ISOMAse
International Society of Ocean, Mechanical and Aerospace Scientists and Engineers

Journal of Ocean, Mechanical and Aerospace
-Science and Engineering-
30th March 2025. Vol.69 No.1

March 30, 2025

Structural of Pedicle Screw on Biomechanical Characteristics of Spinal Scoliosis Correction Deformation

Weriono [a*], Meifal Rusli [a], Hendery Dahlan [a] and Roni Eka Sahputra [b]

[a)] *Mechanical Engineering Department, Faculty of Engineering, Universitas Andalas, Padang, Indonesia*
[b)] *Orthopedics Department, Faculty of Medicine, Andalas University, Padang, Indonesia*

*Corresponding author: weriono@gmail.com

Paper History

Received: 16-February-2025
Received in revised form: 21-March-2025
Accepted: 30-March-2025

ABSTRACT

Scoliosis correction methods often involve orthopedic procedures such as implant placement to stabilize movement and correct spinal deformity. The choice of surgical method is highly dependent on the location and nature of the fracture. Fractures with significant damage require a different approach compared to cases of minor injuries. Three dimensional finite element model of C1–L6 spine was used to simulate conditions with single cylindrical implant fixation under a vertical downward loading force 50 N and cylindrical screw types made of titanium alloy. The human spine, encompassing the cervical, thoracic, and lumbar regions, exhibits a complex biomechanical response when subjected to physiological loads. Displacement that occurs due to axial force can be the result of pedicle screw movement with vertebrae of the spine. Installation of 4 (four) rows of pedicle screws reduces the release of pedicle screws from the spine. The use of more fixation can reduce the stress distribution on the vertebrae of the spine.

KEYWORDS: *Bio-mechanic, Scoliosis, Cylindrical screw, Pedicle screw, Vonmises stress.*

1.0 INTRODUCTION

Scoliosis correction methods often involve orthopedic procedures such as implant placement and bone grafting to stabilize movement and correct spinal deformity [1-2]. Spinal deformities, especially those caused by dislocations or complex fractures, have very unpredictable deformation patterns, thus posing challenges in the planning and implementation of osteotomy surgery. Mistakes or delays in diagnosing spinal fractures can be serious problems that worsen the patient's prognosis [3]. Accurate preoperative planning is an important step in deformity correction. This process must consider the appropriate type of osteotomy and the classification of the spinal deformity to be treated [4-5].

The choice of surgical method is highly dependent on the location and nature of the fracture [6-8]. For example, fractures with significant damage require a different approach compared to cases of minor injuries. Orthopedic surgery aims to restore strength, stability, and mobility to the damaged spine. Therefore, careful planning, including the selection of appropriate implants and corrective techniques, is essential to ensure optimal clinical outcomes [9-10]. In cases of complex spinal injuries, a multidisciplinary approach involving biomechanics, orthopedics, and radiology can increase the success of correction and minimize the risk of complications [11].

The use of implant structures in scoliosis correction, while providing significant benefits, is not without its challenges. Key challenges include mechanical failures, such as rod fractures and distraction mechanism failures, which can lead to unplanned revision surgeries. Understanding these complications is crucial for improving surgical techniques and implant designs. Practitioners and researchers have documented a range of failure modes associated with these implants. These failures compromise the stability and effectiveness of the correction, potentially leading to complications and requiring revision surgeries.

Specifically, reported failures encompass several critical components of the implant system. These include the detachment of pedicle screws from the spine, fracturing of the screws themselves, and separation of the screw from the screw head, fracture of the screw head, and fracture of the connecting rod [12]. Each of these failure types poses a unique set of risks and necessitates careful consideration during surgical planning and execution to minimize the likelihood of occurrence. These cases generally occur several years after implant placement and are thought to be caused by mechanical loads due to the patient's physiological movements in daily activities [13-14].

This study aimed to optimize scoliosis correction procedures by first, identifying spinal regions with robust structural integrity capable of withstanding physiological loads during correction, and second, establishing optimal pedicle screw placement techniques to ensure secure fixation and prevent screw loosening under these loads, thereby improving the long-term stability and effectiveness of scoliosis correction.

ISOMAse
International Society of Ocean, Mechanical and Aerospace Scientists and Engineers
Journal of Ocean, Mechanical and Aerospace
-Science and Engineering-
30th March 2025. Vol.69 No.1
March 30, 2025

2.0 METHOD

2.1 Finite Element Model of Scoliosis Spine

This study employed the three-dimensional finite element model encompassing the C1 to L6 spinal region to simulate the mechanical behaviour of a scoliosis spine under surgical intervention. Specifically, the model replicated two surgical scenarios involving the application of four rows of single cylindrical implant fixations. A vertical downward loading force of 50 N was applied to mimic physiological loads experienced by the spine. The model's comprehensive design incorporated crucial anatomical structures, including cortical and cancellous bone, bony posterior elements, facets, end plates, annulus fibrosus, nucleus pulposus, and the intact thoracolumbosacral ligaments. This detailed representation allowed for a realistic assessment of the loads and stresses distributed throughout the scoliosis spine during the simulated surgical conditions.

The mechanics associated with the loads and stresses impacting upon the spine are worthy of specific consideration here. Such loads and stresses affect both the routine degenerative process and other inflammatory and non-inflammatory diseases of the spine. The fundamental mechanical principles associated with the degenerative and spinal column failure processes were discussed. The model includes cortical bone, cancellous bone, bony posterior elements, facets, end plates, annulus fibrosus, nucleus pulposus, and intact thoraco lumbosacral ligaments of the scoliotic spine.

