

Original

Open Access

Effect of pedicle-screw fixation on the biomechanics of the lumbar spine: A Case Study finite element analysis

Kamran Hassani ^{1*}, Hajir Karimi ¹, Shahrokh Shojaei ², Pedram Tehrani ³

1. Department of Biomedical Engineering, College of Medical Science and Technologies, Tehran Science and Research Branch, Islamic Azad University, Tehran, Iran

2. Department of Biomedical Engineering, Islamic Azad University, Central Tehran Branch, Tehran, Iran

3. Department of Mechanical Engineering, Islamic Azad University, Central Tehran Branch, Tehran, Iran

Abstract

The pedicle-screw fixation is widely used for the surgical treatment of degenerative lumbar disease. The biomechanical effects of the fusion on the vertebral bodies have not still been investigated in detail. In this study, we intended to calculate the stress and strain of the vertebral bodies and intervertebral discs of the lumbar spine after posterior pedicle-screw fixation (PPSF). A three-dimensional (3D) patient-specific finite element (FE) model of the human L1 to L5 spine was established based on the computed tomography (CT)/magnetic resonance imaging (MRI) images. A preload along with a sinusoidal load, were applied to the proximal end (L1). The distal end (L5) was fixed in all directions. The highest stress and strain were observed in the intervertebral disc of L4-L5 and L1-L2. The stress and strain of the unilateral pedicle-screw were higher than the bilateral ones. The results suggested that the unilateral pedicle-screw provides greater stability comparing to bilateral fixation in posterior bending position. The results have implications not only for understanding the stress and strain of the vertebral bodies and intervertebral discs but also, they give comprehensive information to the biomechanical and medical experts concerning the stability of the spine in the posterior bending position.

Keywords Pedicle-screw fixation; Lumbar spine; Posterior fixation; von Mises stress; Finite element analysis.

Introduction

The posterior pedicle-screw fixation (PPSF) uses pedicle graft for stabilization in the lumbar vertebrae resulting in bone fusion [1, 2]. The fusion of the spine is a widely used surgical technique for the treatment of degenerative lumbar spinal disease [3, 4]. However, it has been shown that PPSF may invoke mechanical and physiological alterations of the spine, such as the acceleration of degeneration [5, 6], loss of motion, changes in the centers of intervertebral rotation, and degeneration of the adjacent intervertebral disc [7, 8]. It has been reported that a rigid spinal system may trigger abnormal changes in the load

transfer and stresses following by disc degeneration and bone remodeling [9, 10]. Biomechanical factors, such as the stresses and deformations, in the vertebral bodies and intervertebral discs could be the key in investigating the pros and cons of the PPSF using various forms of loading and boundary conditions. Despite the highly importance of this issue, there is still a lack of knowledge and biomechanical evidence in regard of these biomechanical factors [11]. Due to the experimental complications in calculating the stresses and deformations of the spine after PPSF surgery, the application of the numerical approaches, i.e., finite element (FE), is preferred [12, 13].



© The Author(s) 2023. **Open Access** This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

* Correspondence:
kamran14877@yahoo.com

A FE modeling was used to compare the application of different materials in spacers design [14]. The mechanical behavior of pedicle screws were investigated under the fatigue [15, 16] and bending loadings [17] using FE model of the thoracic and lumbar spines. Transforaminal lumbar interbody fusion approach was used to compare the pros and cons of the one lateral pedicle-screw rod implant and two unilateral and bilateral pedicle-screw rods under a bending load [18]. The role of the structure of the rod on the load bearing of the fused spine under the fatigue load was investigated [19]. A comparative FE study has been done to compare the mechanical behavior of the cobalt-chrome (Co-Cr) and titanium (Ti) rods [20], poly-ether ether ketone (PEEK) and Ti [21], and ultra-high molecular weight polyethylene (UHMWPE) [22] of the lumbar spine under the applied load. However, so far there is a paucity of knowledge on the stresses and deformations in the components of the lumbar spine, i.e., vertebral bodies and intervertebral discs, posteriorly fused by a set of unilateral and bilateral pedicle screws and rods.

In this study, we intended to establish a patient-specific FE model of the lumbar spine. We calculated the stress and strain in the components of the area after PPSF surgery procedure. The results were interpreted in terms of the stress and strain in each intervertebral discs, pedicle screws and rods to address the pros and cons of the PPSF after orthopedic surgery.

2. Materials and Methods

The FE model of the lumbar spine, including the vertebral bodies (L1 to L5) and intervertebral discs, was established based on the CT/MRI data as shown in Fig. 1.

