Nucleus pulposus deformation in response to lumbar spine lateral flexion: an in vivo MRI investigation

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Abstract Whilst there are numerous studies examining aspects of sagittal plane motion in the lumbar spine, few consider coronal plane range of motion and there are no in vivo reports of nucleus pulposus (NP) displacement in lateral flexion. This study quantified in vivo NP deformation in response to side flexion in healthy volunteers. Concomitant lateral flexion and axial rotation range were also examined to evaluate the direction and extent of NP deformation. Axial T2- and coronal T1-weighted magnetic resonance images (MRI) were obtained from 21 subjects (mean age, 24.8 years) from L1 to S1 in the neutral and left laterally flexed position. Images were evaluated for intersegmental ranges of lateral flexion and axial rotation. A novel methodology derived linear pixel samples across the width of the disc from T2 images, from which the magnitude and direction of displacement of the NP was determined. This profiling technique represented the relative hydration pattern within the disc. The NP was displaced away from the direction of lateral flexion in 95/105 discs ($p < 0.001$). The extent of NP displacement was associated strongly with lateral flexion at L2–3 ($p < 0.01$). The greatest range of lateral flexion occurred at L2–3, L3–4 and L4–5. Small intersegmental ranges of axial rotation occurred at all levels, but were not associated with

NP displacement. The direction of NP deformation was highly predictable in laterally flexed healthy lumbar spines; however, the magnitude of displacement was not consistent with the degree of intersegmental lateral flexion or rotation.

Keywords Lumbar spine · Lateral flexion · Nucleus pulposus · Deformation · MRI

Introduction

An increased knowledge of lumbar spine pathomechanics has improved our understanding of the cause and effect of low back pain. However, a major focus has been on sagittal plane motion, particularly flexion, on the assumption that this represents the most functional lumbar motion [1]. Sagittal motion also contributes to the greatest directional range and is most often implicated as an injuring mechanism [2]. Axial and coronal plane motions, however, are important components of spinal segmental mobility, but have not attracted the same attention in the literature due to the complexities of coupled motion.

Existing literature focuses on regional range of coronal plane motion [3, 4] and on functional consequences related to sports [5]. Earlier studies on intersegmental range [6, 7] provide limited insight into the mechanics of side flexion. Little consideration is given to the effect of side flexion on the intervertebral disc (IVD). As IVD dimensions in the coronal plane are approximately 50% greater than in the sagittal plane [1], it is reasonable to infer that lateral movement will generate higher stress distributions within the IVD than sagittal displacement [1]. Combinations of movement in both planes can generate very high intradiscal and annular tensile strains, especially when combined with axial rotation [8] and as such are implicated in injury [1, 9].

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Lateral flexion and axial rotation are coupled movements within the lumbar spine [10]. It is well known that primary movement in one plane induces movement in the other, likely through the combined influence of bony architecture, intervertebral disc, ligamentous compliance and muscle action [11]. However, dispute exists about the relationships between the axial and coronal plane contributions [12]. Despite this, assessment of motion in one direction should give due consideration to the other.

The nucleus pulposus (NP), by virtue of a high proteoglycan content, acts hydrostatically to attenuate load through the disc and distribute force to the annulus and end plates. Examination of hydration profiles in the NP can therefore reflect deformation patterns in response to offset loading. Several *in vivo* studies of healthy individuals, employing magnetic resonance imaging (MRI), have reported IVD deformation in the sagittal and axial plane [13–16] and in scoliosis [17]. Limited data on NP deformation in lateral flexion exist mainly from cadaver studies [18]; however, no investigations to date have reported *in vivo* NP deformation in response to induced lateral flexion.

MRI provides an elegant method of examining NP response to postural changes of the spine. Novel methods of image analysis using T2-weighted MRI images have previously been used to quantify NP deformation [15]. This hypothesis-generating study sought to quantify *in vivo* NP deformation in response to side bending in healthy volunteers. Additionally, the association between lateral flexion and axial rotation range were examined to evaluate the direction and extent of NP deformation.

