Neurospine 2024;21(2):536-543.
https://doi.org/10.14245/ns.2347216.608

Neurospine
pISSN 2586-6583 eISSN 2586-6591

Original Article

Corresponding Author
Min Cheol Chang
https://orcid.org/0000-0002-7629-7213

Department of Physical Medicine & Rehabilitation, College of Medicine, Yeungnam University, 170 Hyeonchung-ro, Nam-gu, Daegu 42415, Korea
Email: wheel633@gmail.com

Received: November 15, 2023
Revised: January 8, 2024
Accepted: January 9, 2024

*Pyung Goo Cho and Seon-Jin Yoon contributed equally to this study as co-first authors.

Finite Element Analysis of Stress Distribution and Range of Motion in Discogenic Back Pain

Pyung Goo Cho[1,*], Seon-Jin Yoon[2,*], Dong Ah Shin[2], Min Cheol Chang[3]

[1]Department of Neurosurgery, Ajou University Medical Center, Suwon, Korea
[2]Department of Neurosurgery, Yonsei University College of Medicine, Seoul, Korea
[3]Department of Physical Medicine & Rehabilitation, Yeungnam University College of Medicine, Daegu, Korea

Objective: Precise knowledge regarding the mechanical stress applied to the intervertebral disc following each individual spine motion enables physicians and patients to understand how people with discogenic back pain should be guided in their exercises and which spine motions to specifically avoid. We created an intervertebral disc degeneration model and conducted a finite element (FE) analysis of loaded stresses following each spinal posture or motion.
Methods: A 3-dimensional FE model of intervertebral disc degeneration at L4–5 was constructed. The intervertebral disc degeneration model was created according to the modified Dallas discogram scale. The von Mises stress and range of motion (ROM) regarding the intervertebral discs and the endplates were analyzed.
Results: We observed that mechanical stresses loaded onto the intervertebral discs were similar during flexion, extension, and lateral bending, which were greater than those occurring during torsion. Based on the comparison among the grades divided by the modified Dallas discogram scale, the mechanical stress during extension was greater in grades 3–5 than it was during the others. During extension, the mechanical stress loaded onto the intervertebral disc and endplate was greatest in the posterior portion. Mechanical stresses loaded onto the intervertebral disc were greater in grades 3–5 compared to those in grades 0–2.
Conclusion: Our findings suggest that it might be beneficial for patients experiencing discogenic back pain to maintain a neutral posture in their lumbar spine when engaging in daily activities and exercises, especially those suffering from significant intravertebral disc degeneration.

Keywords: Finite element, Intervertebral disc, Posture, Discogenic back pain, Lumbar spine

INTRODUCTION

Lower back pain is a widespread issue affecting numerous individuals, and it can cause a wide range of disabilities and often imposes a significant socioeconomic burden,[1] with a reported lifetime prevalence of 60%–80%.[2] Lower back pain is a complex condition that is influenced by various physiological and psychological factors and changes in the brain.[3,4] Intervertebral disc degeneration plays a significant role in patients with lower back pain.[5] Discogenic back pain refers to lower back pain associated with intervertebral disc degeneration that occurs without disc herniation, anatomical deformity, or other clearly identifiable causes of pain and disability.[2,6]

Discogenic back pain is often refractory to oral medication or various procedures, and even surgical treatment does not exhibit a high success rate.[2,6,7] For patients with discogenic back pain, regular exercise and postural education are crucial.[8,9] Numerous previous studies have focused on proper posture in patients with discogenic back pain.[10-13] However, it is not clearly understood which posture causes the most significant mechanical stresses on the intervertebral disc. Precise knowledge regarding the mechanical stress applied to the intervertebral disc following each individual spine motion enables physicians and patients to understand how individuals should be guided in their exercises and which spinal motions to specifically avoid. Previous *in vivo* studies have been conducted to evaluate stress loading on the intervertebral disc resulting from various spinal postures or motions.[14,15] However, these studies were conducted on healthy subjects with no lower back pain, or did not measure intradiscal pressure under various postures.[14,15] In a previous *in vivo* study measuring intradiscal pressure, a needle or pressure sensor was inserted into the intervertebral disc, and this can cause damage to the intervertebral disc and accelerate its degeneration.[16] Therefore, due to the ethical issues, *in vivo* studies are currently limited in their ability to evaluate stress loading on the intervertebral disc following various spinal postures or motions.