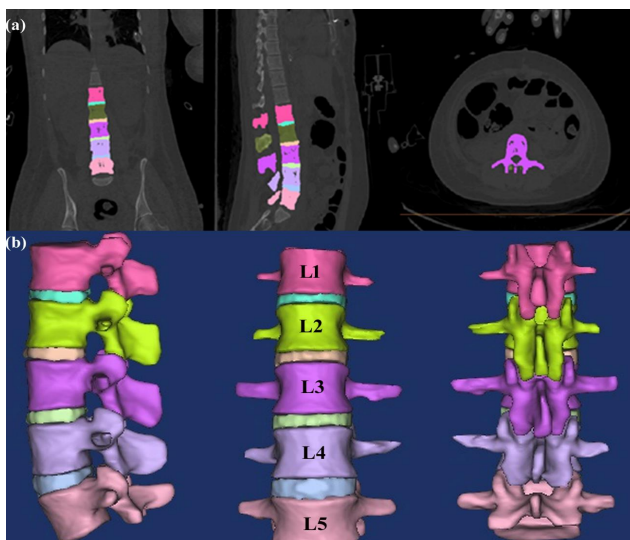


Figure 1. The (a) structure and (b) 3D model of the lumbar spine on a basis of the CT/MRI data in MIMICS software. The model includes L1 to L5 vertebrae and intervertebral discs

The CT/MRI images were obtained from a 41-year-old healthy male (80 Kg) individual. The experimental design was approved by our Institutional Review Board before the study was started. The written informed consent was obtained from study participant adhered to declaration of Helsinki 2008. The images were taken using the CT data. The images were imported in MIMICS software to establish a geometric model of the lumbar spine. The model was reconstructed and modified in Solidworks. Thereafter, it was assembled, meshed, and solved by Ansys Workbench (Canonsburg, Pennsylvania, United States). The model components including, the vertebral bodies, intervertebral discs, unilateral & bilateral pedicle screws and rods, and endplate, were meshed with tetrahedral elements as shown in Fig. 2.

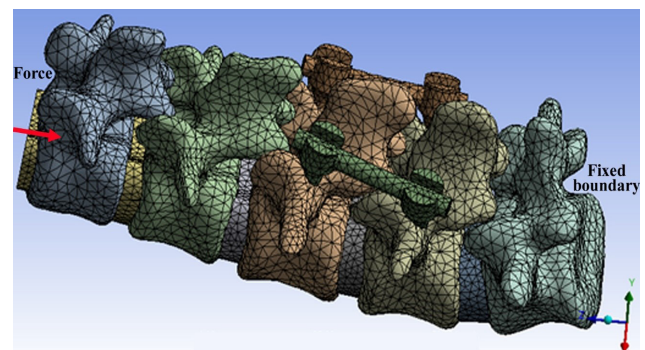


Figure 2. The meshed FE model of the lumbar spine. The proximal end was fixed in all directions and a force was applied to the distal end of the spine. The pedicle screw was also used to fuse L2 and L5 vertebrae.

The pedicle screws and rods were designed by Solidworks. The length, inner, and outer diameters of the pedicle screw were 35, 4.20, and 6.50 mm. Correspondingly, the length and outer diameter of the rods were 46 and 5.50 mm, respectively. The mechanical properties of the FE model as well as the number of elements and nodes are listed in Table 1.

Table 1. Material properties and number of elements/nodes of the FE model [22, 28-30].

Material	Material model	Properties	Elements/nodes
Vertebrae	Elastic	$E=2000 \text{ MPa}$, $\nu=0.30$	42671/70049
Intervertebral disc	Hyperelastic	$C_{01}=3.31 \text{ MPa}$, $C_{01}=0.30 \text{ MPa}$	12811/21059
Endplate	Elastic	$E=23.80 \text{ MPa}$, $\nu=0.40$	7227/13157
Pedicle screws and rods (Ti6Al4V)	Elastic	$E=110 \text{ GPa}$, $\nu=0.30$	1073/2007

The loading and boundary conditions of the model are presented in Fig. 2. A preload of 400 N, representing the body weight, was applied to the proximal end of the lumbar spine (L1). Thereafter, a sinusoidal load, with the os-

cillation of ± 40 N, was applied to represent a vibration loading of the body with the frequency of 5 Hz. It was applied to the same anatomical location of the body. The distal end of the L5 was fixed in all directions. The contact between the vertebral bodies and intervertebral discs were assumed to be tie [23]. The stress and strain distributions of each region of the model were computed by Ansys Workbench. The simulations in Ansys Workbench solver took ~ 3 -5 hours.

