Research – Results Article | J Vis Med. 2024;12:e0112

Category: Medicine (Clinical Science) Peer Reviewed | Open Access

10.30699/jovm.012.e112

Journal of Visualized Medicine | ISSN:3041-9727

Analyzing the Influence of Disc Height on Thoracic Spine Mechanics: A Finite Element Approach

Mohadese Rajaeirad[1*], Alireza Feizkhah[2], Nima Jamshidi[1], Azadeh Ghouchani[1]

1. *Department of Biomedical Engineering, Faculty of Engineering, University of Isfahan, Isfahan, Iran*
2. *Department of Medical Physics and Biomedical Engineering, Tehran University of Medical Sciences, Tehran, Iran*

ABSTARCT

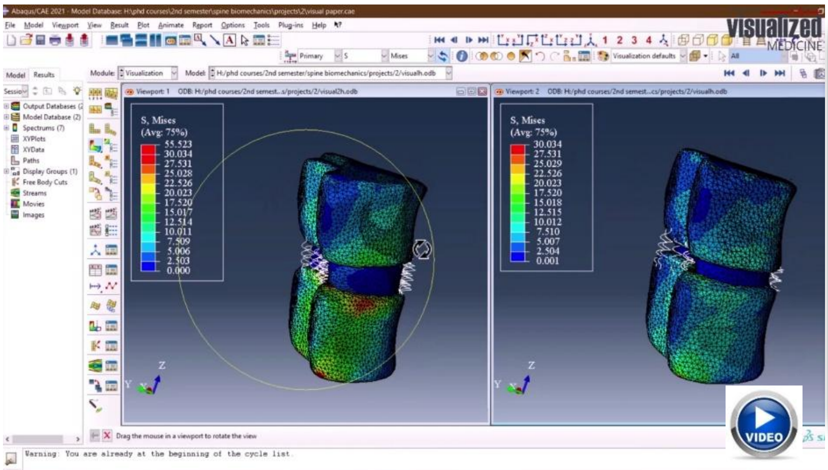
This study investigates the influence of intervertebral disc (IVD) height on thoracic spine biomechanics using finite element analysis (FEA) at the T11-T12 segment. A three-dimensional model, derived from CT imaging, was used to compare normal and doubled IVD thickness. In the normal model, stress was uniformly distributed with a maximum von Mises stress of 0.6 MPa in the IVD and 30 MPa overall, ensuring structural integrity. However, the thicker IVD model exhibited heightened stress levels, with von Mises stresses increasing to 4.5 MPa in the IVD and 55.52 MPa in the whole model, a 7.5- and two-fold rise, respectively. Displacement in the thicker IVD model also increased significantly, particularly in the sagittal and frontal planes, indicating reduced spinal stability. These findings demonstrate that excessive IVD thickness disrupts load distribution, increases stress concentration, and impairs stability, exacerbating the risk of herniation and degeneration. The results align with prior studies and highlight the importance of maintaining optimal IVD height for spinal health. This research contributes valuable insights for clinical applications, such as artificial disc design, emphasizing the critical balance between mobility and stability.

Keywords: Intervertebral Disc Height, Thoracic Spine Mechanics, Finite Element Modeling, Stress Distribution, Spinal Loading

Received: 9 September 2024; **Accepted**: 21 November 2024; **Published Online:** 22 December 2024;

Corresponding Information: **Mohadese Rajaeirad**, *Department of Biomedical Engineering, Faculty of Engineering, University of Isfahan, Isfahan, IranIran* & Email: mohadeserajaeirad@gmail.com

Use DOI and watch the video article online



Highlights:

Finite element analysis was used to study T11-T12 biomechanics with varying IVD heights. Doubling IVD thickness increased stress in the disc and destabilizing the spine. Excessive disc height impairs spinal stability, raising risks of herniation and degeneration. Findings support optimal IVD height preservation for improved clinical and biomechanical outcomes.

Use a device to scan and read the article online

Rajaeirad M, Feizkhah A, Jamshidi N, Ghouchani A. Analyzing the Influence of Disc Height on Thoracic Spine Mechanics: A Finite Element Approach. J Vis Med. 2024;12:e0112.