By analyzing the mechanics of these loads and stresses, the study aimed to shed light on their influence on both routine degenerative processes and various spinal diseases. Furthermore, the model facilitated the examination of fundamental mechanical principles associated with degenerative changes and spinal column failure, ultimately contributing to a deeper understanding of the biomechanical factors critical to scoliosis correction.

2.2 Implant Correction Model

The biomechanical instruments used in scoliosis correction consist of screws, rods, and locks. The instruments were implanted into the pedicle of the spine to be corrected. The thoracic spine has vertebrae C1-L6. The model was used the T3 – T6 vertebra. The C1 position was used as a process that given load of 50 N (head weight) [15] as a tensile load position of the spine on the pedicle screw towards the dorsal posterior on the lamina of the vertebral.

The pedicle screws were used cylindrical screw types made of titanium alloy with an elastic modulus (E) of 110 GPa, $\upsilon = 0.3$ measuring 6mm x θ5mm x 40 mm(D = 6 mm, d = 5 mm, neck = 3 mm, head = 12 mm, rod = 9 mm, dan pitch 0,75 mm, young's modulus 110 GPa, pedicle screw connecting rod ASTM C36000 (B16-92). Normal bone mineral mass consists of concellous bone structure E = 10GPa, $\upsilon = 0.3$, cortical and E = 0.75GPa, $\upsilon = 0.2$ and osteopenia bone mineral E = 5GPa, $\upsilon = 0.3$ cortical bone structure and E = 0.3GPa, $\upsilon = 0.2$ cancellous bone structure [16]. The material is assumed to be homogeneous and isotropic. Hexahedral and tetrahedral elements types were used in cortical, concellous and pedicle screws. The model uses three-dimensional nonlinear contact simulation using MSC Marc / Metant simulation. Contact model with a friction coefficient of 0.1. Element size of 0.975 mm, which was 210,865 elements, while the use of cylindrical screw pedicles, tetrahedral element types, element size 0.9 mm, was 355,568 elements.

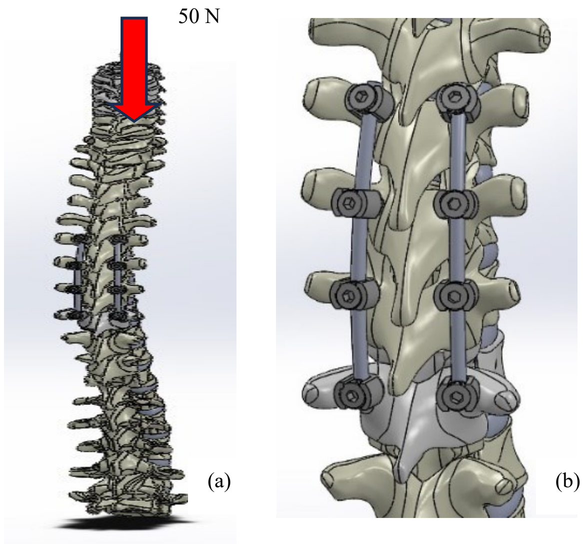

Figure 1: (a) FEM model of the spine, (b) fixation of 4 rows of single cylindrical screws

2.3 Axial Load Simulation

To accurately replicate the physiological loading experienced during normal daily life, this study employed simulation and analysis techniques, specifically focusing on axial load conditions. In these simulations, an axial compression load was consistently applied to the superior node of the first thoracic vertebra surface, effectively mimicking the compressive forces exerted on the spine during routine activities.

These models were constrained in all degrees of freedom at the sacroiliac joint surface. Axial load was applied at different values of the bone mineral mass model. The physiological loading of the head, neck, and the rest of the upper body was about 5 kg mass (50 N).The mechanical response of vertebral cortical and cancellous bone structures, facet joints, end plates, and intervertebral discs in the scoliotic spine with different bone mineral statuses was investigated and analyzed.

3.0 RESULTS

3.1 Effect of Stress Due To Structural Spine

In this study, in order to simplify the calculation process, the material properties were simplified in the mechanical analysis. The mechanical properties of the bone structure in the elastic range were considered, and isotropic, homogeneous, and continuous elastic material models were used to characterize the bone structure. All models were subjected to a vertical downward load 50 N to simulate the physiological activity of the spine. Simulation results using MSC-Marc show variations in the number of fixations of single-threaded cylindrical screw implants with a friction coefficient of 0.1 given an axial load 105 N from the weight of the human head. Figure 2 shows the maximum vonmises stress due to an axial load 50 N with the installation of 4 (four) rows of single-threaded cylindrical implants, which shows a maximum vonmises stress concentration of 104.8MPa.

