Human Internal Disc Strains in Axial Compression Measured Noninvasively Using Magnetic Resonance Imaging

Grace D. O’Connell, BS,* Wade Johannessen, PhD,* Edward J. Vresilovic, MD, PhD,† and Dawn M. Elliott, PhD*

Study Design. Internal deformations and strains were measured within intact human motion segments.

Objective. Quantify 2-dimensional internal deformation and strain in compression of human intervertebral discs using MRI.

Summary of Background Data. Experiments using radiographic or optical imaging have provided important data for internal disc deformations. However, these studies are limited by physical markers and/or disruption of the disc structural integrity.

Methods. MR images were acquired before and during application of a 1000 N axial compression. Two-dimensional internal displacements, average strains, and the location and direction of peak strains were calculated using texture correlation, a pattern matching algorithm.

Results. The average height loss was 0.4 mm, which corresponded to 4.4% compressive strain. The inner AF radial displacement was outward, even with degeneration; the average outward displacement of the inner AF (0.16 mm) was less than the outer AF (0.36 mm). High shear peak strains (2%–26%) occurred near the endplate and at the inner AF. Shear was higher in the anterior AF compared to the posterior.

Conclusion. This technique allows quantification of displacement and strain within the intact disc. The radial displacements of inner AF suggest NP translation under compression. Peak tensile radial strains occurred as vertical bands throughout the anulus, which may contribute to radial tears and herniations. The tensile axial and shear strains at the interface between the AF and endplate could be related to the occurrence of rim lesions. Peak strains at the endplate are likely due to the AF curvature and the oblique fibers angle at fiber insertion sites. In the future, this technique may be used to measure disc strain under a variety of loading conditions, such as bending or torsion, and could also be used to study the mechanical effects of disc degeneration and potential clinical interventions.


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The intervertebral disc is heterogeneous, comprised of unique substructures of the nucleus pulposus (NP), anulus fibrosus (AF), and endplates. These tissues work together to permit flexibility of the spine and support and transfer large multidirectional loads. Disc degeneration is associated with a loss of internal structural integrity of the disc, including compromised material properties and localized fissures and tears. Delineating the properties of the altered stress-strain environment are critical to understanding load transduction at the cellular level and further, treatments focused on reversing the mechanical breakdown. Progress toward understanding and treating degeneration has been hampered because the inner workings of the disc under load are not readily observed. Several motion segment studies have quantified external disc displacement and internal pressure; however, limited success has been achieved when attempting to quantify mechanical behaviors within the disc. Finite element models (FEM) have made progress toward elucidating internal disc mechanics, yet their predictions for internal behaviors are difficult to validate due to lack of experimental data. There remains a critical need for quantitative measures of internal mechanical behavior of the disc under physiologic loading.

Experimental studies have attempted to measure internal disc deformations using radiographic or optical imaging methods. Seroussi et al visualized internal deformations of the disc by placing metal beads in the intact disc using needles and tracking the beads on radiographs. It was demonstrated that both inner and outer AF bulge radially outward in nondegenerate discs. However, in partially denucleated discs, the inner AF bulged inward, while the outer AF maintained an outward bulge. Meakin et al extended this work using optical image tracking to follow the deformation of Alcian blue stain dots on sagittally bisected discs sealed against a sheet of transparent Plexiglas. That study also showed that denucleation altered the movement of the inner AF, which was validated for intact MR images; however, displacement and strains were not quantified. More recently, Costi et al quantified intradiscal strains associated with bending loads using radiographs to track the deformation of thin wires inserted into human intervertebral discs. Tsantrizos et al quantified...
found that the NP migrates within the disc space during bending and that radial strains were larger in degenerate discs compared to nondegenerate discs. Costi et al.\(^{14}\) found high shear strains located in the posterior and posterolateral regions of the disc in compression. Kusaka et al. placed nylon threads into bovine tail discs and acquired magnetic resonance images (MRI) under a compression load to infer internal disc movements in the sagittal plane from the thread cross section.\(^{15}\) They noted that the inner AF moved outward more than the outer AF and observed less bulging of the outer AF than expected.

