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Mechanical influence of facet tropism in patients with chronic discogenic pain disorder

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Aims
The presence of facet tropism has been correlated with an elevated susceptibility to lumbar disc pathology. Our objective was to evaluate the impact of facet tropism on chronic lumbosacral discogenic pain through the analysis of clinical data and finite element modelling (FEM).

Methods
Retrospective analysis was conducted on clinical data, with a specific focus on the spinal units displaying facet tropism, utilizing FEM analysis for motion simulation. We studied 318 intervertebral levels in 156 patients who had undergone provocation discography. Significant predictors of clinical findings were identified by univariate and multivariate analyses. Loading conditions were applied in FEM simulations to mimic biomechanical effects on intervertebral discs, focusing on maximal displacement and intradiscal pressures, gauged through alterations in disc morphology and physical stress.

Results
A total of 144 discs were categorized as 'positive' and 174 discs as 'negative' by the results of provocation discography. The presence of defined facet tropism (OR 3.451, 95% CI 1.944 to 6.126) and higher Adams classification (OR 2.172, 95% CI 1.523 to 3.097) were important predictive parameters for discography-'positive' discs. FEM simulations showcased uneven stress distribution and significant disc displacement in tropism-affected discs, where loading exacerbated stress on facets with greater angles. During varied positions, notably increased stress and displacement were observed in discs with tropism compared to those with normal facet structure.

Conclusion
Our findings indicate that facet tropism can contribute to disc herniation and changes in intradiscal pressure, potentially exacerbating disc degeneration due to altered force distribution and increased mechanical stress.

Article focus
- The effect of facet tropism on the discographic 'positive' disc using clinical data and finite element analysis.

Key messages
- Facet tropism can contribute to disc deformation and load distribution due to external force, potentially intensifying the painful disc through the excessive displacement and asymmetric intradiscal pressure.
- This study serves to enhance our comprehension of the pathomechanical influences of facet tropism on discs identified as 'positive' in discography,

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presenting valuable insights essential to establishing tailored therapeutic exercise protocols for these specific patient cohorts.

Strengths and limitations

- We extended the current understanding of lumbar spine biomechanics utilizing 3D finite element modelling (FEM) to simulate various loading conditions, enabling a more comprehensive analysis of the effects of facet tropism on the discographic 'positive' disc.
- Our study faced limitations regarding the lack of comprehensive investigation into environmental risk factors, the absence of standardized quantitative analysis in discography, neglecting changes in static load in FEM simulations, and the inherent constraints of a cross-sectional design.

Introduction

Lumbar facet tropism denotes a condition characterized by a discordance in the orientation of facet joints between the two sides of the lumbar spine.[1] Specifically, facet tropism manifests when an asymmetry of more than 10° is observed between the angles of facet joints on opposing sides of a particular spine level.[2] This condition is frequently identified as an incidental finding in various imaging methods such as plain radiographs, CT scans, or MRI, impacting the biomechanical dynamics of the spine, and consequently instigating atypical loading patterns and degenerative alterations.[3]

Chronic discogenic pain disorders are a type of chronic low back pain caused by damage or degenerative changes to the intervertebral discs, with a complex interplay between mechanical, biochemical, and neurological factors.[4,5] Provocation discography is considered the reference standard for diagnosing discogenic pain.[6] Mechanical factors play a major role in the development of chronic discogenic pain. When the discs are exposed to repetitive or abnormal mechanical stress, they can become damaged, leading to biochemical and neurological changes. Common mechanical factors contributing to the development of discogenic pain include poor posture, prolonged sitting, and repetitive actions such as lifting heavy objects.[7]

Facet tropism is associated with an increased risk of lumbar disc degeneration, lumbar disc herniation, and chronic low back pain.[2] When the facet joints are angled differently on either side, abnormal loading of the discs can occur, leading to increased stress on the discs and surrounding tissues. Theoretically, this may contribute to disc degeneration and chronic discogenic pain. Our objective was to evaluate the impact of facet tropism on chronic lumbosacral discogenic pain through the analysis of clinical data and finite element modelling (FEM).