Recently, in an effort to overcome the limitations of *in vivo* studies, finite element (FE) modeling that is typically used in industrial fields has been utilized for spinal research.[17-19] FE modeling measures mechanical stresses on each spinal structure without inserting an invasive device into the structure.[17-19] Several studies have evaluated pressures on the intervertebral discs of the lumbar spine according to different postures or motions using FE modeling.[11,12,18] However, these studies were not conducted using an intervertebral disc degeneration model. Normal and degenerated intervertebral discs experience different intradiscal pressures and possess different anatomical characteristics. To obtain clinically relevant research results that are applicable to patients with discogenic back pain, an FE analysis of the intradiscal stress occurring during each spinal posture or motion should be conducted using an intervertebral disc degeneration model.

In the current study, we created an intervertebral disc degeneration model and conducted an FE analysis of loaded stresses following each individual spinal posture or motion.

MATERIALS AND METHODS

1. Model Development

After obtaining approval from the Institutional Review Board of the Severance Hospital (2013-0515-001), a computed tomography (CT) scan of the lumbar spine was obtained from one patient (a 45-year-old man with lower back pain with no structural abnormality in the lumbar spine magnetic resonance imaging scan. It was a high-resolution CT scan encompassing a 1.0-mm section. Based on the CT images, a 3-dimensional (3D) model of the L4–5 lumbar spine was created using the Mimics (Materialise, Leuven, Belgium) software. The obtained 3D geometry was transformed into a hexahedral mesh using IA-FEMesh (The University of Iowa, Iowa City, IA, USA). The final FE model possessed 2 vertebrae (L4 and L5), one intervertebral disc, cartilage endplates, and spinal ligaments. The element type, number of nodes, and number of elements of each component are indicated in Table 1. The facet joint gap was modeled based on the original CT data. Surface-to-Surface contact and frictionless sliding between facet joints were applied. The ligaments were modeled as linear elastic in compression-free conditions. The intervertebral disc was made hyperelastic using the Moony-Rivlin model. The material properties of each component are listed in Table 2.[20-26] The final FE model was exported to Abaqus (Dassault Systemes, Paris, France) for analysis (Fig. 1). To validate the intact FE model, the same load and boundary conditions were used as those described in Yamamoto et al.[27]

Table 1. Element types, number of nodes, and number of elements of each component

Component	Element type	No. of nodes	No. of elements
Cortical bone	Hexahedral C3D8RH	5,388	2,652
Cancellous bone	Hexahedral C3D8RH	8,590	7,197
Posterior bone	Hexahedral C3D8RH	5,707	3,830
Nucleus pulposus	Hexahedral C3D8RH	1,440	1,044
Annulus fibrosus	Hexahedral C3D8RH	1,300	832
Cartilage endplate	Hexahedral C3D8RH	1,984	938
Facet surface	Hexahedral C3D8RH	204	65
Ligaments	Line T3D2H	62	31
Annulus fibers	Line T3D2H	260	416
Total components		24,935	17,005

2. Intervertebral Disc Degeneration Model

The intervertebral disc degeneration model was established according to the modified Dallas discogram scale[28]: grade 0: normal disc; grade 1: radial tears confined to the inner third of the annulus fibrosis; grade 2: radial tears extending to the middle third of the annulus fibrosis; grade 3: a radial tear extending to the outer third of the annulus fibrosis; grade 4: a grade 3 tear with dissection into the outer third of the annulus that involves greater than 30° of the disc circumference; and grade 5: full-thickness tear. As a boundary condition, the inferior surface of the lower vertebra was constrained in all directions. The inter-