JOMAse | Received: 16-February-2025| Accepted: 30-March-2025 | [(69) 1: 75-82]
Published by International Society of Ocean, Mechanical and Aerospace Scientists and Engineers, www.isomase.org., ISSN: 2354-7065 & e-ISSN: 2527-6085

ISOMAse
International Society of Ocean, Mechanical and Aerospace Scientists and Engineers
Journal of Ocean, Mechanical and Aerospace
-Science and Engineering-
30th March 2025. Vol.69 No.1
March 30, 2025

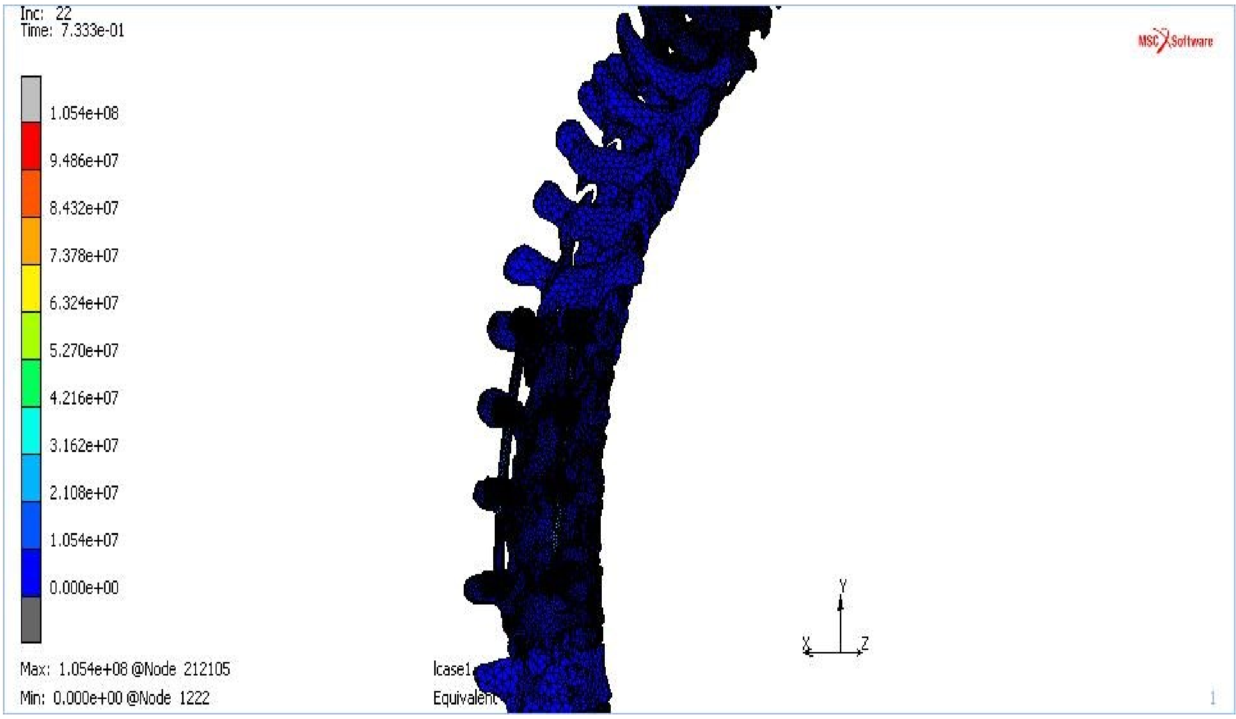

Figure 2: Distribution stress vonmises on scoliosis correction

The increase in the friction coefficient factor, the increase in force and the force vector have an effect on bone strength and bone mineral quality. The results of the maximum vonmises stress due to the axial load of 50 N, the influence of the head weight shown in Figure 2 show that the cut of the pedicle screw - bone interface has a maximum von mises stress concentration of 105.4 MPa with a friction coefficient of 0.1 with a single threaded cylindrical screw implant with a dorsal tensile force. The maximum vonmises stress occurs in the cervical area while the stress in the thoracic is 10.54 MPa lower than the lumbar 21.08 MPa because the thoracic implant was installed, which increased the strength of its structure, while the thoracic has a von mises stress of 0.86 MPa.

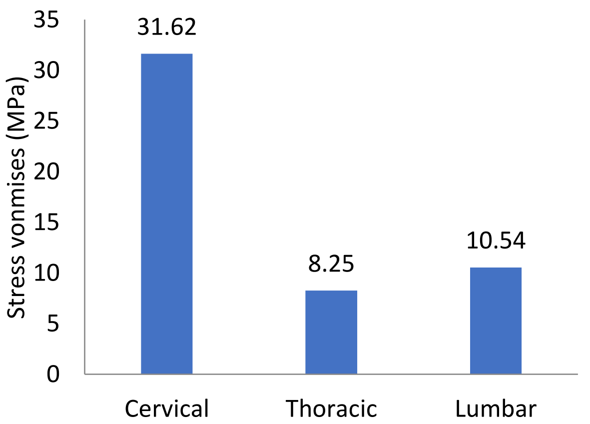

Figure 3: Graph distribution stress vonmises on spine

In Figure 3 depicted the distribution of mechanical stress across the spinal regions reveals a significant disparity, with the cervical region bearing the highest stress load at 31.62 MPa, dramatically exceeding the stress experienced in both the thoracic (8.25 MPa) and lumbar (10.54 MPa) regions. The lumbar region revealed the slightly higher stress than the thoracic, remains considerably less stressed than the cervical region.

Figure 4 presents a visual representation of the bone thread surface following the removal of a pedicle screw implant. The analysis of stress distribution reveals a significant disparity between the average and maximum vonmises stress values. The average vonmises stress experienced by the vertebrae of the spine was measured at 1.781 MPa, indicating a relatively low level of stress across the bone structure. However, a critical observation was the localized occurrence of significantly higher stress concentrations. Specifically, the maximum vonmises stress, recorded at 17.81 MPa, was found on the single cylindrical thread of the pedicle screw. A maximum von Mises stress of 5.34 MPa was observed within the cortical bone at the contact interface between a single cylindrical thread of the pedicle screw and the vertebral bone of the spine, indicating the localized stress concentration in this critical area.