Methods

A total of 21 healthy volunteers were recruited to the study, 11 female and 10 male, with a mean age of 24.8 years (range: 20–34 years). Exclusion criteria included contraindications to MRI or significant degenerative disc disease, as assessed by two senior orthopaedic surgeons (Y.I. and Y.S.). Prior to the study, institutional ethics approval was obtained and each subject provided written consent.

Subjects were initially positioned supine on the gantry of a 0.2-T horizontally open MRI unit (AIRIS mate, Hitachi Inc., Sapporo, Japan). The gantry was inserted into the magnet and a series of T1- and T2-weighted images acquired first in the supine neutral and, following re-positioning, sequences were repeated in the laterally flexed posture.

The axial T2 relaxation sequences were acquired through the mid-disc region from L1–2 to L5–S1 with a fast-spin echo sequence [3120/120 (TR/TE), FOV 260], 8 mm slice thickness and an acquisition time of 6 min 52 s. Slice position was manually determined from individual

planning images and the slice thickness was optimised at each segment to sample the disc volume.

The pelvis was then stabilised with a strap to prevent rotation and the subject was positioned to left side bending with one assistant manually holding the knees to prevent lateral movement. The subjects were then asked to actively laterally flex to the limit of their range. A second assistant applied overpressure at the shoulders to minimise trunk rotation and to achieve a limit of lateral flexion range, which was maintained passively by the assistants during imaging. Mid-disc image sequences at all levels were repeated using the same parameters.

To evaluate segmental rotation, axial T1-weighted images were taken through the bony vertebrae of L1–S1 using a fast-spin echo sequence [385/24.5 (TR/TE), FOV 300] of slice thickness 6 mm and acquisition time of 5 min 45 s. Finally, coronal T1 images [285/24.5 (TR/TE), FOV 300; 6 mm thickness, 1 min 34 s], which were optimal for demonstration of the bony anatomy, were used to examine lateral flexion (Fig. 1).

Image analysis

From the T1 axial images, rotation angles were calculated by a line from the spinous process of each vertebra to the midpoint of the vertebral body. The vertical image frame was referenced as the sagittal plane and the angle

Fig. 1 Coronal T1-weighted image demonstrating lumbar spine lateral flexion achieved by subject positioning

subtended between each was recorded as the degree of axial rotation of that segment. For the S1 segment, a line was taken from the sacral promontory to the midpoint of the S1 body that was extended posteriorly (Fig. 2).

Lateral flexion intersegmental angles were calculated from the T1-weighted coronal images (Fig. 3). Using image analysis software (NIH Image-J, Bethesda, USA), the corners of each vertebral body from L1 to L5 were identified and marked. The angle was then measured at the intersection of the lines extending through the midpoints between the two anterior and two posterior corners. Each angle was measured twice by two blinded assessors resulting in high reliability (ICC, 0.99).

Direction of NP deformation was derived from the neutral and laterally flexed T2-weighted mid-disc axial images using a previously validated technique [15] and image analysis software (NIH Image-J, Bethesda, USA). This technique enabled pixel intensity profiling to represent the relative hydration pattern within the disc.

On neutral and laterally flexed axial images at each intervertebral level from L1–2 to L5–S1, three lines were placed across the mid-disc region from right to left (Fig. 4). Raw pixel data from these line samples were normalised to 100 points, averaged using a Labview software routine (National Instruments, Austin, USA), then imported into Excel where the direction, extent and pattern of hydration were derived for neutral and laterally flexed image pairs.

The NP did not consistently show a symmetrical profile in the neutral position. Inevitably, there was a small directional offset of NP to either side. This variable was taken into account in the calculations for deformation direction and extent of NP.