Methods

Retrospective clinical data

We recruited 163 patients who had undergone provocation discography at the spine clinic of Korea University Medical Center between 1 January 2012 and 31 December 2019. These patients experienced chronic axial lower back pain that persisted for over three months, but had no specific radicular pain extending to their lower limbs. The patients' motor and sensory functions were confirmed to be within normal limits based on their clinical records. The exclusion criteria were as follows: 1) spinal diseases that cause low back pain other than discogenic pain, such as spinal stenosis, infectious disease, spinal tumour, and fracture; 2) incomplete radiological data; and 3) lumbar radiculopathy. The study was conducted retrospectively in accordance with the Declaration of Helsinki,[8] and was approved by the institutional review board of Korea University Medical Center. Owing to the retrospective nature of the study, the requirement for informed consent was waived, and all participant data were stored and used for research purposes anonymously.

Provocation discography was performed and interpreted according to the International Association for the Study of Pain guidelines.[6] The conceptual sequence of the procedural protocol is as follows: pre-evaluation, securing informed consent for the provocation discography procedure, patient preparation, anaesthesia, needle placement, contrast injection, disc evaluation, and post-procedural care. The contrast agent was injected slowly with an automated pressure-controlled discography system. The injection was continued until the patient reported pain, either concordant with accustomed pain or non-concordant pain. The reaction was reported as no pain, dissimilar pain, similar pain, or concordant pain, and the intensity of pain was described using a numerical rating scale. The injection was halted if the patient reported a pain level above six on the visual analogue scale,[9] if the injection volume reached 3 to 4 ml, or if the injection pressure exceeded 50 psi.[6] 'Similar' or 'Concordant' pain was classified as positive, and 'Dissimilar' or 'No pain' was classified as negative. These procedures were conducted by one physician (SHL) with more than ten years of clinical experience in spinal imaging and procedures, and the discographic data were analyzed and confirmed by another physician (NHK).

For the image evaluation, facet joint angles were measured using the method described by Chadha et al.[2] The axial view, which offers the best visualization of the bilateral angles, was chosen, and three auxiliary lines were subsequently added. A midsagittal line was drawn across the vertebrae, passing through the tip of the spinous process and the centre of the disc. Two lines were drawn connecting the anteromedial and posterolateral edges of the superior articular facets. The acute angles between the midsagittal and facet lines and the absolute difference between the two values were measured (Figure 1a). Facet tropism was defined as more than a 10° difference between two joints.[1] The facet orientation angles of the patients were measured based on the CT scan data (Figure 1b). The angles were determined as the median value of three manual measurements based on the axial view in which both facet joints were best observed.

Additionally, in each lumbar segment where provocative discography was performed, the modified Dallas discogram scale and Adams discogram classification were also recorded.[10,11] The Dallas discogram describes six categories (Grades 0 to 5) of information about the annular integrity of target discs based on post-discographic CT scans. Grade 5 represents the most severe degeneration. The Adams discogram classification is divided into five types, with type 5 representing the most severe degeneration.

Two musculoskeletal radiologists (with over 15 years of professional interpreting experience) decided on the values