The maximum vonmises stress in Figure 5 shows 105.4 MPa occurs in the area of the pedicle screw thread and vertebrae spine that experiences binding contact between the pedicle screw and spine. The distribution of vonmises stress due to the installation of 4 (four) rows of single cylindrical threads on the cervical vertebrae was higher than other parts. There was a decrease in vonmises stress between the cervical and thoracic by 260.9% while the cervical and lumbar were 33.3% as seen in Figure 6.

JOMAse | Received: 16-February-2025| Accepted: 30-March-2025 | [(69) 1: 75-82]
Published by International Society of Ocean, Mechanical and Aerospace Scientists and Engineers, www.isomase.org., ISSN: 2354-7065 & e-ISSN: 2527-6085

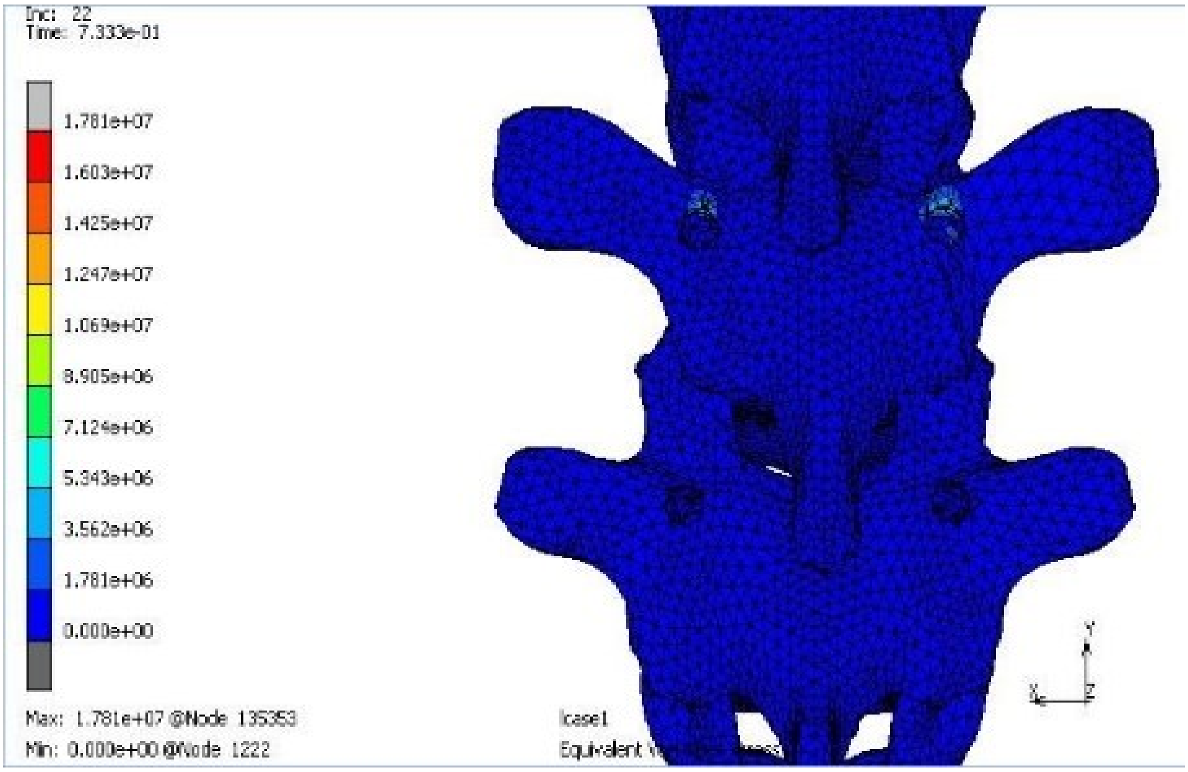

Figure 4.Distribution stress vonmises on vertebrae spine

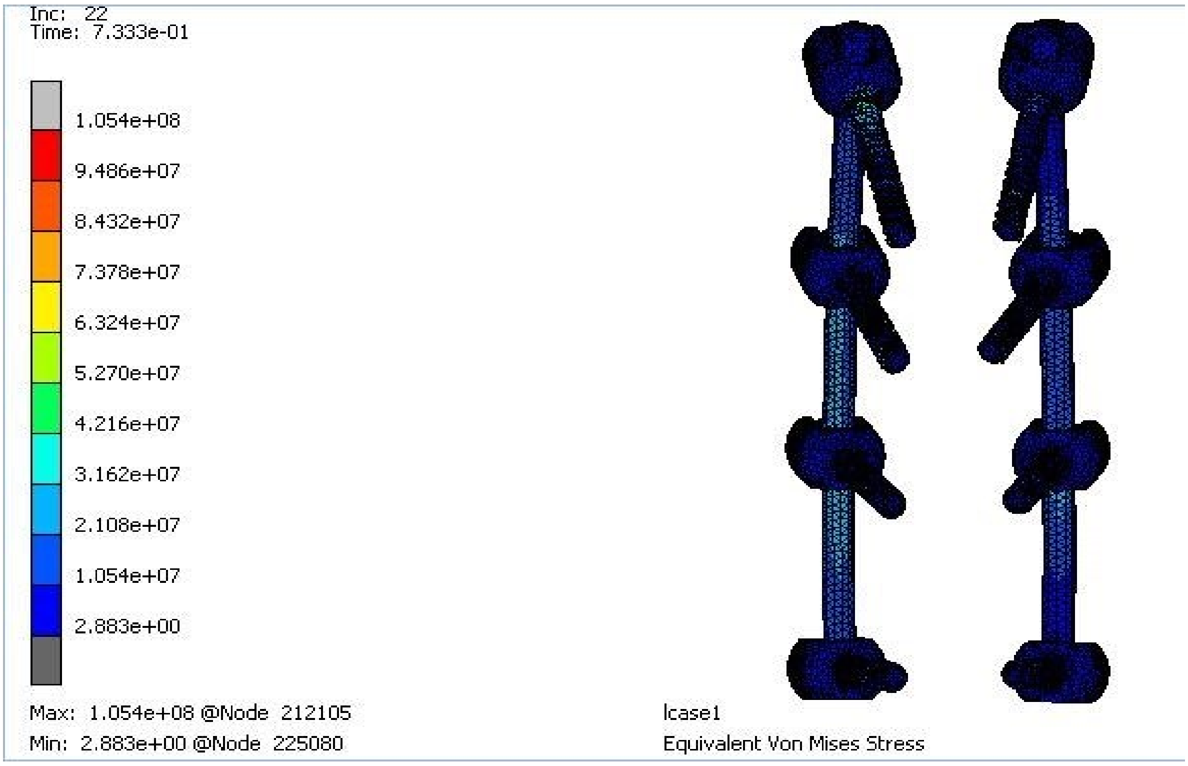

Figure 5: Distribution stress vonmises on pedicel screw

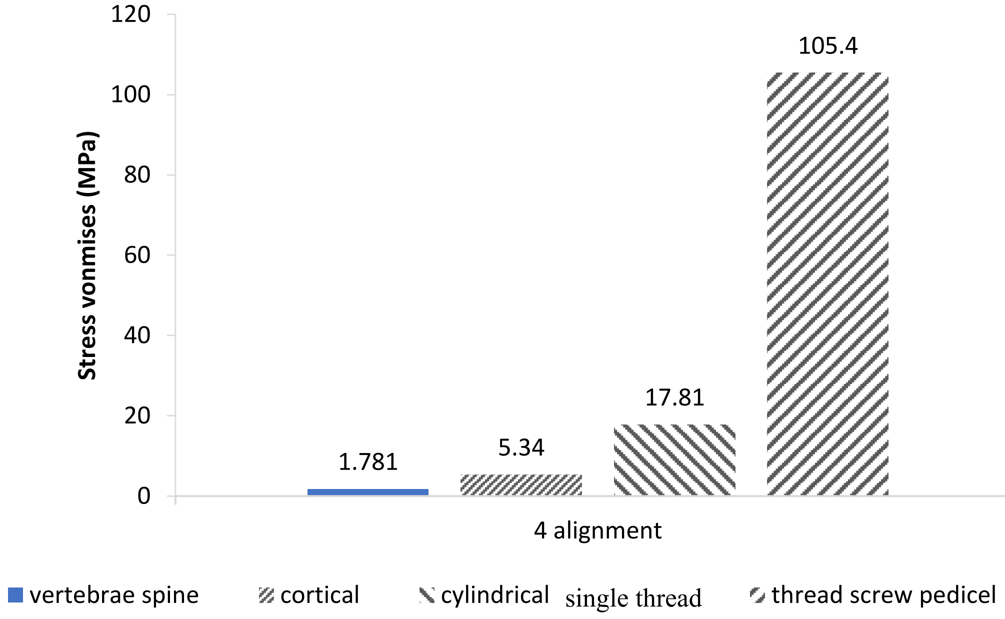

Figure 6: Graph distribution stress vonmises on spine

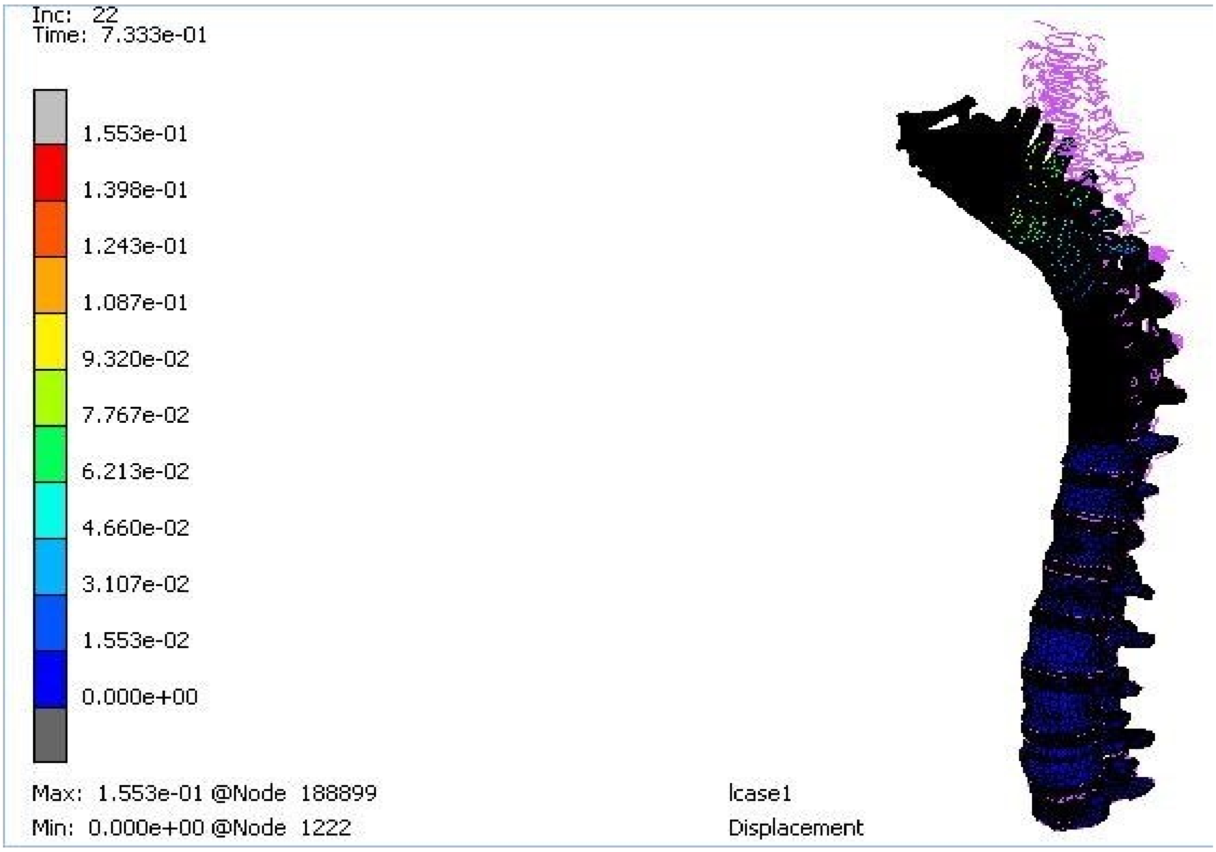

Figure 7: Distribution displacement on scoliosis correction

ISOMAse
International Society of Ocean, Mechanical and Aerospace Scientists and Engineers
Journal of Ocean, Mechanical and Aerospace