Table 2. Material properties used in the finite element model

Component	Young's modulus (MPa)	Poisson ratio	Cross section area (mm^2)	Reference
Cortical bone	12,000	0.3		Shirazi-Adl et al.[20] 1984
Cancellous bone	100	0.2		Wang et al.[21] 2016
Posterior bone	3,500	0.25		Polikeit et al.[22] 2003
Nucleus pulposus	Hyperelastic			
	C10: -0.219197			
	C01: 0.43494			
	D1: 0.000927066	0.499		Shirazi-Adl et al.[20] 1984
Annulus fibrosus	Hyperelastic			
	C10: -0.117485			
	C01: 0.273737			
	D1: 0.66206	0.45		Lavaste et al.[23] 1991
Annulus fibers	500	0.3		Little et al.[24] 2008
Cartilage endplate	24	0.4		Goel et al.[25] 1995
Facet cartilage	24	0.4		Wang et al.[21] 2016
Ligament				Zhong et al.[26] 2006
ALL	20		63.7	
PLL	20		20	
CL	32.9		60	
ITL	58.7		3.6	
ISL	11.6		40	
SSL	15		30	

ALL, anterior longitudinal ligament; PLL, posterior longitudinal ligament; CL, capsular ligament; ITL, intertransverse ligament; ISL, interspinous ligament; SSL, supraspinous ligament.

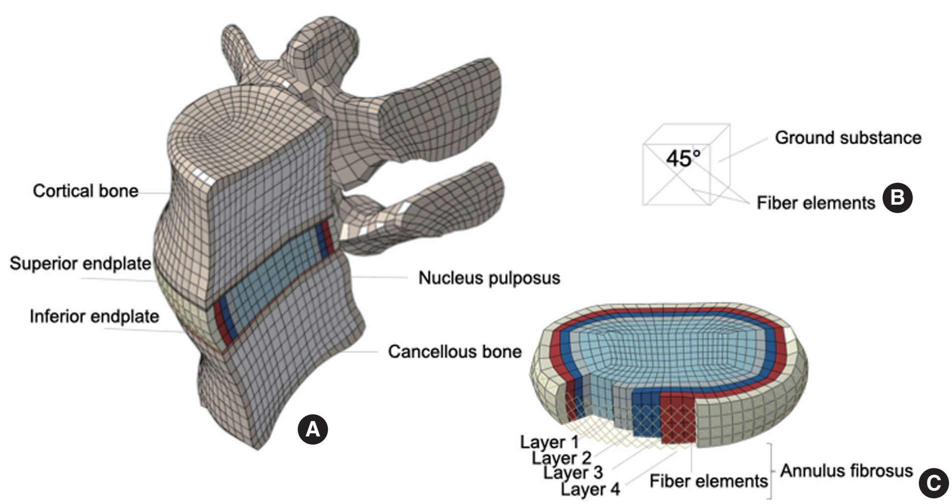

Fig. 1. A finite element model of the L4–5 functional spinal unit implemented in Abaqus software. (A) A section cut in the midsagittal plane. The cortical bone, cancellous bone, endplates, and intervertebral disc are implemented. (B) The annulus fibrosus is composed of fibers at an angle of 45° to the ground substance. (C) The intervertebral disc consists of the nucleus pulposus and 4 layers of the annulus fibrosus.

https://doi.org/10.14245/ns.2347216.608

vertebral disc was composed of the nucleus pulposus and 4 layers of annulus fibrosus. The annulus fibrosus was reinforced with fibers in the ground material. Elements were removed in the middle of the posterior portion of the annulus according to grade. The superior surface of the upper vertebra was coupled to a reference point. Loading was applied at that point and included a 7.5-Nm moment and 280-N compression. The compression force was the weight of the upper body on the spine. The compressive loading was applied in the form of a follower load as suggested by Patwardhan et al.[29] The follower load was constructed by coupling the reference points at the center of gravity of each vertebral body and connecting the 2 points with a connector element. The von Mises stress and range of motion (ROM) regarding the intervertebral discs and endplates were analyzed.