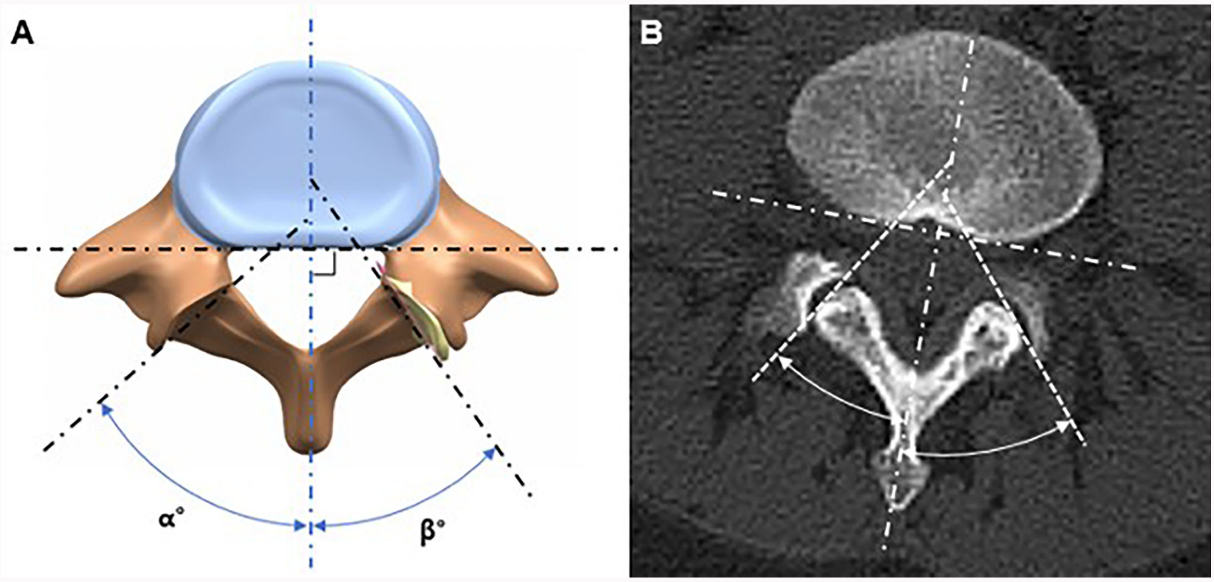

Fig. 1

a) Schematic diagram of facet orientation measurement. The reference plane was defined by the posterior aspect of the vertebral body. The sagittal line was drawn through the spinous process, 90° to the reference plane. The angle between the auxiliary line of the facet joint orientation and the sagittal line was measured. 'α' is the right facet orientation angle, and 'β' is the left. The smaller the angle, the more parallel the facet becomes to the sagittal plane. b) Auxiliary lines applied to the transverse image of L5/S1 level on MRI.

of the facet angles and the degeneration criteria by dividing them according to the participants.

Motion simulation

The detailed procedures for constructing a lumbar spine FEM were sourced from a previous study and the GrabCAD community library.[12,13] We adopted a model of the human lumbar spine from the library, a web community where engineers and designers worldwide can share their computer-aided design (CAD) files. Geometrical information for the human lumbar spine model was extracted from a CT scan of a relatively healthy participant's spine using SOLIDWORKS (Dassault Systèmes SolidWorks Corp, USA), a 3D CAD software, ensuring that the participant was skeletally mature. The model included the cortical bone, cancellous bone, posterior elements, annulus fibrosus, and nucleus pulposus of the L4/5 intervertebral disc. The ligaments included the anterior and posterior longitudinal ligaments, the interspinous ligament, the supraspinal ligament, and the ligamentum flavum. Building on the results of a previous study, we determined a realistic range for the facet angle at L4/5: 46.8° on each angle.[14] Utilizing this range, we created both normal and facet tropism models by varying the facet joint orientations at both L4/5 facet joints in the sagittal plane. We transformed the posterior element of the normal model to create a new facet tropism model in which the angle of one facet joint was highly asymmetric to the other side with regard to the sagittal plane: 46.8° on right angle and 32.4° on left angle. These models were built using the post-processing software NX Nastran (Siemens Digital Industries Software, USA).

The structures of the intervertebral disc, nucleus pulposus, annulus fibrosus, anterior longitudinal ligament, posterior longitudinal ligament, ligamentum flavum, interspinous ligament, and supraspinal ligament were established within the spinal model using the preprocessing function of NX Nastran. In line with relevant FEM verification studies, we incorporated the physical mechanics and mechanical parameters of each component in the normal L4 and L5 vertebral FEMs. These parameters included the density, Young's modulus, and Poisson's ratio for each component.[12,15–18] The material properties of each component were incorporated into NX Nastran. The types of elements and their respective material properties are presented in Supplementary Table i.

The lumbar spine FEM was used to simulate seven conditions, including compressive force, flexion, lateral bending, and axial rotation on both sides, replicating various physiological states.[15,19] In all situations, the stress was primarily focused on the upper L4 vertebral body. Contact conditions were enforced between the disc and the vertebrae, including the facet joint. In addition, the lower part of L5 was constrained to all degrees of freedom during the simulation. Table I presents the different situations, load combinations, forces, and moments applied to the components of the spine. Details are depicted in Figure 2a.

In the lumbar spine FEM, we positioned six nodes at major locations on the L4/5 intervertebral disc to accurately capture the biomechanical behaviour of the spine under loading conditions (Figure 2b). By analyzing the pressure and positional changes in these nodes, we aimed to elucidate their effects on intradiscal pressure and disc displacement, providing novel insights into the role of facet tropism in spinal biomechanics.[20] The outcome measures were the maximal displacement and maximal stress of the L4/5 intervertebral disc, measured by the change in the location (displacement) of the nodes located on the disc and changes in intradiscal pressure on the nodes.