All of these studies serve to advance our knowledge of internal disc mechanical behaviors. While these techniques have generated important data, they are limited by the insertion of physical markers or disruption of the disc’s structural integrity. Physical tracking markers may move separately from the disc material and their insertion, whether wires, threads, or beads, may alter the deformations within the disc. Tracking the movement of stain dots provides improvement over the use of metal beads; however, sagittal bisection of the disc likely depressurizes the NP and releases the circumferential pre-stress within the AF. Furthermore, these studies primarily evaluate displacement only at the middle of the disc height, with sparse data toward the endplate boundaries.

To date, no study has directly measured deformations within the disc without interruption of the structure to place markers or visualize the surfaces. The objective of this study was to directly quantify disc internal displacements and strains under axial compression using MRI and texture correlation. Texture correlation is a technique that can be used to determine displacements without the use of physical markers by matching unique pixel intensity patterns between images during a deformation.\(^{19,20}\) The accuracy and reliability of this approach for soft tissue strain analysis of MRI have been validated.\(^{20}\)

Various forms of texture correlation have been used to track deformations under applied load within bone, tendon, cartilage, and cardiac tissues.\(^{19–25}\) In this study, nondegenerate and moderately degenerate human bone-disc-bone motion segments were evaluated. Two-dimensional displacement, average strain, and the location and direction of peak strain were determined from sagittal MRI of the discs. Additionally, the ability of the technique to detect displacement within each of the disc substructures (e.g., AF, NP, vertebral body) was assessed by quantifying the strength of the matches made between the reference and loaded images.

### Materials and Methods

#### Sample Preparation.
Six human spine sections were obtained from an IRB approved tissue source (NDRI, Philadelphia, PA). T2-weighted images were obtained in order to determine degenerative grade based on the Pfirrmann scale.\(^{26}\) Motion segments were prepared from level L1–L2 or L2–L3 (n = 7; 22–77 years old, Grades 1–4, Table 1). The upper lumbar levels were chosen to minimize the effects of spinal curvature, allowing application of axial compression with minimal bending due to wedged-shaped discs. A bone-disc-bone motion segment was prepared by removing the musculature and posterior facets. The motion segment was potted in polymethyl methacrylate bone cement, then wrapped in gauze and hydrated in a refrigerated phosphate-buffered saline bath for 15 hours before testing. The sample was allowed 3 hours to equilibrate to room temperature before testing and was kept wrapped in saline-soaked gauze during imaging to prevent tissue dehydration.

#### Magnetic Resonance Imaging.
A load frame was constructed of nonmagnetic materials in order to apply axial compressive loads to the intervertebral disc while in the MR scanner (Figure 1). The load frame consisted of a hydraulic cylinder (URR-17-1/2, Clippard Minimatic) connected to a pressurized nitrogen source. Aside from the stainless steel cylinder, all remaining components of the frame were machined from either PVC or Delrin plastic to minimize magnetic susceptibility artifacts. MRI has been used to acquire disc images using similar nonmagnetic compression frames; however, quantitative dis-

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**Table 1. Information Regarding Each Sample, Including Age and Grade, Cross-sectional Area, and Applied Stress**

<table>
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<th>Sample No.</th>
<th>Age (yr)</th>
<th>Grade</th>
<th>Area (mm(^2))</th>
<th>Applied Stress (MPa)</th>
<th>Compressive Strain (%)</th>
<th>Height Loss (mm)</th>
<th>Outer AF Radial Displacement (mm)</th>
<th>Inner AF Radial Displacement (mm)</th>
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The compressive strain and disc height loss were calculated from a single row of nodes at each endplate. Mean (SD) is shown for nondegenerate, degenerate, and pooled samples. Radial displacement average of AAF and PAF for outermost and innermost nodal point at mid-disc height.
placements and strains were not reported.\textsuperscript{16,27} Before imaging, the load frame and hydraulic cylinder were calibrated using an in-line load cell in place of the sample (Model SM150, Interface). The load cell was removed from the system during imaging.

