Jurnal Tribologi 45 (2025) 174-184

Jurnal Tribologi
Website : jurnaltribologi.mytribos.org e-issn: 2289-7232

Analysis of Von Mises stress on Lumbar 4 to Sacral 1 with variation in body mass index

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KEYWORDS

Body mass index
Herniated nucleus pulposus
Lumbar spine
Von Mises stress

ABSTRACT

Bioengineering, a field combining biology and engineering principles, aims to develop medical devices and solutions for spine problems like low back pain and herniated nucleus pulposus. Finite element modeling and analysis with the finite element method (FEM) can provide more accurate results, as in vitro experiments alone are insufficient for analyzing spine biomechanical properties. This study analyzes L4 to S1 in elderly Indonesians using FEM that linking body mass index (BMI) has a significant impact on analyzing the loading on the spine than analyze with von Mises stress. Using Computed Tomography (CT) scan data, a spinal model was reconstructed to simulate mechanical stress across different BMI categories. Results The study reveals that increasing BMI increases von Mises stress values, leading to a widening distribution. The High stress in the front side of the spine can force the nucleus pulposus to the backside, then through the layers of the annulus fibrosis. A normal BMI is ideal for preventing HNP, as it maintains healthy spinal pressure and slows disc degeneration. This study highlights the critical role of BMI management. That can prevent spine-related health issues

Received 2 August 2024; received in revised form 9 November 2024; accepted 13 November 2024.
To cite this article: Wicaksono et al., (2025). Analysis of Von Mises stress on Lumbar 4 to Sacral 1 with variation in body mass index. Jurnal Tribologi 45, pp.174-184.

1.0 INTRODUCTION

Bioengineering is an applied science that combines the principles of biology and engineering and aims to develop devices related to the medical field to obtain revolutionary solutions. In this era, bioengineering science has developed rapidly and produced various health technologies so that it can overcome various complex problems in the medical field. This health technology does not only include the development of implants in humans or medical equipment but also relates to microorganisms such as research related to mechano-bactericidal to control microorganisms (Yaylaci, Özdemir, et al., 2023; Yaylaci, Yaylaci, et al., 2023). By combining knowledge from various aspects in the field of bioengineering, we can now produce more optimal innovations and can improve the quality of life of patients. In this case, it includes research in the areas of bones, teeth, and joints to research related to microorganisms so that it can help the patient's healing process more optimally.

Development of bioengineering solutions for hip, ankle, tooth, and spine problems(Benouis et al., 2024; Nişanci et al., 2020; Zagane, Moulgada, et al., 2023). In the hip problem, various technologies have been developed to overcome multiple problems such as hip prosthesis (Moulgada et al., 2023; Reginald et al., 2023; Zagane, Abdelmadjid, et al., 2023), hip implant (Corda et al., 2023; Göktaş et al., 2022; Terzi et al., 2020), hip arthroplasty (Celik et al., 2022), and hip femoral (Güvercin, Yaylacı, Ölmez, et al., 2022). while on the dental side, it overcomes various problems even such as tooth growth collisions experienced by some people (Kurt et al., 2024). on the other hand, bioengineering plays a role in the modeling of injuries and bone repair such as in the ankle (Güvercin & Yaylaci, 2022), and spine (Eremina et al., 2022; Güvercin, Yaylacı, Dizdar, et al., 2022). One of the common complaints in the spine is low back pain (LBP), which often occurs in the lumbar area and can radiate to the buttocks or legs, affecting about 80% of people. The lumbar spine is between thoracic (T) dan sacrum (S) consists of five vertebrae, this vertebrae characterized by lumbar 1 (L1) to lumbar 5 (L5) and intervertebral discs, this disc consists of 2 parts, namely the outer ring called the annulus pulposus and the inner ring called the nucleus pulposus, with the nucleus pulposus helping to maintain the height of the disc and the annulus fibrosus protecting it. The two main causes of LBP are degenerative disc disease and herniated nucleus pulposus (HNP), which usually occurs at the L4-L5 or L5-S1, due to this area bears most of the body's weight, especially when standing, bending, or lifting objects. HNP occurs when the spinal disc weakens and bulges, causing pressure on the spinal nerves (Mustafa Al-Qaraghli et al. 2023).