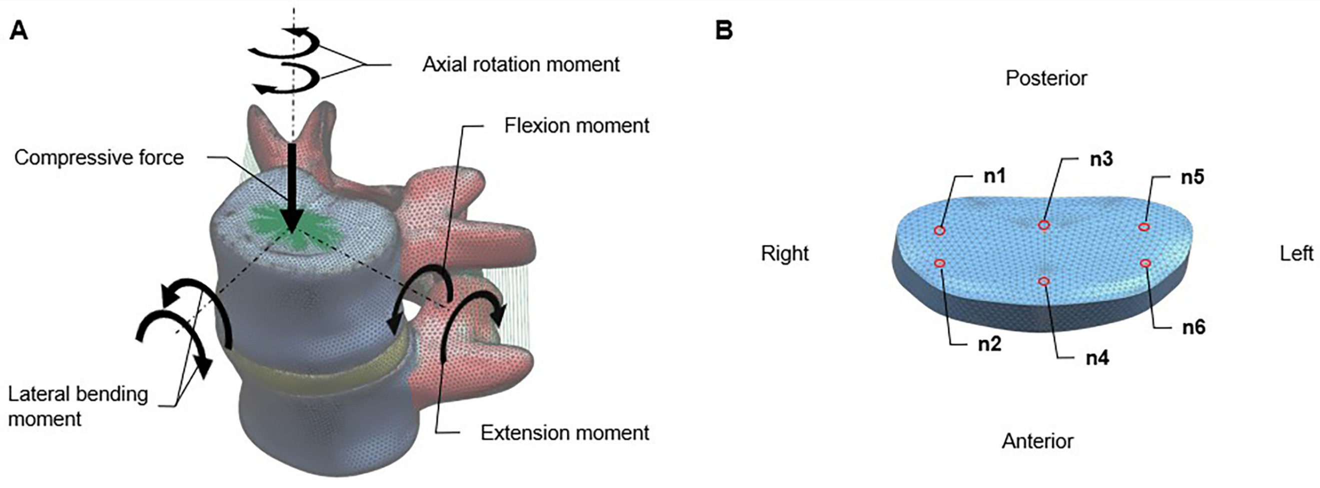

Fig. 2
a) Seven load conditions: compressive force only, axial rotation, right and left lateral bending, right and left axial rotation, flexion, and extension under a compressive force. b) Six nodes at major locations on the L4/5 intervertebral disc.

Table I. The magnitude and combination of loads and moments applied to the intervertebral disc.

Case	Load combination	Force, N	Moment, N-m
Compressive force	Compressive force only	1,175	N/A
Flexion	Compressive force + flexion moment	1,175	7.5
Extension	Compressive force + extension moment	500	7.5
Lateral bending	Compressive force + lateral bending moment	700	7.8
Axial rotation	Compressive force + axial rotation moment	720	5.5

N/A, not applicable.

Statistical analysis

The chi-squared test or independent-samples *t*-test was used to compare data between the positive and negative disc groups. Variables that were significant factors of a discographic 'positive' result in the univariate analysis were subsequently analyzed using a binary logistic regression model. The normality of the data was assessed using the Shapiro-Wilk test. Statistical significance was set at $p < 0.05$. Statistical analyses were performed using SPSS v.25 (IBM, USA).

Subsequently, a multivariate logistic regression model was employed to evaluate the independent association of each factor with discographic results. The three factors that were significant determinants of positive disc findings in the univariate analysis were included in subsequent analyses. The presence of defined facet tropism (OR 3.451, 95% CI 1.944 to 6.126) and higher Adams classification (OR 2.172, 95% CI 1.523 to 3.097) were important predictive parameters for discography-positive discs (Table IV).

Results

Analysis of clinical data

Seven patients were excluded because of the absence of radiological findings, and facet tropism could not be measured. We studied 318 intervertebral levels in 156 patients. The demographic characteristics of the patients are presented and summarized in Table II. A total of 318 intervertebral discs were evaluated using provocation discography. Among them, 144 discs were categorized as 'positive' and 174 discs as 'negative', and univariate analysis was performed for each demographic and clinical variable that affected discographic results (Table III). The distribution of Adams and modified Dallas classification and a disc number of facet tropism defined by the criteria differed significantly between the positive and negative disc groups.

Load distribution to discs on FEM simulation

The intradiscal pressures resulting from the four loading conditions in the model with normal facets were compared with those reported in previous studies.[21–24] The intradiscal pressures of the model were within the range of the other models and close to the median values of all the models. Under extension, lateral bending, and axial rotation, the simulated pressures closely approximated the in vivo intradiscal pressures observed in a study by Wilke et al.[25] The results are presented in detail in Figure 3.