The sample was placed into the custom nonmagnetic device described above. Imaging was performed on a high-field 3T MR scanner (Trio, Siemens Medical Solutions). A high resolution T2-weighted turbo spin-echo sequence was used to acquire a midsagittal MRI with a custom-built 80 mm square surface coil (512 \times 512 matrix size, TR = 3000 milliseconds, TE = 113 milliseconds, 10 averages, total scan time 12.5 minutes). The acquired image had a resolution of 0.234 mm/pixel. For subsequent strain analysis, the image size was increased to 11.8 pixels per mm (0.0847 mm/pixel) by interpolating the signal intensity between pixels to increase the size of the images (Adobe Photoshop 6.0, Inc.).\textsuperscript{28} Initially, the motion segment intensity between pixels to increase the size of the images pixels per mm (0.0847 mm/pixel) by interpolating the signal intensity between pixels to increase the size of the images (Adobe Photoshop 6.0, Inc.).\textsuperscript{28} Initially, the motion segment was imaged under a minimal tare load of 20 N. A 3-mm-thick sagittal slice was acquired to obtain a reference image for texture correlation. A 2-mm-thick axial slice was acquired to calculate the disc area using a custom program described previously.\textsuperscript{29} A step input was used to apply a compressive load of 1000 N and was applied and maintained for 20 minutes, to allow for creep deformation, before repeating the imaging sequences described above to acquire a deformed image. Preliminary studies showed that 20 minutes provided sufficient creep deformation to minimize tissue movement during imaging, with only 0.16 mm (<\(\frac{1}{4}\) pixel) displacement during the imaging time period (Figure 2). In another preliminary study, 2 images were acquired without load and analyzed to determine the potential contribution of noise to strain measurements. With an average signal to noise ratio of 13, noise in the image did not affect strain measurement.

Assessment of Vic2D. Two-dimensional Lagrangian strain was calculated from optical images using commercial software, Vic2D (Vic2D, Correlated Solutions Inc.). Vic2D is a pattern matching algorithm which is used to find the closest match between the undeformed and deformed images and provides a displacement resolution of \(\pm 1/200\)th of a pixel or 0.012 mm. Before applying the correlation technique to images of the intervertebral disc, a parametric study was performed to select the optimal analysis parameters for MR images of the disc and to evaluate whether there was sufficient texture to accurately calculate deformations. The subset, step and strain window size were varied on a representative sample. The subset size controls the region of the image being evaluated to compare between the undeformed and deformed images, which has to be large enough to ensure enough texture for evaluation (varied from 15 to 101 pixels). The step size determines how closely spaced the nodes are located with the smaller values being a more dense grid pattern (varied from 2 to 16 pixels). Finally, the strain window size is a smoothing function used in making the strain maps with an increasing number representing an increased amount of smoothing in the strain maps (varied from 3 to 21 pixels). Strain maps were evaluated for missing data points or default values in the strains over the parameter ranges described above. Average strain and standard deviations were also taken into consideration when selecting the appropriate parameter settings. Because image resolution and tissue texture varies greatly depending on the image source and type of tissue, this type of parametric analysis should always be performed to select appropriate parameters and verify that sufficient texture is present within the tissue image.

Disc Internal Displacement and Strain Analysis. Two-dimensional internal deformations of intact human motion segments were calculated from sagittal MRI acquired in the reference condition (20 N) and in the loaded condition (1000 N compression) using the strain analysis program described above. Axial displacement of the endplate, axial change in disc height, and AF radial displacement at the mid-disc height were evaluated. The outer and inner AF radial displacement (bulge) was calculated as the average of the AAF and PAF nodal displacement at the outer and inner AF site. The images were divided into 4 analysis zones: anterior anulus fibrosus (AAF), posterior anulus fibrosus (PAF), nucleus pulposus (NP), and the vertebral body (VB) (Figure 3). Strain maps were created to visualize the 2-dimensional tissue strains and compare across specimens. The locations of radial, axial, and shear peak strains

![Figure 2](image-url)\textsuperscript{16} Creep displacement of a human disc under 1000 N compressive load. Total displacement during imaging of the deformed image was 0.16 mm, less than \(\frac{1}{4}\) of a pixel.

![Figure 3](image-url)\textsuperscript{28} Texture correlation was used to determine 2-dimensional displacements on 4 subzones: anterior anulus fibrosus (AAF), posterior anulus fibrosus (PAF), nucleus pulposus (NP), and the vertebral body (VB). The coordinate system was defined with \(x_1\) as the disc radial direction and \(x_2\) as the axial direction. Solid white box in the AAF zone represents the subset size used for this study.
were determined, and the average strain components for each disc zone were computed.