Download Citation: RIS | EndNote | Mendeley | BibTeX |

1. Introduction

The intervertebral disc (IVD) height is an important factor in spinal biomechanics, being key to the organization of forces between vertebral bodies and therefore spinal stability and health **(1)**. IVDs are the spinal shock absorbers, which spread mechanical stress and allow motion and flexibility during different postural and movement conditions. However, any change in the height of the IVD can disturb this equilibrium, causing biomechanical stressors and eventually health-related problems. In particular, changes in IVD height have been linked to disrupted load transmission, which may eventually lead to structural degeneration over time **(2, 3)**.

These changes in IVD height are associated with degenerative disc disease (DDD), which is a debilitating disease that significantly affects an individual's mobility as well as their quality of life **(1, 3)**. Studies link reduced disc height to increased intradiscal pressure (IDP) and localized stress, which influence stress distribution throughout the spinal column over time, promoting degenerative change and increasing the risk of injury **(4, 5)**. Biomechanical investigations have shown that normal IVDs distribute loads more evenly, allowing for more efficient load transfer and preservation of stability between vertebrae. In contrast, pathologic higher levels of stress translate to larger displacements and higher risk for spinal instability and injury **(6-9)**.

For instance, the thoracic spine has additional complexity with ribs, which fundamentally affect the biomechanics of the intervertebral disk (IVD) and mechanics overall stability, making it more complex to evaluate. Finite element analysis (FEA) studies have provided information to better understand the role of rib structures in thoracic spinal stabilization and load distribution. For instance, biomechanical studies reveal that injuries to structures such as the anterior longitudinal ligament (ALL) can dramatically impact the stability of the thoracic spine, especially when combined with IVD degeneration **(7)**. Together with experimental analysis, spine biomechanical studies use FEA to reproduce complex situations and to predict the biomechanical response to diverse standings. It is well-known that FEA studies have been used to predict mechanical behavior since it can change under different loading conditions, such as modeling stress distribution, or predicting bone remodeling on the condition that the loading has been modified **(10)**.

Using finite element methods, this study intends to investigate the biomechanical impact of IVD thickness in the thoracic spine, yielding new information on stress distribution, loadbearing capacity and stability of the spine. This study adds valuable data that will help guide clinical decision-making regarding the treatment of the spine based on previous FEA research and improve understanding of spinal biomechanics in altered structural states.

2. Protocol

Finite element analysis (FEA) to determine the influence of intervertebral disc (IVD) height on the biomechanics of the thoracic spine, specifically at the T11-T12 segment. Using the CT image data in DICOM format, a three-dimensional model of T11 and T12 vertebrae and the IVD was created in the Mimics software for analysis, which was anatomical and reproducible. The vertebrae were segmented, and IVD geometry was reconstructed based on anatomical contours using lofting. Two models were developed: a normal lumbar IVD height, and a model doubling the height of the disc, accomplished by displacing the T12 vertebra along the Z-axis. Separating the cancellous part of each vertebrae was a 1-mm cortical bone layer **(10, 11)**.

Adaptive remesh methods were used to obtain tetrahedral meshes for the final geometries, with surface elements constrained to 1 mm side length and volume elements limited to a maximum of 1.5 mm in line with geometric detail versus computational efficiency. The material properties assigned to the distinct components of the disc included isotropic elastic properties for the cortical and cancellous bone and viscoelastic properties for the nucleus pulposus and annulus fibrosus as outlined in Table 1.

Boundary and loading conditions simulated physiological restrictions. The base of T12 was fixed in all directions, while a load of 500 N was applied vertically along the Z-axis through a reference point above the superior surface of vertebra T11, approximately representing two-thirds of body weight **(12)** (Figure 1). Vertebrae–IVD interactions were modeled through tied node-based constraints as a mean to mimic natural bonding. Ligaments were modeled as springs with the stiffness of anterior longitudinal ligament (ALL) set to 8.74 N/mm and posterior longitudinal ligament (PLL) set to 5.83 N/mm **(13)**.

Biomechanical impact for different disc heights was studied with stress distribution and displacement analysis. To examine the effect of enhanced IVD thickness on spinal stability, critical parameters inside the IVD and adjacent vertebrae, between the normal and customized models, were compared.

Table 1. Material properties assigned to components of the finite element model.