For comparison of intradiscal displacement and loading stress in normal and facet tropism groups, the disc placement and physical stress for the static load and six dynamic loads were estimated using FEM simulation (Figure 4). In the static position, disc placement revealed a larger change on the left

Table II. Patients' baseline characteristics.

Variable	Patients (n = 156)
Sex (male:female), n (%)	93:63 (59.6:40.4)
Mean age, yrs (SD; range)	42.5 (13.7; 18 to 78)
Mean body mass, kg (SD; range)	64.6 (9.9; 44.1 to 102.0)
Mean height, m (SD; range)	1.67 (0.09; 1.47 to 1.87)
Mean BMI, kg/m^2 (SD; range)	23.1 (3.0; 16.1 to 35.8)
Mean symptom duration, mths (SD)	38.9 (46.5)
Median symptom duration, mths (IQR)	22 (6 to 48)
Mean initial pain intensity, NRS score (SD; range)	6.6 (1.4; 3 to 9)

NRS, numerical rating scale.

Table III. Univariate analysis for demographic and clinical data of target discs (n = 318).

Variable	Positive disc (n = 144)	Negative disc (n = 174)	p-value
Mean age, yrs (SD)	41.7 (13.1)	44.1 (13.8)	0.114
Mean body mass, kg (SD)	64.1 (10.1)	64.4 (9.2)	0.749
Mean height, m (SD)	1.67 (0.09)	1.68 (0.09)	0.237
Mean BMI, kg/m^2 (SD)	23.0 (3.0)	22.9 (3.0)	0.656
Level, n			
L2/3	3	4	
L3/4	20	41	
L4/5	67	64	
L5/S1	54	65	0.128
Adams classification, n (%)			
Type 1	5	36	
Type 2	0	14	
Type 3	19	36	
Type 4	53	67	
Type 5	67	21	< 0.001
Modified Dallas classification, n (%)			
Grade 0	1	13	
Grade 1	3	14	
Grade 2	2	15	
Grade 3	17	31	
Grade 4	60	77	
Grade 5	61	24	< 0.001
Z-joint angle			
Mean right, ° (SD)	44.0 (15.3)	44.6 (10.7)	0.432
Mean left, ° (SD)	44.6 (12.1)	43.4 (10.8)	0.314
Facet tropism			
Number (%)	62 (43.1)	36 (20.7)	< 0.001
Mean angular difference, ° (SD)	15.1 (5.2)	14.0 (4.2)	0.271

side of the lesser sagittal facet angle, similar to the flexion position. In both the static and flexion positions, the load-induced stress on the disc tissue increased significantly on the right side with a greater sagittal facet angle. In addition, the axial rotation position on the side with a greater sagittal facet angle received greater load stress on the disc than in the opposite rotation position. In addition, the changes in disc placement during flexion-extension, bilateral bending, and right-left rotation in tropism were significantly greater than that in the normal facet.

Discussion

Upon analyzing clinical data, it was discerned that the discographic 'positive' disc group displayed a more pronounced degree of disc degeneration and a greater frequency of facet tropisms. Regression analysis of the clinical data concerning the identified discs revealed that facet tropism presented a relative risk of 3.451 as a contributing factor to a positive disc. These outcomes were attributed to biomechanical discrepancies stemming from structural asymmetries, prompting the need for a FEM simulation. The predicted results revealed an asymmetric load stress distribution and excessive changes in disc placement during dynamic positions in the intervertebral disc accompanied by facet tropism. Our findings suggest that the facet with a more sagittal orientation, linked to a lesser sagittal facet angle, manifests increased intradiscal stress on the disc during contralateral axial rotation, ipsilateral bending, and flexion postures. Furthermore, these postures elicit more substantial alterations in disc displacement compared to the normal facet group.

From a clinical perspective, unlike the suggested principle of large joint instability, the pathological condition of the spine has been described as abnormal qualitative motion changes and load distribution failure.[26–28] In an experimental study by Sengupta and Fan,[29] as the degenerative change of the intervertebral disc progressed, the intradiscal pressure decreased, and the difference between the intradiscal pressures in the neutral and flexion-extension postures increased. In other words, the internal pressure changes increased according to the posture of the degenerative disc (described as a decrease in the neutral zone). Other finite element studies have revealed that as the degree of lumbar intervertebral disc degeneration increases, the change in shear stress within the intervertebral disc becomes more apparent in response to spinal motion.[21,30] Thus, the clinically significant pathological model of the intervertebral disc predicts internal disc displacement. Our results indicate that the change in intradiscal pressure distribution with facet tropism did not distinctly differ from that with symmetric angles of the facet. The disc displacement based on the posture

Table IV. Multivariate analysis of the three key determinants of discography-positive disc (binary logistic regression analysis).