RESULTS

The von Mises stress values during flexion, extension, and lateral bending were not significantly different, and all were greater than those that occurred during torsion (Fig. 2). Based on the comparison among the grades during flexion, lateral bending, and torsion, there was no significant difference in the peak von Mises stress values. However, during extension, peak von Mises stresses were greater in grades 3–5 than those in the others. Grades 3 and 4 were 22.7% and 25.7% higher than grade 0, respectively; grade 5 was 17.8% larger than grade 0 (Fig. 2). ROM was measured during flexion, extension, lateral bending, and torsion by applying a moment of 6 Nm. The ROM values were within 10% of the results reported by Yamamoto et al.[20] ROM for each motion is indicated in Fig. 3. The ROM values during flexion and extension were greater than those during lateral bending and torsion. From the comparison among the grades, during lateral bending and torsion there was no significant difference in peak von Mises stress. However, during flexion, ROM in grade 5 was greater than that in others, and grade 5 exhibited 5.2% greater ROM than did grade 0. During extension, ROM in grade 4 was greater than that in others, and grade 4 exhibited 8.2% greater ROM than did grade 0 (Fig. 3). The von Mises stress was greatest in the posterior portions of the intervertebral disc (Fig. 4) and endplates (Fig. 5) in all the grades. Peak stresses loaded onto the intervertebral discs were greater in grades 3–5 than those in grades 0–2.

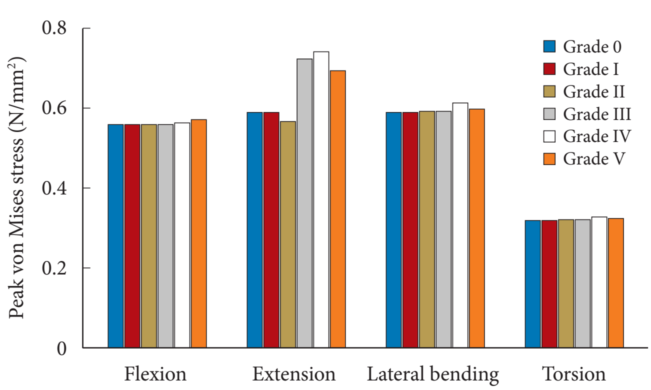

Fig. 2. The peak von Mises stress value acting on the end plate during extension. During extension, the peak von Mises stress values are greater in grades 3–5 than those in the others.

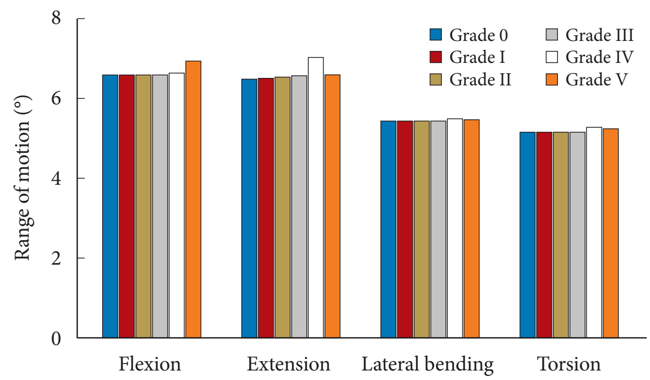

Fig. 3. Range of motion in the L4–5 functional spinal unit according to each spinal motion. During flexion, the value is greatest in grade 5; during extension, it is greatest in grade 4.

