dimensional poroelastic finite element model of the L3/L4 disc segment. During short-term compression loading, the fluid expression and imbibition and intradiscal pore pressures were most dependent on the endplate permeability. Over a longer time period of compression, results were more dependent on porosity.

As the disc deforms due to loading, both pore pressure and fluid expression decays within the nucleus. The porous nature of the disc components compact when compressed producing resistance against permeating pore fluid. Thus, permeability decreases with consolidation time increasing the required time for pore pressure dissipation and restricting fluid transport. Further decreasing the cartilage endplate permeability and porosity exacerbate this situation. The largest permeability and porosity result in the greatest disc height loss, but during rest this loss is recovered. Total disc height loss decreases when both permeability and porosity are decreased due to less fluid expression. However, less fluid imbibes the disc during rest resulting in a net total disc height loss.

The results of this study suggest intradiscal nutritional delivery is highly dependent on the cartilage endplate health. Therefore, it is reasonable to conclude endplate aging and degeneration have a substantial impact on disc degeneration. Solute transport due to diffusion and disc swelling due to osmotic potential were not included in the analysis.