Variable	B	SE	Wald	OR	p-value	95% CI
Facet tropism	1.239	0.293	17.898	3.451	< 0.001	1.944 to 6.126
Adams classification	0.776	0.181	18.349	2.172	< 0.001	1.523 to 3.097
Modified Dallas classification	0.171	0.184	0.867	1.187	0.352	0.828 to 1.702
Constant	-4.130	0.602	47.115	0.016	< 0.001	N/A

B, unstandardized regression coefficient; N/A, not applicable; SE, standard error; Wald, Wald static.

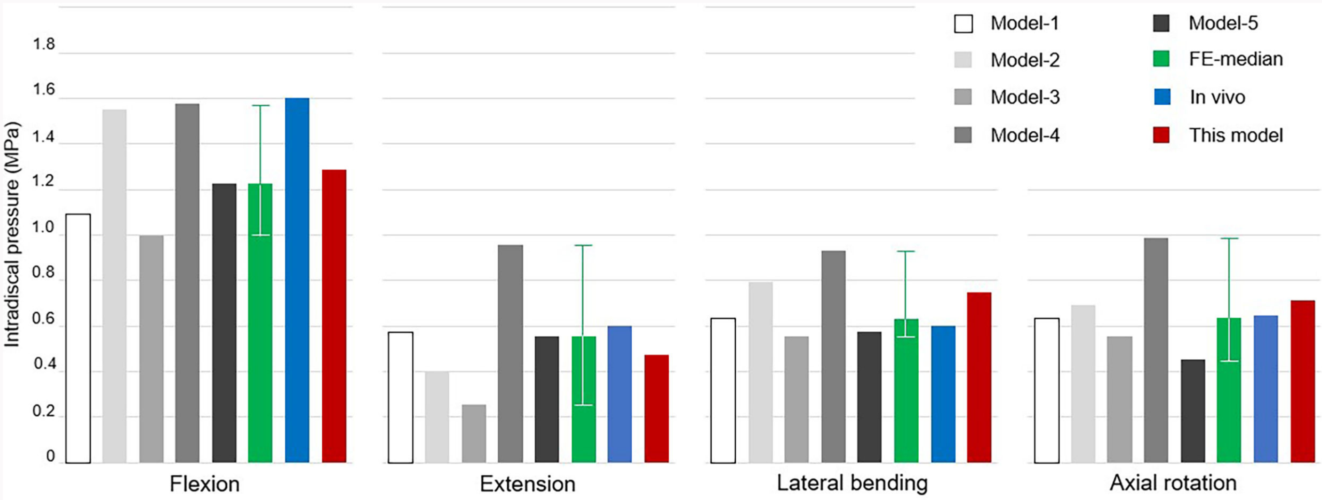

Fig. 3
Comparison between the intradiscal pressures of five finite element models and in vivo measurements for flexion, extension, lateral bending, and axial rotation. The green bar represents the median value of all finite element models and their range (error bars) of results. The red bar shows the results of this model. FE, finite element.

variations, however, showed relative differences between the two models.

Our study demonstrated that facet tropism may contribute to disc herniation and alterations of intradiscal pressure. This finding aligns with those of previous studies that have demonstrated an association between facet joint orientation, lumbar disc degeneration,[20] and facet joint osteoarthritis.[14,31] Facet joints play a crucial role in counteracting compressive forces on intervertebral discs, and facet tropism can disrupt this force distribution, potentially causing imbalanced stress and leading to disc injuries.[32] Recent studies have corroborated our findings, emphasizing the significance of facet orientation in the biomechanics of the lumbar spine.[15,33] For instance, Kanat et al[34] emphasized that asymmetrical morphological and physiological features of the human body can result in directional asymmetry and the onset of lumbar disc degeneration. Jelec et al[35] discussed the influence of facet orientation and tropism on spinal degeneration, suggesting that more pronounced facet tropism could accelerate disc degeneration in the lower lumbar spine. Gellhorn et al[36] highlighted the association between facet joint osteoarthritis and disc degeneration, further underscoring the significance of facet tropism in lumbar spine biomechanics. Another study demonstrated a positive correlation between the facet joint angle of lumbar disc herniation and degeneration of the upper proximal segment of the intervertebral disc, supporting the potential involvement of facet tropism in disc degeneration.[37]