Component / Section		Assigned Values		
Cortical Bone (10)		E = 12000 MPa, v = 0.3		
Cancellous Bone (10)		E = 100 MPa, v = 0.2		
Nucleus Pulposus (11)		E = 2 MPa, v = 0.45 at t = 0		
	Prony series coefficients:			
		g_1=0.638	k_1=0.00	τ_1=0.141
		g_2=0.156	k_2=0.00	τ_2=0.141
		g_3=0.120	k_3=0.00	τ_3=0.141
		g_4=0.638	k_4=0.00	τ_4=0.141
		g_5=0.638	k_5=0.00	τ_5=0.141
Annulus Fibrosus (11)		E = 8 MPa, v = 0.45 at t = 0		
	Prony series coefficients:			
		g_1=0.638	k_1=0.00	τ_1=0.141
		g_2=0.638	k_2=0.00	τ_2=0.141
		g_3=0.638	k_3=0.00	τ_3=0.141
		g_4=0.638	k_4=0.00	τ_4=0.141
		g_5=0.638	k_5=0.00	τ_5=0.141

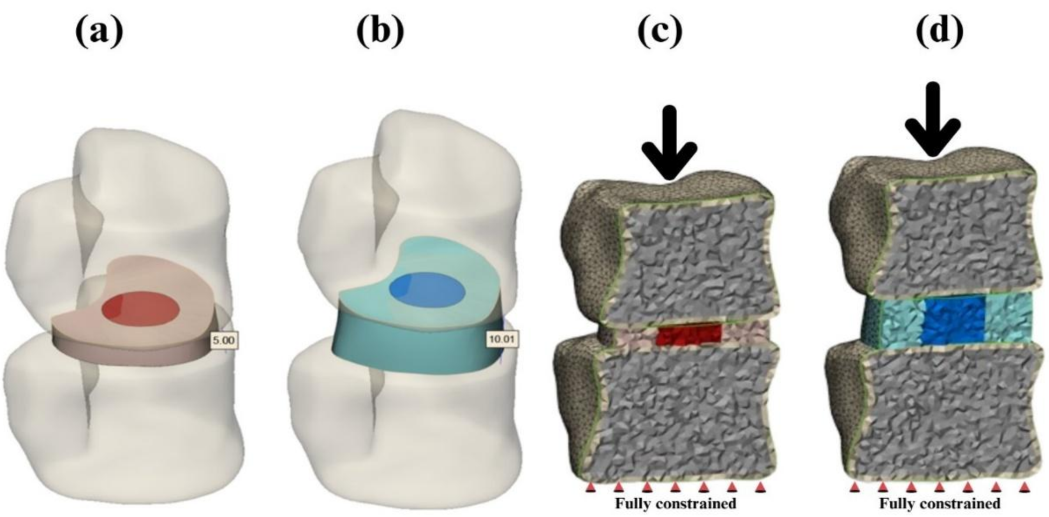


Figure 1. Mathematically designed model based on the patient parameters **(Design by Authors, 2024)**.

3. Results and Discussion

3.1 Stress Distribution

In the healthy IVD model, the stress was uniformly spread across the annulus fibrosus, with a maximum von Mises stress of 0.6 MPa under compressive loads, reflecting optimal load-bearing indicating at the physiological level. The maximum stress across the whole model was 30 MPa, ensuring that all parts hold acyclic loads with no accumulation of damage. These results are in line with previous studies that prioritise balanced stress distribution for disc health and longevity **(5, 14)**.

In comparison, the higher stress level was observed in the thicker IVD model. The maximum von Mises stress in the annulus fibrosus increased to 4.5 MPa, which was approximately 7.5 times that in normal model, and the stress of the overall model was up to 55.52 MPa. The stress was focused mainly on the front and back regions, reflected an uneven load distribution that might hasten structural degeneration and increase the probability of hernia. This finding emphasizes the injurious biomechanical effect of increased IVD thickness, which may aggravate degeneration and increase instability **(14, 15)**.

Figure 2 shows the von Mises stress distribution lines at different thicknesses.

