

# Effect of aging and degeneration on the human intervertebral disc during the diurnal cycle: A finite element study

**Citation for published version (APA):**

Massey, C. J., Donkelaar, van, C. C., & Marcolongo, M. (2010). Effect of aging and degeneration on the human intervertebral disc during the diurnal cycle: A finite element study. In *Proceedings of the 2010 IEEE 36th Annual Northeast Bioengineering Conference (NEBEC 2010) 26-28 March 2010, United States, New York* (pp. 10CH38232-1/2). Institute of Electrical and Electronics Engineers. <https://doi.org/10.1109/NEBC.2010.5458133>

**DOI:**

[10.1109/NEBC.2010.5458133](https://doi.org/10.1109/NEBC.2010.5458133)

**Document status and date:**

Published: 01/01/2010

**Document Version:**

Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

**Please check the document version of this publication:**

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

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# Effect of Aging and Degeneration on the Human Intervertebral Disc during the Diurnal Cycle: A Finite Element Study

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**Abstract**—Alterations in the major biochemical constituents of intervertebral discs coincide with aging and degeneration, and can alter the disc's ability to support load. The most significant biochemical change that occurs in degeneration is the loss of proteoglycans in the nucleus pulposus. During a diurnal cycle, the disc experiences approximately 16 hours of functional loading, followed by 8 hours of recovery. An axisymmetric, poroelastic model was created using ABAQUS finite element software. Standard poroelastic theory is utilized, but a user-defined material was written to include the effects of osmotic swelling, which is directly related to proteoglycan content. Due to the high stresses in the nucleus, the annulus fibrosus must remodel itself to account for the change in properties of the nucleus. The stress experienced by the nucleus increases greatly in Grade 2 from Grade 1, but then decreases in Grade 3, and even Grade 4 experiences lower stresses than in Grade 2. The osmotic pressure in the central nucleus decreases approximately 75% with degeneration. This explains the increasing inability of Grades 3 through 5 to recover the fluid lost during loading, since the osmotic pressure gradient is the primary mechanism with which fluid flows back into the disc.

## INTRODUCTION

Intervertebral disc (IVD) degeneration occurs with aging, and may be a major cause of back pain. The IVD is the primary compression-carrying component of the spine. Its roles are to transmit and distribute loads, and allow for the necessary flexibility of the spine. It is comprised of a central gel-like nucleus pulposus (NP), an outer annulus fibrosus (AF), and upper and lower endplates consisting of cartilaginous and bony portions. Alterations in the major biochemical constituents of the IVD have been shown to coincide with aging and disc degeneration and can subsequently alter the discs' ability to support load. The most significant biochemical change that takes place in disc degeneration is the loss of proteoglycans in the NP [1]. These hydrophilic molecules help to retain and replenish the fluid in the disc.

The role of fluid in the NP is vital to the IVD's ability to handle loads. As a healthy disc experiences normal daily loading, a swelling pressure is generated inside the NP, transferring the load to the AF. The ability of the NP to absorb and retain water is a function of its chemical composition, most notably its proteoglycan content [2].

During a diurnal cycle, the IVD experiences approximately 16 hours of functional loading (standing, sitting, etc.), followed by 8 hours of recovery (lying prone). Therefore, the

fluid lost during the functional loading period must be replenished in half the time. As the disc is compressed and fluid is exuded, the density of the fixed charges within the nucleus pulposus is increased, creating an osmotic gradient with the interstitial fluids surrounding the disc. This osmotic potential aids in drawing fluid back into the disc.

## METHODS

An axisymmetric, poroelastic model was created using ABAQUS v6.5 finite element software. The model consists of an NP, an AF, cartilaginous and bony portions of the adjacent endplates, and cancellous and cortical portions of the corresponding vertebrae. The standard poroelastic theory is utilized, but a user-defined material was written to include the effects of osmotic swelling. The model response was validated against experimental results such as axial displacement, radial displacement of the outer AF, and total fluid lost.

Material properties for each tissue were referenced from literature. However, where these properties were not reported for each degenerative grade, values at each end of the spectrum were gathered and the intermediate values were interpolated. Where no specific degenerative results existed, assumptions were made based on the effects of degeneration on the tissue.

Fixed charge density profiles for healthy (Grade 1) and degenerated (Grade 5) are shown in Fig. 1, as adapted from

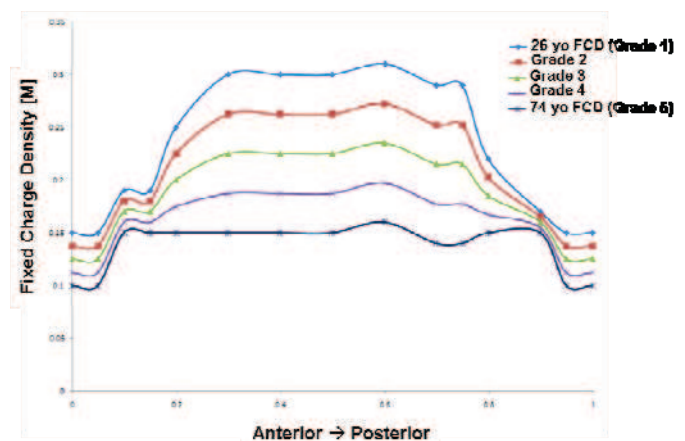


Fig. 1. The interpolated fixed charge density profiles used to model changes in PG content of the IVD with degeneration

Urban [3]. Although the 26 year old disc may not be a Grade 1, it is treated as such for the purpose of this study, as is the 74 year old as a Grade 5. The profiles for Grades 2-4 were linearly interpolated from these reported values.