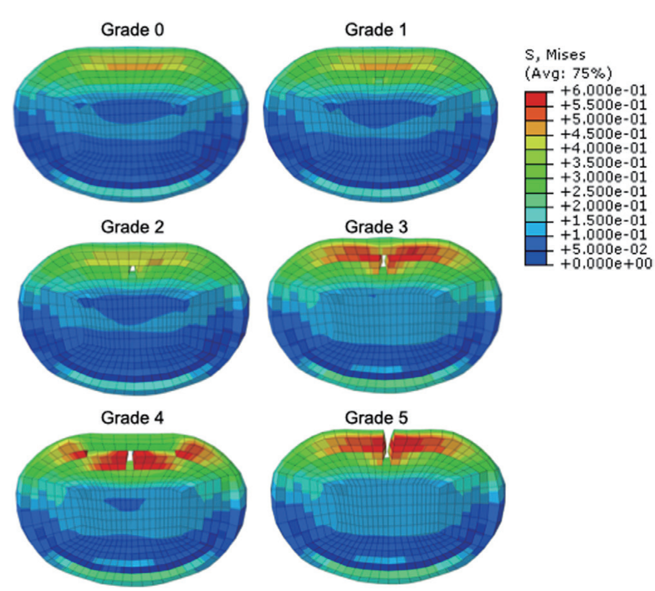

Fig. 4. Contours of von Mises stress acting on the intervertebral disc during extension. All peak stresses are loaded onto the posterior portion of the annulus fibrosus. Peak stresses in grades 3–5 are greater than those in grades 0–2.

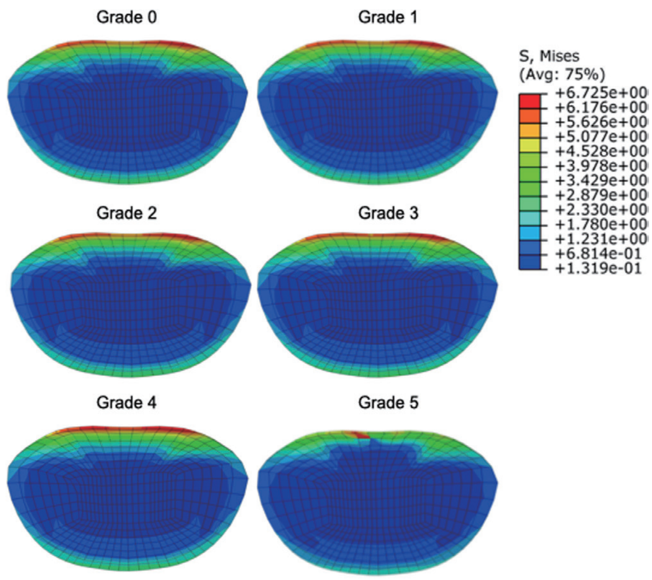

Fig. 5. Contours of von Mises stress acting on the endplate during extension. All peak stresses are loaded at the posterior portion of the endplate.

DISCUSSION

In our study, we observed that mechanical stresses loaded onto the intervertebral disc were similar during flexion, extension, and lateral bending, and all of these were greater than those observed during torsion. From the comparison among the grades, the mechanical stresses during extension were greater in grades 3–5 than that in others. During extension, mechanical stress loaded onto the intervertebral disc and endplate was greatest in the posterior portion. Mechanical stresses loaded onto the intervertebral disc were greater in grades 3–5 compared to those in grades 0–2. Additionally, ROMs during flexion and extension were greater than those observed during lateral bending and torsion. From the comparison among the grades, ROM during flexion was highest in grade 5; during extension, it was highest in grade 4.

We demonstrated that flexion, extension, and lateral bending directs the stress or pressure to the L4–5 intervertebral disc to a similar degree in patients with discogenic back pain. Therefore, medical staff should emphasize to patients with discogenic back pain the importance of maintaining a neutral posture in the lumbar spine during daily activities and exercise. Neutral posture in the lumbar spine refers to a natural and relaxed alignment with slight lumbar lordosis to produce the least amount of pressure on the spinal column, discs, and nerves.[30] In clinical practice, the importance of maintaining a neutral position for patients with lower back pain has been emphasized. We scientifically confirmed the importance of a neutral position of the lumbar spine using FE analysis. Also, stress loaded onto intervertebral discs was particularly high during extension for patients with severe degeneration of intervertebral discs (grades 3–5). This indicates that patients with severe degeneration of the intervertebral disc should particularly avoid extension of the lumbar spine.