-Science and Engineering-
30th March 2025. Vol.69 No.1
March 30, 2025

3.2 Displacement Effect of Scoliosis Correction

The increase in the friction coefficient factor, the increase in force and the direction of the force affect the bone strength and bone mineral quality. The maximum displacement results shown in Figure 7 show that from the pedicle screw-bone interface there is a maximum displacement concentration of 155.3 mm with a friction coefficient of 0.1 with a tensile force cylindrical screw implant. The maximum displacement occurs in the cervical and neck areas at the contact between the screw and bone shown in Figure 8. The cervical area has the highest displacement compared to other areas. The thoracic area has a displacement of 15.53 mm, while the lumbar area is 32.07 mm shown in Figure 8.

Simulating normal vertebral bone mineral quality, this study examines the behaviour of cylindrical screw implants and single-threaded cylindrical screws when subjected to tensile loading at spine. The findings indicated that the pedicle screw-bone connection experienced greater movement and structural changes. Furthermore, bone strength and bone mineral quality play a critical role in determining the strength of the pedicle screw-bone interface, consequently affecting the screw's movement toward the bone interface. Simulation results using MSC-Marc show variations in vertebrae spine given a tensile load in Figure 9, showing a displacement of 5.53x10-4 mm on screw pedicel, which is the highest for cervical single thread cylindrical implants with a friction coefficient of 0.1. Screw displacement determines how far the object being fastened moves when the screw is turned so that the highest displacement occurs without causing the screw thread to move past the thread pitch of 0.75 mm.

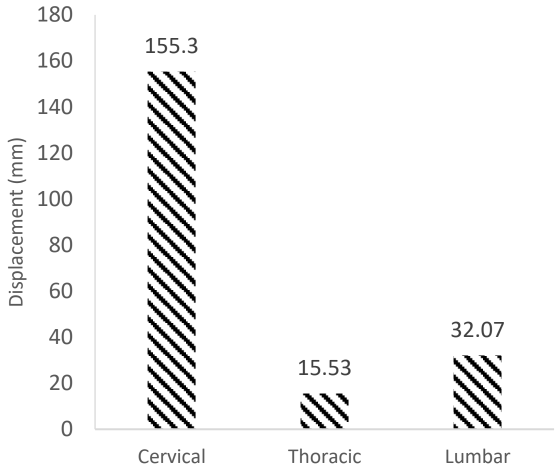

Figure 8: Graph distribution displacement on spine

The distribution of vonmises stress due to the installation of 4(four) rows of single cylindrical threads on the cervical vertebrae is higher than other parts, namely there is a decrease in vonmises stress between the cervical and thoracic by 100% while the cervical and lumbar are 20.6%. The use of cylindrical single thread screws with friction coefficient 0.1 has a displacement of 3,107 x 10^{-2} mm on cervical spine; decreased by 4.31 x 10^{-4} mm. The increasing of the contact force can provide bond strength between the pedicle screw interface and the bone, so that the pedicle screw did not come off easily.