Descriptive statistics were used to inspect the data for the direction and extent of NP deformation, in addition to lateral flexion and rotation range at the lumbar levels: L1–2 to L5–S1. The direction of NP deformation in response to posture and segmental level was also recorded. Unpaired *t* tests were used to determine whether a gender difference in flexibility was present. The NP position in neutral and lateral flexion was compared using a paired *t* test. Differences in lateral flexion angles between levels were examined using ANOVA. Finally, simple linear regression was used to test for associations between (i) segmental lateral flexion and (ii) NP deformation and lateral flexion. In all statistical tests, a probability of $p < 0.05$ was used as the criterion to record significant differences.

Results

There was no difference between gender for lateral flexion range of motion ($p = 0.47$); therefore, data were pooled for subsequent analyses. A summary of the results for side flexion, coincident rotation, and the extent and direction of NP deformation for L1–2 to L5–S1 segmental levels is provided in Table 1. In 95% of all cases, a right-sided NP deformation occurred in response to end-range left side flexion, with the exceptions found primarily at L5–S1.

There was a significant difference at all segmental levels contrasting the NP pixel intensity position adopted in the side flexion compared with neutral axial images ($p < 0.001$) (Fig. 4). The most pronounced change in the deformation of the nucleus position was recorded for L2–3, L3–4 and L4–5 (Fig. 4). There was a moderate association

Fig. 2 Calculation of lumbar segment rotation angles from axial images (a) and modification of the Cobb method for calculating segmental lateral flexion angles

Fig. 3 Measurement of pixel intensity in neutral and laterally flexed positions. Average pixel data were sampled from three coronal lines per segment from the paired T2-weighted axial images to represent the relative hydration pattern of NP

Fig. 4 Inter-relationships between segmental side flexion, coincident rotation and the extent of NP deformation following unilateral sustained left side flexion position. Marked change occurred in the apical segments

between magnitude of side flexion and NP deformation only at L2–3 ($r = 0.54$, $p < 0.01$) (Table 1).

The greatest side flexion range was demonstrated at L3–4 and L4–5 (Fig. 4), which were significantly different from other adjacent levels ($p < 0.005$). Coincident rotation was small in contrast and showed no association with side flexion range (Fig. 4).

The apical segments showed the greatest displacement of the NP, which was mirrored in part by the relative extent

of side flexion. There were no associations between NP deformation and segmental axial rotation.

Discussion

This study, involving young, asymptomatic subjects, sought to quantify NP deformation in response to side flexion and to examine side flexion and segmental rotation range relative to a lateral NP deformation.

The results showed a strong correlation between direction of NP deformation and direction of lateral flexion, with 95% of segments (100/105) deforming towards the contralateral side of lateral flexion. The directional relationship between NP deformation and lateral flexion was expected to be strong, assuming a predictable hydrostatic behaviour of NP as it attenuates load in the healthy disc [19]. It was of interest to note that five IVDs deformed towards the side of lateral flexion. Four of these occurred at L5–S1, where smaller ranges of lateral flexion were recorded (mean: 5.4°), and one at L2–3.

From the MRI assessment, there was a significant shift of NP signal intensity away from the direction of side

Table 1 Summary of lumbar mobility and internal disc deformation responses to sustained left side flexion in healthy volunteers

	L1–2	L2–3	L3–4	L4–5	L5–S1
Side bend ($^\circ$) [mean (SD)]	5.2 (2.24)	6.7 (2.22)	6.7 (1.64)	6.7 (3.48)	5.4 (3.86)
Rotation ($^\circ$) [mean (SD)]	0.01 (1.97)	0.96 (2.13)	0.38 (1.74)	0.24 (2.07)	0.68 (2.78)
NP deformation (%)	11.3 (9.75)	18.2 (11.0)	22.5 (7.1)	22.1 (7.95)	7.9 (9.86)
NP direction (%)	21/21 (100)	20/21 (95)	21/21 (100)	21/21 (100)	18/21 (81)

bending, with a mean deformation of 22.5% at the apex of the lumbar curve (L3–4) (refer Table 1). There was a significant correlation between the magnitude of NP deformation and range of lateral flexion at L2–3.