Results

The lamellar architecture for the AF and the trabeculae within the vertebral bodies were clearly observed in the MR images (Figure 3). The 1000 N applied load corresponded to a compressive stress of \(0.74 \pm 0.15\) MPa, based on cross-sectional areas calculated from the axial reference MR images (Table 1). The average disc height loss was \(0.4 \pm 0.2\) mm, which corresponded to \(4.4\% \pm 1.3\%\) axial compressive strain (Table 1). All components of strain in the bone were nearly zero (\(0.1\% \pm 0.2\%\), \(-0.1\% \pm 0.5\%\), \(0.4\% \pm 0.2\%)\), for radial, axial, and shear, respectively, Figure 4), indicating that the majority of the deformations were confined to the intervertebral disc. Endplate failure was not observed in any of the discs. This was confirmed by the axial displacements measured along the superior and inferior endplates: the linear nodes along the superior and inferior endplates remained linear with a constant axial displacement or a gradual change along the endplate length.

From the parametric study, all 4 tissue regions provided sufficient texture for analysis, with the exception of the NP in 1 of the discs. With a small sample size or step size, missing data points or default values occurred in the strain maps. The average strain values were most sensitive to the subset size. As the subset size increased the average strain plateaued and stabilized with a decrease in the standard deviation (Figure 5A). The average strains stabilized for each tissue zone evaluated at a subset size of 41, 51, or 61 pixels; therefore, a size of 61 pixels was selected for strain analysis in all zones (Figure 3). As the step size or strain window size increased, the standard deviation decreased and the integrity of the strain maps improved. However, a very large step size or strain window size affected the local strain details. The analysis showed that optimal settings included a step size of 8 pixels and a strain window size of 11 pixels, based on the integrity of the strain maps and the standard deviation (Figure 5B).

Radial displacement at the mid-disc height was examined for both the AAF and PAF to determine the magnitude and direction of AF bulging. The average radial displacement of the outer AF was \(0.36 \pm 0.10\) mm (Table 1), calculated as the average radial displacement for the outer AAF and PAF nodes. Outward bulging of the outer AF was observed in all samples save for the anterior region of 1 moderately degenerate disc (#6 in Figure 6). The average radial displacement of the inner AF was \(0.16 \pm 0.16\) mm and was a positive outward bulge for 6 of the 7 discs (Table 1). Three of the discs (#5–7 in Figure 6) exhibited inward bulging of 1 side of the AF; however, the displacement on the other side was outward and larger in 2 of the samples. For 1 sample (#5 in Figure 6) the inward bulge was greater than the outward bulge.

AF contained peak radial strain (\(E_{11}\)) regions of tension (1%–19%) and/or compression (1%–6%) that were often banded vertically (Figures 4, 7, and 8, arrows; Table 2). The NP radial tensile strains ranged from 3% to 10% and peak compressive strains ranged from 1% to 10% and located as bands. The site of the peak strain is denoted by an asterisk in Figures 7 and 8. The average radial strain for the discs was 2.6% in the AAF, \(-0.04\%\) in the NP and 1.6% in the PAF (Table 3).

The axial strain (\(E_{22}\)) was large and compressive along a horizontal band at the mid-disc height, with peak
strains ranging from 2% to 25% throughout the disc (Figures 4, 7, and 8; arrow, Table 2). Tensile strains occurred near the endplates in 5 of the 7 discs, with peak strains ranging from 0.1% to 5% (Figures 4, 7, and 8, asterisk). The peak compressive strain tended to be higher in the AAF (11% ± 7%) compared with the PAF (6% ± 3%), and the average axial compressive strain was 5.9% in AAF and 3.4% in PAF (Tables 2 and 3, respectively). The peak compressive strain in the NP was 8% ± 4% with an average strain of 4.0%.