The extent of ROM values at specific positions indicates the potential to generate stress or pressure in the intervertebral disc, and these values were observed to be significantly greater during flexion and extension. Furthermore, ROM was even greater in severe disc degeneration (grade 4 or 5). These findings highlight the importance of the neutral position of the lumbar spine, particularly in patients with severe intervertebral disc degeneration.[30]

Additionally, during extension, mechanical stress loaded onto the intervertebral disc and endplate was greatest in the posterior portion. The sinuvertebral nerve (a branch of the spinal nerve root), is considered to be a primary contributor to discogenic back pain in response to mechanical and chemical irritation.[31] The sinuvertebral nerves are distributed at the posterior portion of the disc, along the outer layer of the annulus fibrosus.[31] Furthermore, when the annulus of the intervertebral disc is torn, the sinuvertebral nerves grow inward along the tear.[32] When extending the lumbar spine, there is a high possibility of mechanical irritation to sinuvertebral nerves in the posterior area of intervertebral disc. The extension position can also lead to an annulus tear in the posterior portion of the intervertebral disc and cause the sinuvertebral nerve to grow inward toward the nucleus pulposus. The extension posture of the lumbar spine can trigger or exacerbate discogenic back pain. This negative influence was particularly pronounced when disc degeneration was severe.

Several studies have evaluated the influence of posture and motion on the lumbar spine through FE analysis.[11,12] Kuo et al.[12] investigated increments in intradiscal pressure during standing, flexion, extension, and rotation. Intradiscal pressure was increased in all of the postures, most markedly during flexion. They suggested that lumbar flexion is the posture or motion that should be most avoided to prevent disc degeneration. Cho et al.[11] evaluated how pressures on lumbar spine change during different postures such as standing, erect sitting on a chair, slumped sitting on a chair, and sitting on the floor using FE analysis. The pressures on the nucleus pulposus, annulus fibrosus, and cortical bone during standing and erect sitting postures were not

https://doi.org/10.14245/ns.2347216.608

significantly different. However, during slumped sitting in a chair and sitting on the floor, there was significantly increased pressure on the nucleus pulposus, annulus fibrosus, and cortical bone. In particular, sitting on the floor induced even greater pressure on the nucleus pulposus and annulus fibrosus than did slumped sitting in a chair. They concluded that maintaining a neutral posture is important to reduce intradiscal pressure and cortical bone stress associated with degenerative disc disease or spinal deformities. These previous studies emphasized the importance of adopting or maintaining a neutral posture based on the results of their FE analyses.[11,12] However, the FE analyses conducted in the previous studies did not utilize the intervertebral disc degeneration model. Our study is first to conduct FE analysis to investigate stresses loaded onto various spinal postures or motions using a model of intervertebral disc degeneration. Furthermore, we analyzed and compared the stress loaded onto the lumbar spine based on the severity of intervertebral disc degeneration. However, our study has some limitations. First, we did not evaluate the distribution of stress loaded onto the intervertebral disc or endplate during postures or motions other than extension. Second, we conducted our research targeting only the L4–5 lumbar region, where discogenic back pain occurs most commonly, rather than targeting the entire lumbar spine. Third, Young's modulus or the Poisson ratio, both of which can vary for each grade, were not taken into account in this experiment. Our study solely acquired morphology from the patient's CT images, failing to fully represent the physical properties of the degenerative disc. There are various methods available to ascertain the physical properties of degenerative discs,[33-35] and it is recommended to integrate these into future research. Fourth, FE analysis simplifies complex spinal structures and cannot reflect all the factors that can occur *in vivo*. Accordingly, additional clinical research based on the results of our study should be conducted.

CONCLUSION

In conclusion, we demonstrated using FE analysis that mechanical stresses loaded onto intervertebral discs are significantly increased in flexion, extension, and lateral bending in patients with discogenic back pain. In patients with severe disc degeneration, mechanical stress was observed to be greater (particularly during extension) compared to that observed in mild disc degeneration. Moreover, during extension mechanical stress loaded onto the intervertebral disc and endplate was focused in the posterior portion and was greater in patients with severe disc degeneration than that in patients with mild disc degeneration. Our findings suggest that it might be beneficial for patients experiencing discogenic back pain to maintain a neutral posture in their lumbar spine when engaging in daily activities and exercises, especially those suffering from significant intravertebral disc degeneration.