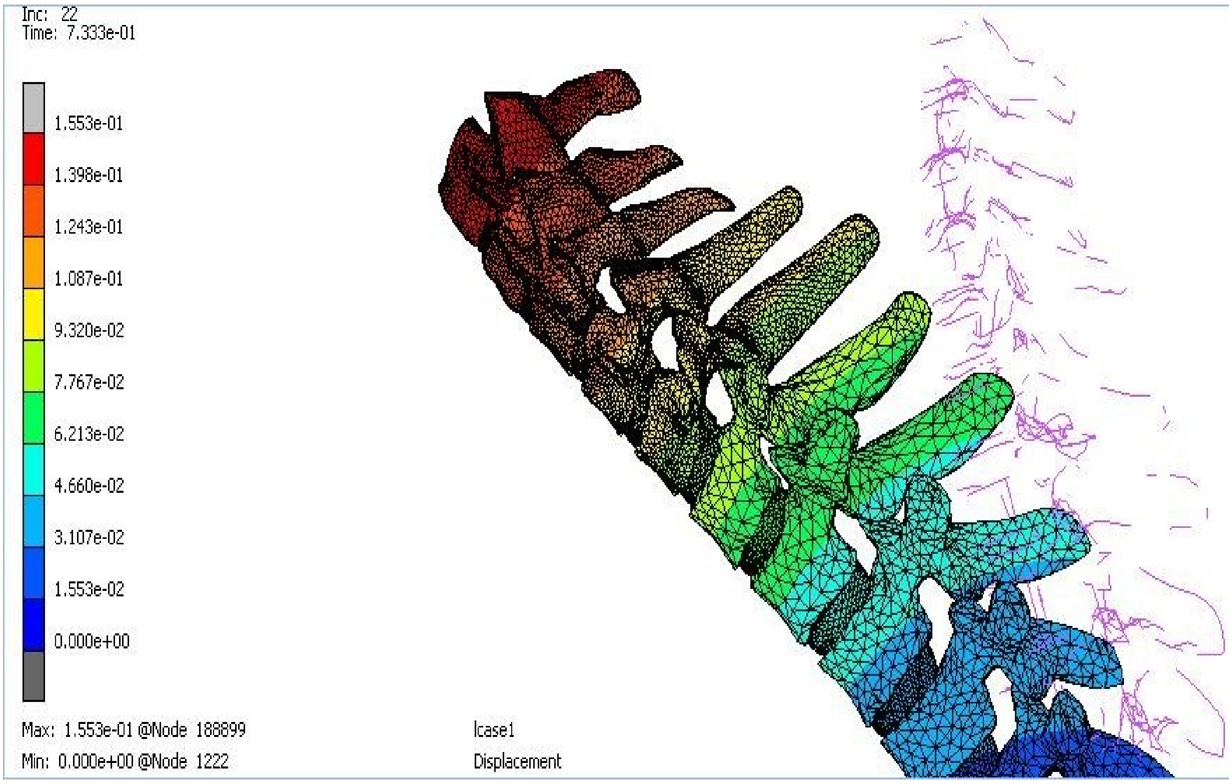

Figure 9: Distribution stress vonmises on cervical spine

JOMAse | Received: 16-February-2025| Accepted: 30-March-2025 | [(69) 1: 75-82]
Published by International Society of Ocean, Mechanical and Aerospace Scientists and Engineers, www.isomase.org., ISSN: 2354-7065 & e-ISSN: 2527-6085

The relationship between displacement and loose screws was that the greater the displacement of the screw. The easier it was for the screw to come loose from the object, which was attached to. Therefore, to avoid loose screws, it is necessary to choose screws with a displacement that appropriate to the object being fastened, and it is necessary to provide filler material to increase the coefficient of friction.

3.3 Discussion

The results of the spinal simulation using MSC-Marc show single-threaded cylindrical screw implants with a friction coefficient of 0.1 given an axial load 50 N from the weight of the human head and the results of the maximum vonmises stress of 4 (four) rows of single-threaded cylindrical implants occur in the cervical area. The distribution of vonmises stress due to the installation of 4 (four) rows of single cylindrical threads on the cervical vertebrae is higher than other parts, namely there is a decrease in vonmises stress between the cervical and thoracic by 260.9% while the cervical and lumbar are 33.3%. The effect of scoliosis correction on head load can affect the structural strength of the spine. The stress that occurs due to axial force can be reduced by installing several rows of pedicle screws to other parts of the spine.

In the thoracic region shown in Figure 4 with the installation of 4 (four) rows of single thread cylindrical implants, the distribution of displacement due to the installation of 4 (four) rows of single cylindrical threads on the cervical vertebrae is higher than other parts, namely there is a decrease in vonmises stress between the cervical and thoracic by 100% while the cervical and lumbar are 20.6%. The effect of scoliosis correction on head load can affect the connection of pedicle screws with spine vertebrae. Displacement that occurs due to axial force can be the result of pedicle screw movement with vertebrae of the spine. Installation of 4 (four) rows of pedicle screws reduces the release of pedicle screws from the spine. Installation of several rows of pedicle screws can reduce displacement that occurs to other parts of the spine.

Implementing patient-specific finite element models, incorporating individual spinal anatomy and bone density, could lead to personalized surgical planning and improved outcomes. Furthermore, investigating the influence of muscle forces and soft tissue contributions on spinal biomechanics during correction would provide a more comprehensive understanding of the loading environment. Finally, studies exploring the effectiveness of minimally invasive surgical techniques and novel implant technologies, such as shape memory alloys or biodegradable materials, could offer promising advancements in scoliosis treatment.

4.0 CONCLUSION

In this study the effect biomechanical response in the cervical, thoracic and lumbar spine due to physiological load. Higher stress in the scoliosis spine with variation of fixation of the scoliosis correction implant is mainly located on the concave side of the thoracic primary curve compared to the convex side. Displacement that occurs due to axial force can be the result of pedicle screw movement with vertebrae of the spine. Installation of 4 (four) rows of pedicle screws reduces the release of pedicle screws from the spine. The using of more fixations can reduce the stress distribution on the vertebrae of the spine due to physiological load. With the stress being distributed, the stress between the screws and the spine will be lower, thus reducing the occurrence of pedicle screw loosening. Based on the findings of this study, several avenues for future research can be explored to further enhance our understanding and optimization of scoliosis correction procedures. Future work could investigate the long-term biomechanical behavior of the spine with varying pedicle screw configurations, including fatigue analysis under cyclic physiological loading to predict implant longevity. Additionally, exploring the impact of different screw materials and designs on stress distribution and screw-bone interface stability would be valuable.