The shear strain (E_{12}) was highest near the endplate and at the inner AF locations, with peak absolute values of shear strains ranging from 5% to 26% at the AAF, 3% to 18% in the NP and 1% to 11% at the PAF (Figures 4, 7, and 8, arrows; Table 2). The peak shear strain was higher in the AAF (11% ± 7%, n = 7) compared with the PAF (6% ± 3%). The average shear strain was 5.0% in the AAF, 3.3% in the NP, and 2.6% in the PAF (Table 3).

**Discussion**

Two-dimensional internal displacements under compression were measured noninvasively by applying texture correlation to MR images of nondegenerate and degenerate bone-disc-bone motion segments. Nodal displacements were used to calculate 2-dimensional Lagrangian strain components of the midsagittal plane. The applied load (1000 N, ~1.2× body weight) corresponded to 0.74 MPa applied compressive stress (Table 1), representing moderate to low physiologic stresses encountered while sitting or walking.

The radial displacements at the mid-disc height were evaluated for the outer and inner AF boundary. The observed outward bulge of the outer AF was as expected based on the compression of a thick walled vessel that has been predicted in models. The magnitude of AF outward bulge (0.4 mm) was similar to values reported by previous studies: 0.3 to 0.6 mm. The radial displacement of the inner AF was positive (outward) for 6 of the 7 samples (Table 1). NP pressurization causes the outward radial bulge of the inner AF that would otherwise be predicted to be inward in the absence of a pressurized center based on previous denucleation studies and predicted by FEM. While some degenerated samples had an inner AF surface deforming inward, the other side was always outward and of a high magnitude (Figure 6). This may be due to NP shifting under applied load, as previously observed on axial MRI sections during bending. The outer AF outward displacement was larger than the inner AF displacement, which requires tensile radial strains in a volume conserving system, as was observed in Figure 4, 7, and 8 (E_{11}, arrows).

Tensile radial strains are produced when the outer AF boundary deforms outward more than the inner AF, which can be observed as vertical bands in Figures 4, 7, and 8 (positive E_{11}, arrows). It is thought that radial tears begin at the inner AF and progress toward the outer boundary; therefore, these peak tensile strains may contribute to radial tears and herniations. Matrix stiffness increases with degeneration, which may be a remodeling response to reduce radial strain and protect the inner AF from radial tears. Nearby regions of compression stress were also observed (negative E_{11}, arrows). The strain environments encountered by AF cells in these adjacent tensile and compressive AF regions are quite
different; although the effect on cell function is unknown, it would be difficult to detect by assays which pool cells across the AF.

Tensile axial strain \(+E_{22}\) had peaks toward the endplate and shear strains \(E_{12}\) had peaks toward both the endplate and the inner AF. The peak strains at the endplate are likely due to the AF curvature, which is large at both the inner and outer AF, and due to the oblique fiber angle where the AF fibers insert into the endplate and vertebral body. Large interlamellar shear stresses in the disc have been predicted from FEM with applied compression loads.\(^{12}\) Predicted shear stresses were higher along the innermost layer of the AF,\(^{12}\) consistent with the site of large \(E_{12}\) observed here. The large shear strain observed at the endplates in the present study corresponded to strains predictions by FEM.\(^{10}\) It is likely that effects of lamella curvature and material inhomogeneity at the insertion site would account for the large shear strains, further emphasizing the utility of direct internal strain measurement to compare with FEM. Compressive axial strains \(E_{22}\) were highest along the midtransverse plane. The cause of the horizontal banding within the AF axial strain map is unknown and has not been predicted by FEM.

Figure 7. Radial \(E_{11}\), axial \(E_{22}\), and absolute shear \(E_{12}\) strain maps of the AAF, NP, and PAF for a moderately degenerate disc (\#2 in tables). All strains are represented as a percent of strain. Peak strain location denoted by an asterisk, features described in the text are denoted by a solid arrow. Note that the zero strain location changes for each image.