The unit was loaded with a 0.5 MPa pressure on the upper vertebra, and a 0.1 MPa recovery load. As is seen in experimental studies, a steady-state condition is found after several loading and recovery cycles due to the exchange of fluid. Therefore, each simulation consisted of 4 diurnal cycles, with the last one being considered the steady-state cycle.

### RESULTS

Fig. 2 shows the von Mises stress contour plots of the NP and AF, as well as the NP by itself. This stress value is the stress experienced by the tissue, which is found by taking the stress in the solid portion of the tissue minus the osmotic pressure. Stress at the NP-AF interface increases with degeneration, as does the stress in the majority of the AF. There is an increase in the center of the NP, as well as the NP side of the NP-AF interface.

Pore pressure in the central NP can be seen to increase with degeneration. The high pore pressures are not just contained in the NP, but spill over the NP-AF interface into the inner AF. The outer AF has practically no pore pressure due to the free-flow boundary condition there. The steady state pore pressure does not change very much with degeneration.

For each grade, the highest osmotic pressures are seen in the central NP, and decrease radially outwards towards the outer AF. The central NP decreases the most with degeneration.

### DISCUSSION

The AF experiences the highest stress at its interface with the NP and at the outer corners, where the attachment to the

cartilaginous endplates causes a high stress concentration. Both of these are artifacts of the model. The high concentration of stress at the NP-AF interface is likely an artifact of the abrupt change in material properties across the interface. In the actual tissue, there is a transition zone, which would prevent this by gradually changing properties. Also, in the actual tissue, the AF connects directly to the adjacent vertebrae around the outer edge, and the endplates are completely covered by the annulus fibrosus. There are also no sharp angles or edges in the actual tissue, which is a major cause of stress concentrations.

Due to the high stresses in the NP, the AF must remodel itself to account for the change in properties of the NP. The stress experienced by the NP increases greatly in Grade 2 from Grade 1, but then decreases in Grade 3, and even Grade 4 experiences lower stresses than in Grade 2.

The osmotic pressure in the central NP decreases approximately 75%. This explains the increasing inability of Grades 3 through 5 to recover the fluid lost during the loading periods, since the osmotic pressure gradient is the primary mechanism with which fluid flows back into the disc.

For the steady-state cycle, pore pressure does not change with degeneration. However, pore pressure after the first hour of the first cycle is the smallest at the outer AF, since this boundary allows free exchange of fluid across it. Moving radially inwards towards the center of the NP, the pore pressure increases at every grade. The entire NP and inner AF have the highest values. The pore pressure increases as degeneration occurs, likely due to the decrease in the permeability of the bony endplate from Grade 1 to Grade 5. Since this is the smallest permeability value, it begins the rate limiter of fluid leaving the disc through the endplates.

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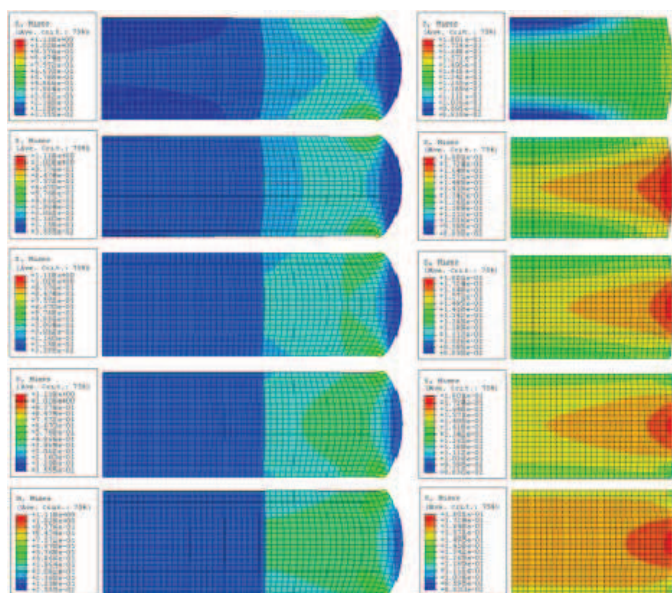


Fig. 2. Comparison of the von Mises stress profiles for Grades 1 through 5 of the NP and AF (left) and NP only (right)