ACKNOWLEDGEMENTS

Universitas Andalas and Workshop Scopus Camp for study design, data collection or analysis, decision to publish, or preparation of the manuscript.

REFERENCES

[1] Al-Tamimi, A.A., Peach, C., Fernandes, P.R., Cseke, A. & Bartolo, P.J. (2017). Topology optimization to reduce the stress shielding effect for orthopedic applications. *Procedia Cirp*, *65*, 202-206.https://doi.org/10.1016/j.procir.2017.04.030.

[2] Haddas, R., Xu, M., Lieberman, I. & Yang, J. (2019). Finite element based-analysis for pre and post lumbar fusion of adult degenerative scoliosis patients. *Spine Deformity*, *7*(4), 543-552.

[3] Roth, K.A., Beheshtiha, S.A., van der Meer, R., Willems, C.P., Arts, J.J., Ito, K. & van Rietbergen, B. (2021). Validation of a finite element model of the thoracolumbar spine to study instrumentation level variations in early onset scoliosis correction. *Procedia CIRP*, *99*, 25–28.

[4] Kamal, Z., Rouhi, G., Arjmand, N. & Adeeb, S. (2019). Stability-based model of a growing spine with adolescent idiopathic scoliosis: A combination of musculoskeletal and finite element approaches. *Medical Engineering & Physics, 64*, 46–55. https://doi.org/10.1016/j.medengphy.2018.12.018.

[5] Weriono, W., Rusli, M., Sahputra, R.E. & Dahlan, H. (2024). Pedicle screw bond strength and resistance characteristics with various mineral quality. *TEM Journal, 13*(1), 809–813.

[6] Yu, J., Li, L., Wang, T., Sheng, L., Huo, Y. & Yin, Z. (2015). Intramedullary nail versus plate treatments for distal tibial fractures: A meta-analysis. *International Journal of Surgery, 16*, 60–68. https://doi.org/10.1016/j.ijsu.2015.02.058.

[7] Newcomb, A., Baek, S., Kelly, B.P. & Crawford, N.R. (2017). Effect of screw position on load transfer in lumbar pedicle screws: A non-idealized finite element analysis. *Computer Methods in Biomechanics and*

Biomedical Engineering, 20, 182–192. https://doi.org/10.1080/10255842.2016.1205040.

[8] Benzel, E.C. (2015). *Biomechanics of Spine Stabilization* (3rd ed.). Elsevier.

[9] Casstevens, C.M., Le, T. & Wyrick, J. (2012). Management of extra-articular fractures of the distal tibia: Intramedullary nailing versus plate fixation. *Journal of the American Academy of Orthopaedic Surgeons, 20*(11), 675–683.

[10] Palanca, M., Oliviero, S. & Dall'Ara, E. (2022). Micro FE models of porcine vertebrae with induced bone focal lesions: Validation of predicted displacements with digital volume correlation. *Journal of the Mechanical Behavior of Biomedical Materials, 125*, 104872. https://doi.org/10.1016/j.jmbbm.2021.104872.

[11] Veldhuizen, A.G., Wever, D.J., & Webb, P.J. (2000). The aetiology of idiopathic scoliosis: Biomechanical and neuromuscular factors. *European Spine Journal, 9*, 178–184. https://doi.org/10.1007/s005860000228.

[12] Weriono, W., Rusli, M., Sahputra, R.E. & Dahlan, H. (2022). Finite element analysis of stress on thoracic and pedicle screw interface with various loading and bone quality. *AIP Conference Proceedings, 2545*, 020013. https://doi.org/10.1063/5.0108783.

[13] Hashemi, A., Bednar, D. & Ziada, S. (2009). Pullout strength of pedicle screws augmented with particulate calcium phosphate: An experimental study. *The Spine Journal, 9*, 404–410. https://doi.org/10.1016/j.spinee.2008.02.002.

[14] Nowak, B. (2019). Experimental study on the loosening of pedicle screws implanted to synthetic bone vertebra models and under non-pull-out mechanical loads. *Journal of the Mechanical Behavior of Biomedical Materials, 98*, 200–204. https://doi.org/10.1016/j.jmbbm.2019.06.015.

[15] Song, X.X., Jin, L.Y., Li, X.F., Qian, L., Shen, H.X., Liu, Z.D. & Yu, B.W. (2018). Effects of low bone mineral status on biomechanical characteristics in idiopathic scoliotic spinal deformity. *World Neurosurgery*, *110*, e321-e329. https://doi.org/10.1016/j.wneu.2018.03.129.

[16] Bunmaprasert, T., Chaibhuddanugul, N., Keeratiruangrong, J., Raphitphan, R., Sugandhavesa, N. & Liawrungrueang, W. (2021). Corrective osteotomy of global sagittal imbalance in the neglected fracture-dislocation thoracic spine. *Journal of Orthopaedic Surgery and Research, 16*(1), Article 315. https://doi.org/10.1186/s13018-021-02561-3.

JOMAse | Received: 16-February-2025| Accepted: 30-March-2025 | [(69) 1: 75-82]
Published by International Society of Ocean, Mechanical and Aerospace Scientists and Engineers, www.isomase.org., ISSN: 2354-7065 & e-ISSN: 2527-6085