3. Results

The stress and strain contours of lumbar spine are shown in Fig. 3. The results showed that the highest stress is 81.863 MPa in the area where the strain was 0.0937 respectively. These values belonged to the proximal end of the lumbar spine (L1), where the load was applied to the model.

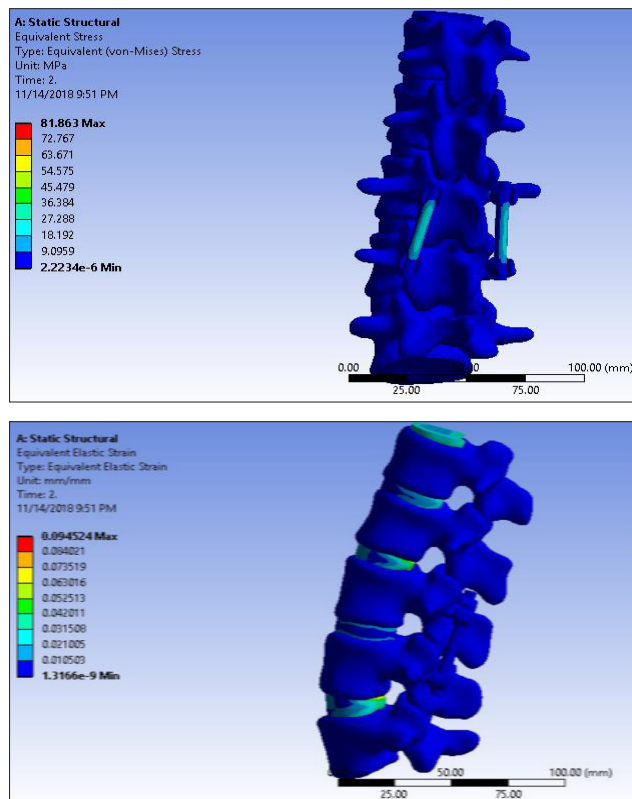


Figure 3. The contours of the (a) maximum von Mises stress and (b) maximum strain of the lumbar spine under the applied load.

The contours of the stress and strain of the intervertebral discs are illustrated in Figs. 4 and 5, respectively. The highest (2.02 MPa) and lowest (0.39 MPa) stresses were observed in the L4-L5 and L3-L4 intervertebral discs, respectively. The highest and lowest strains were also found at the L1-L2 and L4-L5 intervertebral discs.

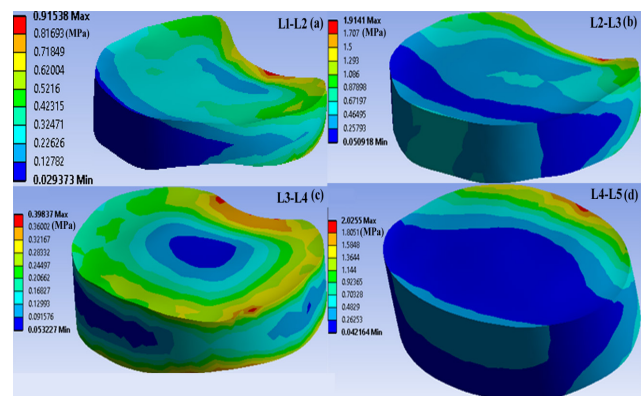


Figure 4. The contours of the maximum von Mises stress in the (a) L1-L2, (b) L2-L3, (c) L3-L4, and (d) L4-L5 intervertebral discs under the applied load.

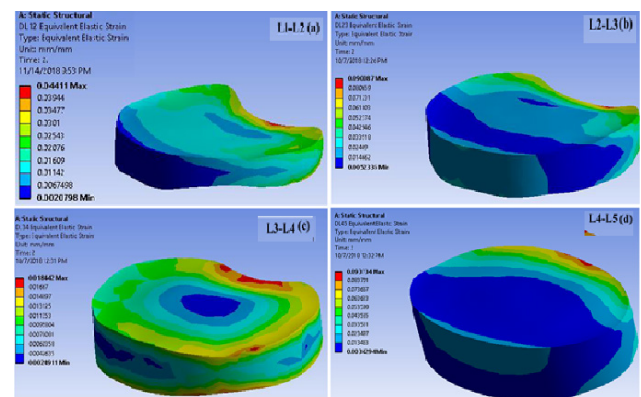


Figure 5. The contours of the maximum strain in the (a) L1-L2, (b) L2-L3, (c) L3-L4, and (d) L4-L5 intervertebral discs under the applied load.