T2-weighted MRI images have been used to map NP hydration profiles in response to changes in spinal posture. Pixel histograms of single [14] or average data [15] have elaborated the putative effect of postural adaptations on IVD hydrostatic behaviour.

Hydration, and therefore signal intensity, as represented from T2-weighted images is not uniform across the IVD or even within the NP. Methods of measuring pixel intensity from a single sample across the IVD may be relatively insensitive to the overall hydration change, particularly if the sampling profiles are not representative of the IVD.

The greatest range of lateral flexion range occurred at the apex of the lateral curve, L2–3 and L3–4, and the least at the upper and lower limits of the curve. Studies by Percy et al. [2, 6], using biplanar radiography of volunteers in an erect position, have reported smaller segmental ranges of motion in lateral flexion than the current study, but greater ranges at L5–S1 and L1–2. This difference may reflect supine positioning within the confines of the MRI in which the pelvis and lower limbs were stabilised, whilst lateral flexion was induced via shoulder and thoracic spine movement. Such positioning may potentially limit the available range at the lumbosacral junction and upper lumbar spine. Additionally, there is a tendency for the spine to demonstrate a correction to neutral at the curve inflexion points, which lie close to the transitional levels. This phenomenon is illustrated in a balanced thoracolumbar scoliosis curve where the inflexion vertebrae show a neutral disc alignment.

Segmental rotation ranges were small by comparison to previous studies [6]. This finding most likely reflects

subject positioning into lateral flexion where rotation was only a secondary response. Care should be taken not to overinterpret these findings with respect to coupling patterns given the constrained nature of the positioning used in the present study. Reports of associations between coronal and axial plane motion provide no consensus as to the directional influence of one motion over the other [12].

There are a number of limitations to this study, which have the potential to influence the interpretation of these data. Measurement errors may arise with the small ranges of lateral flexion and NP deformation, particularly at L5–S1, and the relative initial resting position of the NP. However, repeated assessment showed acceptable accuracy.

Additionally, it is known that 20–25% of the population demonstrate evidence of mild physiological scoliosis [20]. A pre-existing degree of scoliosis would inevitably influence both the NP position in neutral and the potential range of lateral flexion and axial rotation. The available side flexion range may be compromised due to the coupled rotation. It would be of interest to examine the influence of scoliosis in future studies and map the association between NP deformation and the magnitude of the deformity.

There was no significant correlation between rotation range and NP deformation. This is not unexpected given the small ranges of rotation demonstrated. Further elaboration of this in future studies, where rotation was unconstrained, would help define the extent of association between both elements of coupled motion.

This study was limited to young subjects with no history of back pain or macroscopic degenerative change on MRI. Future studies could consider the response of annular injury and degenerative changes of the IVD to end-range side bending and rotation, using this MRI-based technique of hydration mapping.

Fig. 5 Relatively symmetrical 3-D profile of NP in neutral (*right*) in contrast to the profile derived in side flexion (*left*). Surface intensity plots of NP emphasise the displacement of the side flexed NP (*left*) away from the neutral position

The technique employed in the current study involved three line samples across the IVD to integrate and average the assessment of directional NP deformation. More complex 3-D profile maps of the annulus and NP would confer an improved evaluation of hydration patterns across the entire intervertebral disc [17, 21] as illustrated in Fig. 5.

It would be of interest to replicate this study in an open magnet MR imager, which would permit both physiological axial loading and unconstrained lateral flexion. More accurate consideration of conjunct rotation and coupling patterns would then be possible.

Conclusion

This study in young normal volunteers has demonstrated that NP deforms in a predictable direction towards the convexity in a laterally flexed lumbar spine. There was a significant degree of change in NP hydration pattern between the neutral and laterally flexed position, most pronounced at the mid-lumbar levels and less so at L1–2 and L5–S1. The degree to which the NP deforms generally correlates with the degree of segmental lateral flexion. Axial rotation, occurring concomitantly with primary lateral flexion, did not correlate with NP deformation or lateral flexion range. In this study, physiological coupling patterns of the lumbar segments could not be inferred as side flexion was constrained.

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