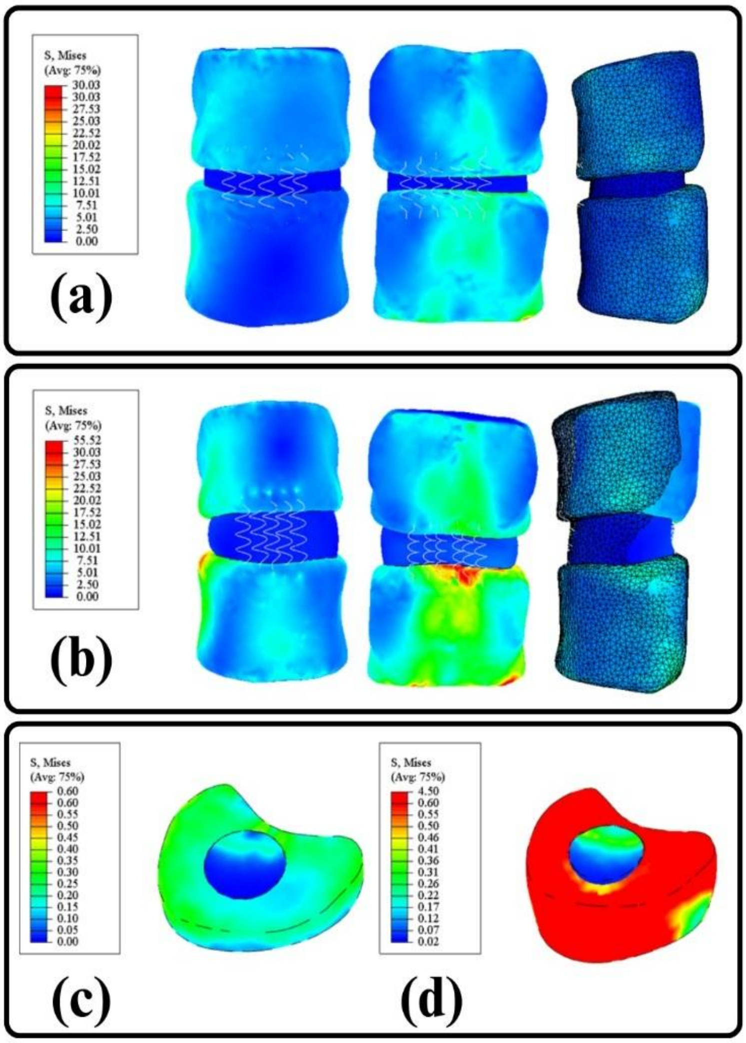


Figure 2**.** Von Mises stress (MPa) distribution contours: (a) Whole model with normal IVD thickness. (b) Whole model with increased IVD thickness. (c) Normal IVD thickness. (d) Increased IVD thickness **(Design by Authors, 2024)**.

3.2 Displacement Patterns

The values obtained for displacement in the normal IVD model were consistent with our established norms, demonstrating adequate stability of the T11-T12 motion segment. In contrast, the thicker IVD model exhibited markedly greater displacement, indicating increased mobility and changed load characteristics. U2 and U1 displacements in the sagittal (U2) and frontal (U1) planes increased significantly, suggesting excessive disc height reduces spinal stability. This emphasizes the need for an ideal disc height, since both cases, i.e., too low or too high heights can disturb the stability of the motion segment. These results highlight the tightrope that must be walked in disc design to maintain healthy spinal biomechanics.

Figure 3 shows the Displacement contours at different thicknesses.