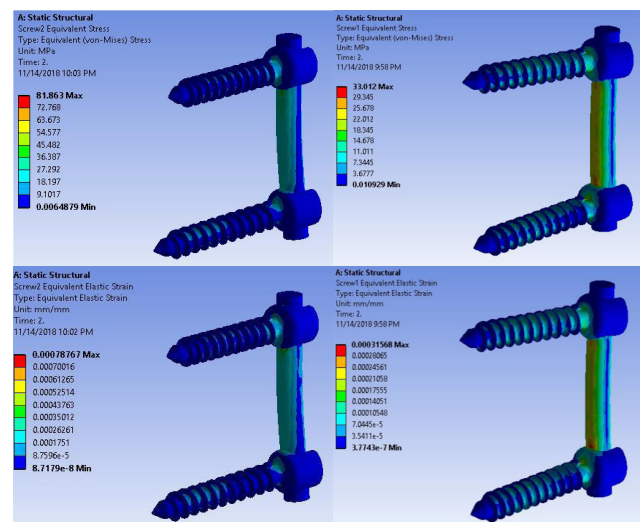


Figure 6. The contours of the maximum von Mises stress in the (a) unilateral (left) and (b) bilateral (right) pedicle screw. The contours of the maximum strain in the (c) unilateral (left) and (d) bilateral (right) pedicle screw.

The stress and strain of the unilateral (left) & bilateral (right) pedicle screws and rods were calculated and exhibited in Fig. 6. The stresses of 81.86 and 33.01 MPa were observed in the unilateral and bilateral implants, respectively. The strain in the unilateral and bilateral implants were 0.00078 and 0.00031.

4. Discussions

FE analysis enabled us to calculate the stress and strain values in the lumbar spine under complicated loadings and boundary conditions. Due to the importance of geometry and structure of the model for FE analysis, application of a patient-specific model is highly recommended. This study also used a patient-specific FE model of the human lumbar spine which was established according to the CT/MRI images. The FE model was consisted of the vertebral bodies, intervertebral discs, and endplate. The model was fixed posteriorly using Ti-based pedicle screws and rods. The spinal instrumented fusion was a method for surgical treatment of lumbar degenerative spinal diseases, such as spinal stenosis and spondylolisthesis. Although it is an accepted method for treatment of degenerative lumbar diseases, other investigations have shown effects of spinal fusion, including chronic back pain, loss of motion, and degeneration of adjacent segment [6, 24]. Due to fusion-related problems, less rigid stabilization was assumed to be an alternative method to avoid mentioned problems [25, 26]. In this study, we aimed to employ a patient-specific FE model of the lumbar spine (Fig. 1), after PPSF surgery. We wanted to calculate the stress and strain in the vertebral bodies, intervertebral discs, pedicle screws and rods. A preload, following by a sinusoidal load, was applied to the proximal end of the spine (L1) and the distal end (L5) (Fig. 2). The stress and strain of the proximal end of the lumbar spine were higher than that of the distal part (Fig. 3). This was due to the loading and boundary condition of the model. On the other hand, the highest strain at the posterior side of the model was observed in the L1 body. Investigating the distribution of the stress (Fig. 4) and strain (Fig. 5) of the intervertebral discs, we found out the highest stress was at the distal end (L4-L5) while the highest strain was at the proximal end (L1-L2). Since the lumbar spine, under the applied load, experienced a rollback then the concentrations of the stress and strain were mostly located at the posterior/dorsal side of the intervertebral discs. The stress and strain of 0.46 MPa and 0.02 were reported at L3-L4 intervertebral disc [27], which are 6% and 8% higher than that of the concurrent study. The strain here stands for the strain differences between two nodes at the bottom and top of the intervertebral disc. The applied force to the posterior side of the spine was tolerated by the Ti unilateral and

bilateral pedicle screws and rods (Fig. 6). The unilateral pedicle screws and rods tolerated the highest amounts of the stress and strain. It indicated that the lumbar spine posterior movement tolerated higher forces at the left of the spine compared to the right side. The results suggested that the unilateral pedicle-screw provided greater stability when compared to the bilateral fixation in posterior bending position. The average stress of the unilateral & bilateral pedicle screws and rods have been reported to be 35 MPa [22], where the average stress of this study was calculated 37 MPa,. This comparison maybe validated our numerical results.