Figure 8. Radial \(E_{11}\), axial \(E_{22}\), and shear \(E_{12}\) strain maps of the AAF, NP, and PAF for a degenerate disc (\#6 in tables). All strains are represented as a percent of strain. Peak strain location denoted by an asterisk, features described in the text are denoted by a solid arrow. Note that the zero strain location changes for each image.
The use of texture correlation analysis on MRI of the intervertebral disc was verified through a parametric study. The ability to find a unique match between reference and deformed image pairs is dependent on the inherent texture of the images. While the accuracy and reproducibility of this approach has previously been assessed and validated, no gold standard exists to compare the internal displacements and strains measured in this study. However, the whole disc displacements and strains correspond well to those reported for motion segment testing. There was a 0.1 to 0.6 mm decrease in disc height, which corresponded to 3% to 6% compressive strain. FEM models predict 0.5 to 0.7 mm decrease in disc height under 1000 N compression, similar to this study. Disc height loss of 0.8 to 1.5 mm has been reported under similar loads; these somewhat higher values are likely due to the use of crosshead displacement, which overestimates disc tissue strain. Other explanations may be inclusion of the neutral zone in the cited studies, which the 20 N tare load likely eliminated in the present study (0.1–0.3 mm neutral zone displacement occurs between 0 and 20 N). Differences in applied loading protocols, and the use of nonoptical strain measurements. The compression modulus, calculated as stress/strain, was 19 ± 9 MPa, which is within the range of previous human motion segment studies. In general, the whole disc displacement, stress, strain, and modulus was representative of human data in the literature.

The methods used in this study are subject to some limitations. Viscoelastic creep during image acquisition was reduced by allowing 20 minutes of creep before acquisition; however, based on preliminary studies, approximately 0.16 mm of additional creep during the imaging time could have affected the internal deformations. Water movement through the disc while under compression was not thought to affect the strain analysis due to the image being acquired in a steady state condition, and an average decrease in signal intensity of 5.8% did not affect selection of the deformed node, since the decrease in signal intensity is locally uniform. In addition, a small sample size was used in this study, which prevented statistical comparisons. Although the upper levels were used for this study, future studies will use the lower lumbar levels and study the degenerative changes of internal tissue strain. Future work will attempt to extend analyses of the strain distribution beyond the peak and average values reported here so that qualitative observations (e.g., vertical banding of strain regions) can be quantitatively expressed.

## Conclusion
This is the first study to use MRI to noninvasively measure internal strains within the intact human intervertebral discs.

### Table 2. Peak Strain in the Anterior Anulus Fibrosus (AAF), Nucleus Pulposus (NP), and the Posterior Anulus Fibrosus (PAF) for Each Strain Component: Radial (E_{11}), Axial (E_{22}), and Absolute Shear (E_{12})

<table>
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<tr>
<th>Sample No.</th>
<th>AAF (+/-)</th>
<th>AAF (+/-)</th>
<th>NP (+/-)</th>
<th>NP (+/-)</th>
<th>PAF (+/-)</th>
<th>PAF (+/-)</th>
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<td>NA</td>
<td>10.0</td>
<td>8.9</td>
<td>4.7</td>
<td>11.0</td>
</tr>
</tbody>
</table>

| Average    | 8.1 (6.2) | 2.9 (1.4) | 5.4 (2.5) | 4.9 (4.0) | 6.7 (3.1) | 3.4 (2.0) | 1.8 (2.1) | 11.3 (7.4) | 1.8 (1.6) | 7.8 (4.0) | 1.0 (0.7) | 6.1 (2.5) | 11.2 (7.3) | 8.5 (5.8) | 6.0 (2.9) |

All strains shown as percent. Mean (SD) is shown for all samples.
NA indicates not applicable.

### Table 3. Average Strain in the Anterior Anulus Fibrosus (AAF), Nucleus Pulposus (NP), and the Posterior Anulus Fibrosus (PAF) for Each Strain Component: Radial (E_{11}), Axial (E_{22}), and Absolute Shear (E_{12})