In this study, we extended the current understanding of lumbar spine biomechanics utilizing 3D FEM to simulate various loading conditions, enabling a more comprehensive analysis of the effects of facet tropism on the lumbar spine. The observed differences in disc displacement between the normal and facet tropism groups emphasize the effect of facet tropism on spinal motion. Our results are consistent with those of a previous study on lumbar spine biomechanics, which demonstrated that disc herniation predominantly occurs posteriorly.[38] Furthermore, the most significant disc displacement was observed during the axial rotation towards the contralateral side of the more sagittal-oriented facet joint, indicating that specific movements may exacerbate the biomechanical effects of facet tropism on the lumbar spine. Recent studies have corroborated this finding, further emphasizing the importance of facet joint orientation in the development of disc herniation.[39,40]

Although some results from the FEM simulation demonstrated dynamic load asymmetry, a more notable finding in this study was the difference in disc displacement occurring during dynamic motion. Based on these results, an increase in the shear force within the intervertebral disc can

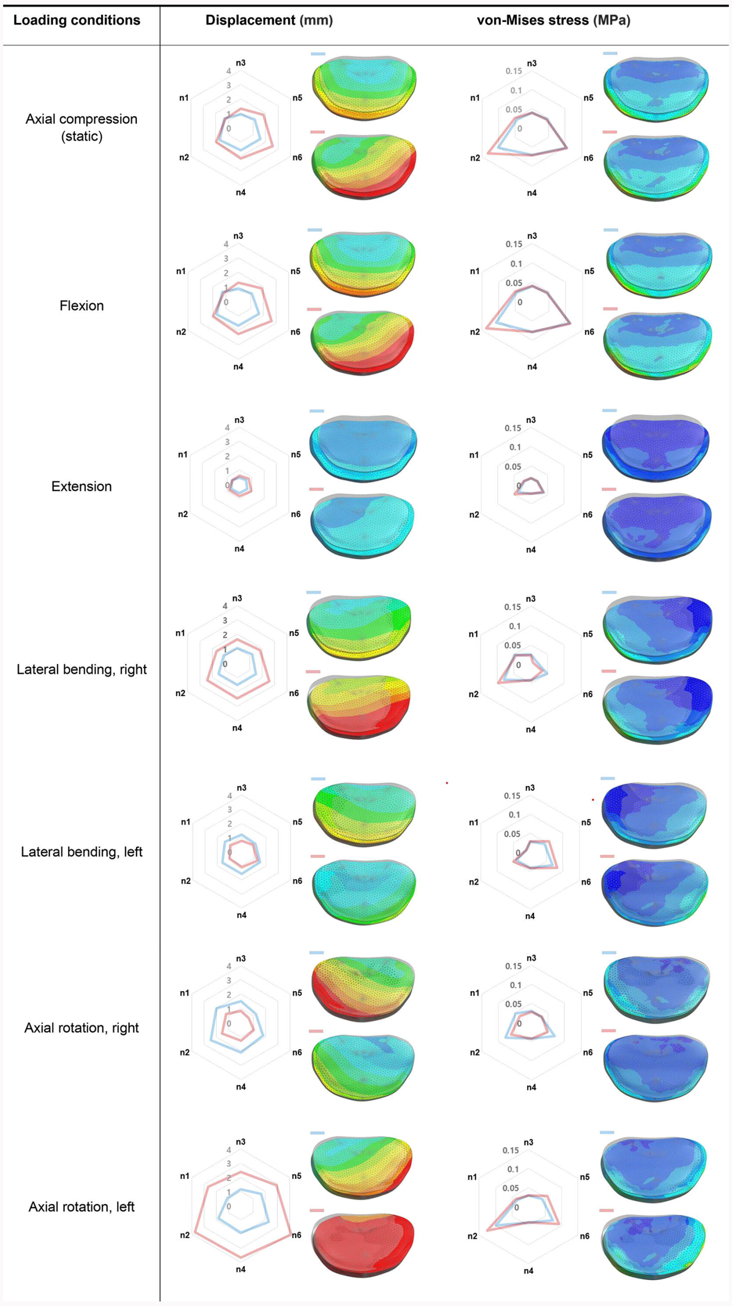

Fig. 4

Radial plots and coloured illustrations show the placed distances and load distribution simulated under a static load and six dynamic loads. The disc graphics are on a cranial view: the top is dorsal side of spine, and the bottom is central side of spine. The greater sagittal facet angle (right facet) is placed on the left side of the graphic, and the lesser sagittal facet angle (left facet) on the right side.