Although this study has tried to perform an accurate FE analysis based on the patient-specific CT/MRI data of a male, but the numerical results here are to be investigated more. The mechanical properties of the intervertebral disc were considered to be simply isotropic, however, it has been shown that the intervertebral disc is highly anisotropic under the applied load. The boundary condition which was implemented into our model might not be as similar as that of the anatomical condition of the human body. This needs to be addressed in future studies.

5. Conclusions

In this study, we tried to calculate the stress and strains in the components of the lumbar spine, including the vertebral bodies and intervertebral discs. The patient-specific FE model of a healthy male individual was used for the analyses. A preload, following by a sinusoidal load, was applied to the proximal end of the lumbar spine (L1) while the distal end plate (L5) was fixed in all directions. The results revealed a higher strain at the proximal end of the spine model. The highest stress was found at the L4-L5 intervertebral disc, where the fixed boundary condition was considered. In contrast, the highest strain among the intervertebral discs were located at the proximal end of the model (L1-L2). The results suggested that a load out of the weight of the body results in a posterior rollback of the lumbar spine. The results also implied that a rate of degeneration in the intervertebral discs is higher at L4-L5. These findings have implications for understanding the vulnerable sites of the lumbar spine in terms of the stress and strain, posteriorly being fixed by pedicle screws and rods.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare that they have no competing interests.