NOTES

Conflict of Interest: The authors have nothing to disclose.

Funding/Support: This study was supported by CGBio.

Author Contribution: Conceptualization: PGC, SJY, DAS, MCC; Data curation: PGC, SJY, DAS, MCC; Formal analysis: PGC, SJY, DAS, MCC; Methodology: PGC, SJY, DAS, MCC; Visualization: PGC, SJY, DAS, MCC; Writing – original draft: PGC, SJY, DAS, MCC; Writing – review & editing: PGC, SJY, DAS, MCC.

ORCID

Pyung Goo Cho: 0000-0001-7087-8597
Seon-Jin Yoon: 0000-0002-3255-5081
Dong Ah Shin: 0000-0002-5225-4083
Min Cheol Chang: 0000-0002-7629-7213

REFERENCES

1. Wu A, March L, Zheng X, et al. Global low back pain prevalence and years lived with disability from 1990 to 2017: estimates from the Global Burden of Disease Study 2017. Ann Transl Med 2020;8:299.
2. Yang S, Boudier-Revéret M, Chang MC. Use of pulsed radiofrequency for the treatment of discogenic back pain: a narrative review. Pain Pract 2021;21:594-601.
3. Chang MC. Mild cognitive impairment and major depressive disorder as confounders in the study on association between chronic low back pain and brain atrophy. Pain 2023;164:e237.
4. Ivo R, Nicklas A, Dargel J, et al. Brain structural and psychometric alterations in chronic low back pain. Eur Spine J 2013;22:1958-64.
5. Zheng CJ, Chen J. Disc degeneration implies low back pain. Theor Biol Med Model 2015;12:24.
6. Chang MC, Park D. The effect of intradiscal platelet-rich plasma injection for management of discogenic lower back pain: a meta-analysis. J Pain Res 2021;14:505-12.
7. Fujii K, Yamazaki M, Kang JD, et al. Discogenic back pain:

literature review of definition, diagnosis, and treatment. JBMR Plus 2019;3:e10180.
8. George SZ, Fritz JM, Silfies SP, et al. Interventions for the management of acute and chronic low back pain: revision 2021. J Orthop Sports Phys Ther 2021;51:CPG1-CPG60.
9. Gordon R, Bloxham S. A systematic review of the effects of exercise and physical activity on non-specific chronic low back pain. Healthcare (Basel) 2016;4:22.
10. Alamin TF, Agarwal V, Zagel A, et al. The effect of standing vs. variants of the seated position on lumbar intersegmental angulation and spacing: a radiographic study of 20 asymptomatic subjects. J Spine Surg 2018;4:509-15.
11. Cho M, Han JS, Kang S, et al. Biomechanical effects of different sitting postures and physiologic movements on the lumbar spine: a finite element study. Bioengineering (Basel) 2023;10:1051.
12. Kuo CS, Hu HT, Lin RM, et al. Biomechanical analysis of the lumbar spine on facet joint force and intradiscal pressure--a finite element study. BMC Musculoskelet Disord 2010;11:151.
13. Li JQ, Kwong WH, Chan YL, et al. Comparison of in vivo intradiscal pressure between sitting and standing in human lumbar spine: a systematic review and meta-analysis. Life (Basel) 2022;12:457.
14. Sato K, Kikuchi S, Yonezawa T. In vivo intradiscal pressure measurement in healthy individuals and in patients with ongoing back problems. Spine (Phila Pa 1976) 1999;24:2468-74.
15. Wilke HJ, Neef P, Caimi M, et al. New in vivo measurements of pressures in the intervertebral disc in daily life. Spine (Phila Pa 1976) 1999;24:755-62.
16. Polga DJ, Beaubien BP, Kallemeier PM, et al. Measurement of in vivo intradiscal pressure in healthy thoracic intervertebral discs. Spine (Phila Pa 1976) 2004;29:1320-4.
17. Byun DH, Shin DA, Kim JM, et al. Finite element analysis of the biomechanical effect of coflex™ on the lumbar spine. Korean J Spine 2012;9:131-6.
18. Kang S, Chang MC, Kim H, et al. The effects of paraspinal muscle volume on physiological load on the lumbar vertebral column: a finite-element study. Spine (Phila Pa 1976) 2021;46:E1015-21.
19. Wang J, Geng Z, Wu J, et al. Biomechanical properties of lumbar vertebral ring apophysis cage under endplate injury: a finite element analysis. BMC Musculoskelet Disord 2023;24:695.
20. Shirazi-Adl SA, Shrivastava SC, Ahmed AM. Stress analysis of the lumbar disc-body unit in compression. A three-dimensional nonlinear finite element study. Spine (Phila Pa 1976) 1984;9:120-34.
21. Wang L, Zhang B, Chen S, et al. A validated finite element analysis of facet joint stress in degenerative lumbar scoliosis. World Neurosurg 2016;95:126-33.
22. Polikeit A, Nolte LP, Ferguson SJ. The effect of cement augmentation on the load transfer in an osteoporotic functional spinal unit: finite-element analysis. Spine (Phila Pa 1976) 2003;28:991-6.
23. Lavaste F, Skalli W, Robin S, et al. Three-dimensional geometrical and mechanical modelling of the lumbar spine. J Biomech 1992;25:1153-64.
24. Little JP, de Visser H, Pearcy MJ, et al. Are coupled rotations in the lumbar spine largely due to the osseo-ligamentous anatomy?--a modeling study. Comput Methods Biomech Biomed Engin 2008;11:95-103.
25. Goel VK, Monroe BT, Gilbertson LG, et al. Interlaminar shear stresses and laminae separation in a disc: finite element analysis of the l3-l4 motion segment subjected to axial compressive loads. Spine (Phila Pa 1976) 1995;20:689-98.
26. Zhong ZC, Wei SH, Wang JP, et al. Finite element analysis of the lumbar spine with a new cage using a topology optimization method. Med Eng Phys 2006;28:90-8.
27. Yamamoto I, Panjabi MM, Crisco T, et al. Three-dimensional movements of the whole lumbar spine and lumbosacral joint. Spine 1989;14:1256-60.
28. Aprill C, Bogduk N. High-intensity zone: a diagnostic sign of painful lumbar disc on magnetic resonance imaging. Br J Radiol 1992;65:361-9.
29. Patwardhan AG, Havey RM, Meade KP, et al. A follower load increases the load-carrying capacity of the lumbar spine in compression. Spine 1999;24:1003-9.
30. O'Sullivan K, O'Dea P, Dankaerts W, et al. Neutral lumbar spine sitting posture in pain-free subjects. Man Ther 2010;15:557-61.
31. Shayota B, Wong TL, Fru D, et al. A comprehensive review of the sinuvertebral nerve with clinical applications. Anat Cell Biol 2019;52:128-33.
32. Tenny S, Gillis CC. Annular disc tear [Updated 2023 Aug 7]. In: StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2023 Jan-. Available from: https://www.ncbi.nlm.nih.gov/books/NBK459235/.
33. Natarajan RN, Williams JR, Andersson GB. Recent advances in analytical modeling of lumbar disc degeneration. Spine (Phila Pa 1976) 2004;29:2733-41.

 https://doi.org/10.14245/ns.2347216.608

34. Natarajan RN, Williams JR, Andersson GB. Modeling changes in intervertebral disc mechanics with degeneration. J Bone Joint Surg Am 2006;88 Suppl 2:36-40.
35. Ruberté LM, Natarajan RN, Andersson GB. Influence of single-level lumbar degenerative disc disease on the behavior of the adjacent segments--a finite element model study. J Biomech 2009;42:341-8.