<table>
<thead>
<tr>
<th>Sample No.</th>
<th>AAF</th>
<th>NP</th>
<th>PAF</th>
<th>AAF</th>
<th>NP</th>
<th>PAF</th>
<th>AAF</th>
<th>NP</th>
<th>PAF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>-1.2 (1.4)</td>
<td>1.5 (1.4)</td>
<td>5.2 (1.1)</td>
<td>-0.2 (1.0)</td>
<td>-2.2 (1.1)</td>
<td>-5.6 (0.7)</td>
<td>3.0 (1.1)</td>
<td>4.5 (1.8)</td>
<td>0.5 (1.6)</td>
</tr>
<tr>
<td>2</td>
<td>0.6 (0.7)</td>
<td>0.9 (2.3)</td>
<td>2.6 (2.6)</td>
<td>-2.1 (1.1)</td>
<td>-3.6 (1.3)</td>
<td>-3.4 (1.7)</td>
<td>3.3 (1.3)</td>
<td>1.7 (0.9)</td>
<td>1.6 (1.1)</td>
</tr>
<tr>
<td>3</td>
<td>-2.0 (2.3)</td>
<td>—</td>
<td>-2.0 (2.2)</td>
<td>-11.5 (2.8)</td>
<td>—</td>
<td>-3.9 (1.9)</td>
<td>13.7 (5.6)</td>
<td>—</td>
<td>3.3 (1.6)</td>
</tr>
<tr>
<td>4</td>
<td>7.6 (3.8)</td>
<td>1.1 (0.9)</td>
<td>-1.4 (1.8)</td>
<td>-9.7 (8.3)</td>
<td>-4.3 (1.3)</td>
<td>-1.5 (0.8)</td>
<td>5.6 (2.9)</td>
<td>2.1 (1.1)</td>
<td>2.0 (1.6)</td>
</tr>
<tr>
<td>5</td>
<td>5.6 (3.7)</td>
<td>-3.4 (3.9)</td>
<td>-2.1 (1.2)</td>
<td>-6.0 (3.8)</td>
<td>-1.5 (1.8)</td>
<td>-0.3 (0.9)</td>
<td>2.0 (1.8)</td>
<td>7.0 (4.2)</td>
<td>3.1 (1.2)</td>
</tr>
<tr>
<td>6</td>
<td>6.6 (2.3)</td>
<td>-1.9 (4.8)</td>
<td>2.8 (2.3)</td>
<td>-6.7 (1.7)</td>
<td>-8.3 (2.3)</td>
<td>-3.9 (1.5)</td>
<td>4.0 (3.0)</td>
<td>3.7 (1.9)</td>
<td>3.8 (1.7)</td>
</tr>
<tr>
<td>7</td>
<td>1.4 (1.9)</td>
<td>1.7 (1.6)</td>
<td>2.3 (2.0)</td>
<td>-5.0 (2.3)</td>
<td>-4.1 (2.1)</td>
<td>-5.3 (1.5)</td>
<td>3.4 (2.4)</td>
<td>1.2 (1.1)</td>
<td>2.9 (1.9)</td>
</tr>
</tbody>
</table>

| Average    | 2.6 (3.9) | -0.04 (2.1) | 1.6 (2.5) | -5.9 (4.0) | -4.0 (2.4) | -3.4 (1.9) | 5.0 (4.0) | 3.3 (2.2) | 2.6 (0.2) |

All strains shown as percent. Mean (SD) is shown for all samples.
bral disc. This technique provides a method to examine the interactions of the disc components under load. The findings in this study provide new information about the interface between the AF and the endplate, most notably high tensile axial and shear strains. These could be the cause for the high occurrence of endplate related failures, such as rim lesions. Inward bulge of the NP with degeneration was not observed; rather, the NP translates, associated with alterations in tensile strain in the AF. The strain values and gradients measured in this study can be used to validate and improve predictions of disc finite element models. Ultimately, MRI and texture correlation may be used to measure intradiscal strain fields under a variety of loading conditions, such as bending or torsion, and could also be used to study the mechanical effects of nucleotomy or other clinical interventions.

**Key Points**

- Internal displacements and strains were quantified within the intact disc by applying texture correlation to sagittal MR images acquired before and during axial compression.
- Outward radial bulge of the inner AF was observed for 6 of the 7 samples. The radial displacements of inner AF suggest NP translation under compression.
- Peak tensile radial strains occurred as vertical bands throughout the annulus, which may contribute to radial tears and herniation.
- The peak shear strains at the interface between the AF and endplate are likely due to the AF curvature and the oblique fibers angle at fiber insertion sites, and they could be related to the occurrence of rim lesions.
- In the future, this technique may be used to measure disc strain under a variety of loading conditions, such as bending or torsion, and could also be used to study the mechanical effects of disc degeneration and potential clinical interventions.

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**References**