Received: May. 2023 Accepted: Jun. 2023

Published online: Jun. 2023

DOI: 10.22034/ASAS.2023.406496.1026

References

- [1] Sato T, Yonezawa I, Todo M, Takano H, Kaneko K. Biomechanical Effects of Implant Materials on Posterior Lumbar Interbody Fusion: Comparison of Polyetheretherketone and Titanium Spacers Using Finite Element Analysis and Considering Bone Density. *J Biomed Sci Eng* 2018;11:45.
- [2] Matge G. Cervical cage fusion with 5 different implants: 250 cases. *Acta Neurochir* 2002;144:539-50.
- [3] Ottardi C, Galbusera F, Luca A, Prosdocimo L, Sasso M, Brayda-Bruno M, et al. Finite element analysis of the lumbar destabilization following pedicle subtraction osteotomy. *Med Eng Phys* 2016;38:506-9.
- [4] Luca A, Ottardi C, Lovi A, Brayda-Bruno M, Villa T, Galbusera F. Anterior support reduces the stresses on the posterior instrumentation after pedicle subtraction osteotomy: a finite-element study. *Europ Spine J* 2017;26:450-6.
- [5] Cunningham BW. Basic scientific considerations in total disc arthroplasty. *Spine J* 2004;4:S219-S30.
- [6] Lee CK. Accelerated degeneration of the segment adjacent to a lumbar fusion. *Spine* 1988;13:375-7.
- [7] Eck KR, Bridwell KH, Ungacta FF, Lapp MA, Lenke LG, Riew KD. Analysis of titanium mesh cages in adults with minimum two-year follow-up. *Spine* 2000;25:2407-15.
- [8] Kuslich SD, Danielson G, Dowdle JD, Sherman J, Fredrickson B, Yuan H, et al. Four-year follow-up results of lumbar spine arthrodesis using the Bagby and Kuslich lumbar fusion cage. *Spine* 2000;25:2656-62.
- [9] Fritzell P, Hägg O, Nordwall A. Complications in lumbar fusion surgery for chronic low back pain: comparison of three surgical techniques used in a prospective randomized study. A report from the Swedish Lumbar Spine Study Group. *Europ Spine J* 2003;12:178-89.
- [10] Hilibrand AS, Robbins M. Adjacent segment degeneration and adjacent segment disease: the consequences of spinal fusion? *Spine J* 2004;4:S190-S4.
- [11] Nemoto O, Asazuma T, Yato Y, Imabayashi H, Yasuoka H, Fujikawa A. Comparison of fusion rates following transforaminal lumbar interbody fusion using polyetheretherketone cages or titanium cages with transpedicular instrumentation. *Europ Spine J* 2014;23:2150-5.
- [12] Wang Z, Fu S, Wu Z-x, Zhang Y, Lei W. Ti2448 pedicle screw system augmentation for posterior lumbar interbody fusion. *Spine* 2013;38:2008-15.
- [13] Vadapalli S, Sairyo K, Goel VK, Robon M, Biyani A, Khandha A, et al. Biomechanical rationale for using polyetheretherketone (PEEK) spacers for lumbar interbody fusion—a finite element study. *Spine* 2006;31:E992-E8.
- [14] Xiao Z, Wang L, Gong H, Zhu D. Biomechanical evaluation of three surgical scenarios of posterior lumbar interbody fusion by finite element analysis. *Biomed Eng Online* 2012;11:31.
- [15] Yang T, Chen K, Lv Y. Fatigue life analysis of fixed structure of posterior thoracolumbar pedicle screw. *Engineering* 2013;5:292.
- [16] Major Š, Kocour V, Cyrus P. Fatigue life prediction of pedicle screw for spinal surgery. *Frattura ed Integrità Strutturale* 2016;10:379-88.
- [17] Amaritsakul Y, Chao C-K, Lin J. Biomechanical evaluation of bending strength of spinal pedicle screws, including cylindrical, conical, dual core and double dual core designs using numerical simulations and mechanical tests. *Med Eng Phys* 2014;36:1218-23.
- [18] Chen S-H, Lin S-C, Tsai W-C, Wang C-W, Chao S-H. Biomechanical comparison of unilateral and bilateral pedicle screws fixation for transforaminal lumbar interbody fusion after decompressive surgery—a finite element analysis. *BMC Musculoskelet Disord* 2012;13:72.
- [19] Lindsey C, Deviren V, Xu Z, Yeh R-F, Puttlitz CM. The effects of rod contouring on spinal construct fatigue strength. *Spine* 2006;31:1680-7.
- [20] Su BW, Shimer AL, Chinthakunta S, Salloum K, Ames CP, Vaccaro AR, et al. Comparison of fatigue strength of C2 pedicle screws, C2 pars screws, and a hybrid construct in C1–C2 fixation. *Spine* 2014;39:E12-E9.
- [21] Chou W-K, Chien A, Wang J-L. Biomechanical analysis between PEEK and titanium screw-rods spinal construct subjected to fatigue loading. *Clin Spine Surg* 2015;28:E121-E5.
- [22] Biswas JK, Rana M, Majumder S, Karmakar SK, Roychowdhury A. Effect of two-level pedicle-screw fixation with different rod materials on lumbar spine: A finite element study. *J Orthop Sci* 2018;23:258-65.
- [23] Lee H-H. Finite element simulations with ANSYS Workbench 17: SDC publications; 2017.
- [24] Gillet P. The fate of the adjacent motion segments after lumbar fusion. *Spine* 2003;28:338-45.
- [25] Sengupta DK. Dynamic stabilization devices in the treatment of low back pain. *Orthop Clin North Am* 2004;35:43-56.
- [26] Mulholland RC, Sengupta DK. Rationale, principles and experimental evaluation of the concept of soft stabilization. *Arthroplasty of the Spine: Springer*; 2004. p. 142-9.
- [27] Fan W, Guo L-X. Finite element investigation of the

effect of nucleus removal on vibration characteristics of the lumbar spine under a compressive follower preload. *J Mech Behav Biomed Mater* 2018;78:342-51.

[28] Sengul E, Ozmen R, Yaman ME, Demir T. Influence of posterior pedicle screw fixation at L4-L5 level on biomechanics of the lumbar spine with and without fusion: a finite element method. *Biomed Eng Online*. 2021 Oct 7;20(1):98. doi: 10.1186/s12938-021-00940-1. PMID: 34620170; PMCID: PMC8499536.

[29] Pan, J.-H.; Chen, C.-S.; Liu, C.-L.; Chou, P.-H. Biomechanical Effects of a Novel Pedicle Screw W-Type Rod Fixation for Lumbar Spondylolysis: A Finite Element Analysis. *Bioengineering* 2023, 10, 451. <https://doi.org/10.3390/bioengineering10040451>

[30] Xu C, Huang C, Cai P, Fang Z, Wei Z, Liu F, Li J, Liu Y. Biomechanical Effects of Pedicle Screw Positioning on the Surgical Segment in Models After Oblique Lumbar Interbody Fusion: An in-silico Study. *Int J Gen Med*. 2022;15:1047-1056 <https://doi.org/10.2147/IJGM.S352304>

Submit your manuscript to Advances in the standards and applied sciences journal and benefit from:

- Convenient online submission
- Rigorous peer review
- Open Access: articles freely available online
- High visibility within the field
- Retaining the copyright to your article

**Submit your next manuscript at:
journal.standards.ac.ir**