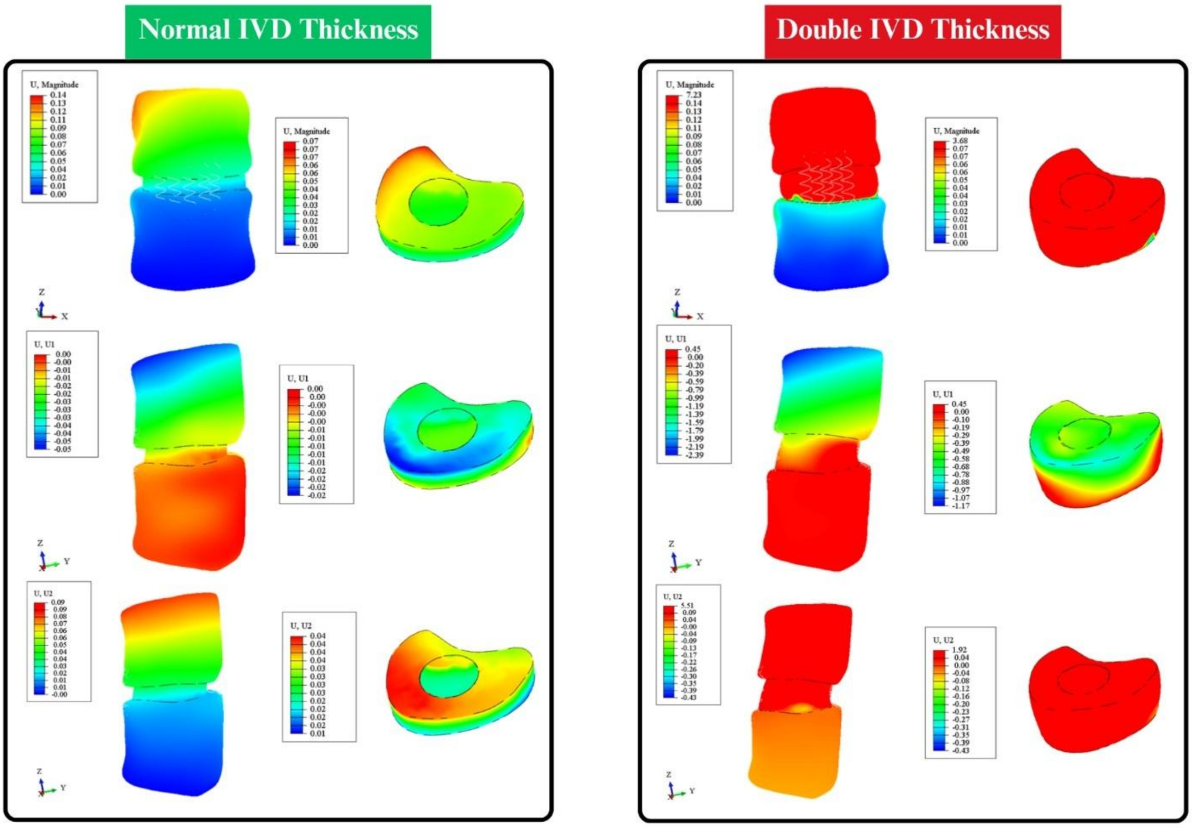


Figure 3. Displacement contours (mm): Comparison of normal IVD thickness and increased IVD thickness in finite element models **(Design by Authors, 2024)**.

The findings highlight the biomechanical importance of preserving normal IVD height. More specifically, abnormal disc spacing not only leads to increased stress and displacement, but also alters the normal dynamics of motion, which can result in compensatory movement patterns, strain on surrounding ligaments and musculature, and in turn chronic pain. While it may seem like thicker discs would be better, with more cushioning, they change the natural distribution of stress, overload neighboring vertebrae, and cause a higher risk of degenerative changes. Such biomechanical changes can diminish function, limit range of motion, and worsen underlying degenerative processes in the spine, especially in those with existing conditions like degenerative disc disease.

Clinically, these results emphasize the importance of considering IVD height during surgical planning. In addition, achieving or restoring normal IVD height should be a focus of rehabilitation strategies to help improve spinal stability and minimize the risk of degenerative changes.

This level of von Mises stress of 30 MPa for the normal spine is relatively in good agreement with that reported by Ardatov et al **(5)** under similar conditions 33 MPa. The average intradiscal pressure of 0.6 MPa is well-aligned with Dai et al **(14)**, who found values of more than 0.5 MPa at the T11-T12 region. Lu et al **(15)** under axial loads, also evidence stresses higher than 30 MPa in this region. These consistencies confirm the fidelity of the FEA model and support its robustness in modeling spinal biomechanics.

Although this study contributes significantly to our understanding of IVD components, this simplified material property approach limits the generalizability of the study. Considering patient-specific material properties and including more segments of the spine can improve the accuracy and applicability of the model.

This research emphasizes the importance of IVD height in sustaining spinal stability and distributing load. Disc thickness that is too low is harmful, but excessive thickness is a serious danger to structure and spine health. This finding is important for optimizing the dimensions of the disc to achieve a balance between mobility and stability in clinical and biomechanical settings, including artificial disc design.

4. Declarations

Acknowledgment

The authors of the present study would like to thank the Smart University of Medical Sciences and the technical team of JoVm for their support.

Ethical Considerations

Not applicable.

Conflict of Interest

The authors declare that they have no competing interests.

Financial Support and Sponsorship

This research received no specific grant from any funding agency in the public sector.