be anticipated. Evidence from animal experiments supports the notion that shear force can lead to disc deformation and increased pain. Yamada et al[41] discovered that excessive biomechanical loading, which can lead to shear forces, is a probable cause of intervertebral disc degeneration. They observed that this loading increased apoptosis in the nucleus pulposus cells, which are crucial for maintaining the integrity and flexibility of the lumbar disc. This suggests that changes in disc displacement and a potential increase in shear force could lead to disc degeneration and the associated pain.

Furthermore, our findings regarding intradiscal pressure support the hypothesis that facet tropism can alter stress distribution within the disc, potentially contributing to discogenic pain and annular fissures.[42] Our results demonstrated that the intradiscal pressure in the facet tropism group was higher than that in the normal group, suggesting that facet tropism may exacerbate disc degeneration by increasing mechanical stress on the disc. This observation aligns with recent investigations of the relationship between intradiscal pressure and facet tropism.[15]

The findings suggest that facet tropism plays a role in redistributing both static and dynamic axial loads within the spinal unit, resembling processes observed in degenerative disc conditions associated with facet tropism.[43] Although a definitive causal relationship between these biomechanical variations and disc degeneration remains unclear, abnormal loading on the disc has the potential to initiate a series of tissue degenerative events.[44] Consequently, it has been proposed that tailored exercise protocols should prioritize movements that engage deep muscles without increasing axial load on the disc.[45] Moreover, training strategies aimed at reducing spinal flexion, lateral bending (towards a less sagittal facet orientation), and axial rotation (towards a more sagittal facet orientation) may be beneficial. However, further meticulously designed clinical studies are required to validate the effectiveness of these approaches in managing discogenic pain disorders.

Our study has some limitations. First, it was limited by the lack of a comprehensive investigation into environmental risk factors such as smoking, which are known to influence intervertebral disc disease. Future studies should consider these factors to comprehensively understand disc degeneration. Second, the absence of a quantitative analysis of the provocation discography results was a limitation. This was due to the incorporation of manual and automated methods, which may have introduced variability into the results. Future research could benefit from a more standardized approach to discographic analysis. Third, changes in the static load were not considered in our FEM simulations. We chose a standard load based on the literature for a standard body type. Biomechanical data may vary depending on the degree of axial load applied to the disc; however, we intentionally controlled for other variables to focus on the contribution of facet tropism. The modelling has not been carried out for each patient or for each spinal level, and the two models were not patient-specific. Only the coronal angle of the facet joint surface was considered. Fourth, the reliability analysis for the angle measurement and the classification of degeneration was insufficient. However, the median value was taken after three measurements to improve the accuracy of the angle measurement. In addition, for radiologists with clinical experience of over 15 years, the variability in the angles through simple measurement would not be significant, and the reliability of evaluation such as Adams criteria was excellent in a previous study.[46] Finally, our study is inherently limited by its cross-sectional design. To gather more comprehensive data, future studies should consider conducting longitudinal studies using well-defined cohorts.

In conclusion, our study offers valuable insights into the significance of facet tropism in lumbar disc degeneration and herniation. By analyzing clinical data and applying FEM simulations, we demonstrated that facet tropism may contribute to disc herniation and alterations in intradiscal pressure. Our findings suggest that facet tropism may exacerbate disc degeneration by altering the force distribution on the intervertebral discs and increasing the mechanical stress on the disc. These findings emphasize the importance of facet tropism in the diagnosis and treatment of lumbar disc degeneration and herniation.

Supplementary material

Table showing the material properties of the anatomical elements used to reconstruct the finite element model of the spine unit.

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Data sharing

The data that support the findings for this study are available to other researchers from the corresponding author upon reasonable request.

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Ethical review statement

This study was conducted retrospectively in accordance with the Declaration of Helsinki, and was approved by the institutional review board of Korea University Ansan Hospital: IRB No. 2019AN0133.

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