References

1. Inoue N, Orías AAE. Biomechanics of Intervertebral Disc Degeneration. Orthop Clin North Am. 2011;42(4):487. [DOI:10.1016/j.ocl.2011.07.001] [PMID] [PMCID]
2. Stokes IAF, Iatridis JC. Mechanical Conditions That Accelerate Intervertebral Disc Degeneration: Overload Versus Immobilization. Spine. 2004;29(23):2724-32. [PMID] [PMCID] [DOI:10.1097/01.brs.0000146049.52152.da]
3. Jeong JG, Kang S, Jung GH, Cho M, Kim H, Kim KT, et al. Biomechanical Effect of Disc Height on the Components of the Lumbar Column at the Same Axial Load: A Finite-Element Study. J Healthc Eng. 2022;2022(1):7069448. [DOI:10.1155/2022/7069448] [PMID] [PMCID]
4. Wilke HJ, Herkommer A, Werner K, Liebsch C. In Vitro Analysis of the Intradiscal Pressure of the Thoracic Spine. Front Bioeng Biotechnol. 2020;8: 614. [DOI:10.3389/fbioe.2020.00614] [PMID] [PMCID]
5. Ardatov O, Pachaleva J, Aleksiuk V, Maknickas A, Uzieliene I, Vaiciuleviciute R, et al. Modeling the Effect of Annulus Fibrosus Stiffness on the Stressed State of a Vertebral L1 Body and Nucleus Pulposus Bioengineering. 2024;11(4): 305. [DOI:10.3390/bioengineering11040305] [PMID] [PMCID]
6. Iatridis JC, Nicoll SB, Michalek AJ, Walter BA, Gupta MS. Role of Biomechanics on Intervertebral Disc Degeneration and Regenerative Therapies: What Needs Repairing in the Disc and What Are Promising Biomaterials for Its Repair?. Spine J. 2013;13(3):243-62. [DOI:10.1016/j.spinee.2012.12.002] [PMID] [PMCID]
7. Sun X, Wang J, Liu X, Tao H, Jin W, Shen K. Degeneration of Injured Intervertebral Discs Affected by Anterior Longitudinal Ligament Injury in Rabbits. Int J Clin Exp Pathol. 2018;11(2): 595.
8. Wilson RL, Bowen L, Kim W, Cai L, Schneider SE, Nauman EA, Neu CP. In Vivo Intervertebral Disc Deformation: Intratissue Strain Patterns within Adjacent Discs during Flexion-Extension. Sci Rep. 2021;11(1):729. [PMID] [PMCID] [DOI:10.1038/s41598-020-77577-y]
9. Żak M, Pezowicz C. Effect of Overload on Changes in Mechanical and Structural Properties of the Annulus Fibrosus of the Intervertebral Disc. Biomech Model Mechanobiol. 2021;20(6): 2259-67. [DOI:10.1007/s10237-021-01505-w] [PMID] [PMCID]
10. Hosseinzadeh-Posti M, Kamal Z, Rajaeirad M. Exploring Vertebral Bone Density Changes in a Trunk with Adolescent Idiopathic Scoliosis: A Mechanobiological Modeling Investigation of Intact and Unilaterally Paralyzed Muscles. Comput Methods Biomech Biomed Engin. 2024; 1-17. [DOI:10.1080/10255842.2024.2377345] [PMID]
11. Farajpour H, Jamshidi N. Effects of Different Angles of the Traction Table on Lumbar Spine Ligaments: A Finite Element Study. Clin Orthop Surg. 2017;9(4):480-8. [PMID] [PMCID] [DOI:10.4055/cios.2017.9.4.480]
12. Mankin HJ, Mow VC, Buckwalter JA. Articular Cartilage Repair and Osteoarthritis. Orthop Basic Sci. 2000;2:472-88.
13. Zhang Q, Chon T, Zhang Y, Baker JS, Gu Y. Finite Element Analysis of the Lumbar Spine in Adolescent Idiopathic Scoliosis Subjected to Different Loads. Comput Biol Med. 2021;136: 104745. [PMID] [DOI:10.1016/j.compbiomed.2021.104745]
14. Dai H, Liu Y, Han Q, Zhang A, Chen H, Qu Y, et al. Biomechanical Comparison between Unilateral and Bilateral Percutaneous Vertebroplasty for Osteoporotic Vertebral Compression Fractures: A Finite Element Analysis. Front Bioeng Biotechnol. 2022;10:978917. [PMCID] [PMID] [DOI:10.3389/fbioe.2022.978917]
15. Lu H, Zhang Q, Ding F, Wu Q, Liu R. Establishment and Validation of a T12-L2 3D Finite Element Model for Thoracolumbar Segments. Am J Transl Res. 2022;14(3):1606.