LBP or HNP complaints can arise due to several factors, including age, excess weight, poor posture or frequent bending, lifting heavy loads with incorrect positioning, and other factors (Azharuddin, 2014). Disc degeneration often leads to disc herniation. As people age, discs lose water and become more susceptible to tearing, which can cause the nucleus pulposus to bulge out. This usually happens gradually over time. However, sudden heavy pressure can also cause acute disc herniation. Other causes include connective tissue disorders and congenital issues. HNP is quite common, affecting 5 to 20 out of 1000 adults each year (Kılıç 2015; Mustafa Al-Qaraghli et al. 2023). In HNP, changes in the disc include reduced water content in the nucleus pulposus and damage to disc material. This leads to inflammation and pressure on surrounding nerves, causing pain. (Schoenfeld & Weiner, 2011).

Several studies have been conducted to determine the effect of loading on the behavior of intervertebral discs such as; Masni-Azian and Tanaka's study examined the impact of loading on intervertebral discs with 3 variations of the intervertebral disc model but only centered on L4 to L5 not reaching the S1 area (Masni-Azian & Tanaka, 2018). Then in 2021, Shi et al conducted a study with a model that covered up to S1 with a constant vertical load of 500N and used young adult patients under 30 years of age(Shi et al., 2021). Then in the current study, will be carried out with a model up to S1 and using elderly patients. These elderly patients were chosen because at this age disc degeneration often occurs. In addition, we are interested in linking body mass index into our simulation because body mass index has a significant impact on analyzing the loading on the spine(Delgado-López & Castilla-Díez, 2018; Ghezelbash et al., 2017), according to Ammarullah et al., body mass index (BMI) significantly affects the loading on bones, as demonstrated in their study using finite element models (Ammarullah et al., 2022).

This lumbar spine analysis is related to BMI to help estimates the risk of bone health in different populations and support the development of more accurate health guidelines. BMI is related because it is a contributing factor to several diseases that arise in the spine, such as LBP. LBP is common among young and adult populations (Lucha-López et al., 2023; Soiza et al., 2018) ,which occurs when a person experiences HNP. We would like to understand the effect of differences in a person's BMI on the von Mises stress occurring in the intervertebral discs from the L4 to S1 vertebrae. Additionally, we want to know the direction in which a HNP occurs.

2.0 MATERIALS AND METHODS

2.1 Data Collection

The finite element (FE) model of the lumbar spine, covering segments L4 to S1, was derived from a healthy 55-year-old male volunteer weighing 66 kg and standing 168 cm tall. This individual had no history of trauma or fractures, and clinical imaging confirmed the absence of any spinal diseases, ensuring a complete and normal FE model. The volunteer was recruited by the Department of Spine Surgery at Dr. Kariadi Hospital in Semarang, provided informed consent under relevant regulations, and received approval from the Ethics Committee with Ethical Clearance No. 108/EC/KEPK/fk-UNDIP/IV/2022 for this study.

2.2 Finite Element Modelling

Computed tomography images of the lumbar spine from L4 to S1 were processed for boundary detection using Mimics 21.0 (Materialise, Belgium), after which geometric models were constructed. These spinal models were imported into Geomagic Studio 2021 (Geomagic, USA) for refinement, noise reduction, and detailed surface smoothing. SolidWorks 2023 SP 0.1 (Dassault Systèmes, USA) was then utilized to model the intervertebral discs with high precision. The FE mesh and model were generated using ANSYS Workbench (ANSYS, Inc., USA). The material properties of the model, detailed in Table 1, were based on previously published studies (Shi et al., 2021).

Table 1: Material properties.

Component	Element Type	Elastic Modulus (MPa)	Poisson's Ratio
Cortical bone	Isotropic, tetra element	12000	0.3
Cancellous bone	Isotropic, tetra element	100	0.2
Annulus fibrosus	Isotropic, tetra element	4.2	0.45
Nucleus pulposus	Isotropic, tetra element	1	0.5
Endplate	Isotropic, tetra element	2000	0.2

Meshing was performed with ANSYS software using a tetrahedron mesh and full integration normal, with a mesh size of 1 mm on the contact surface of the frame. The study found that the difference in results between simulations with a 1 mm mesh and a 0.5 mm mesh was minimal, around 0.5%.

2.3 Boundary and Loading Condition

The bottom surface of the S1 vertebra was fully constrained, as depicted in Figure 1. Then the model is given a vertical load that corresponds to World Health Organization (WHO) in collaboration with the International Obesity Taskforce (IOTF) classifies BMI specifically for the Asia-Pacific region into five categories (Weisell, 2002). The loading applied was based on the BMI variations: 394.65 N for underweight, 500 N for normal, 615.89 N for at-risk of obesity, 665.93 N for obesity I, and 794.98 N for obesity II.

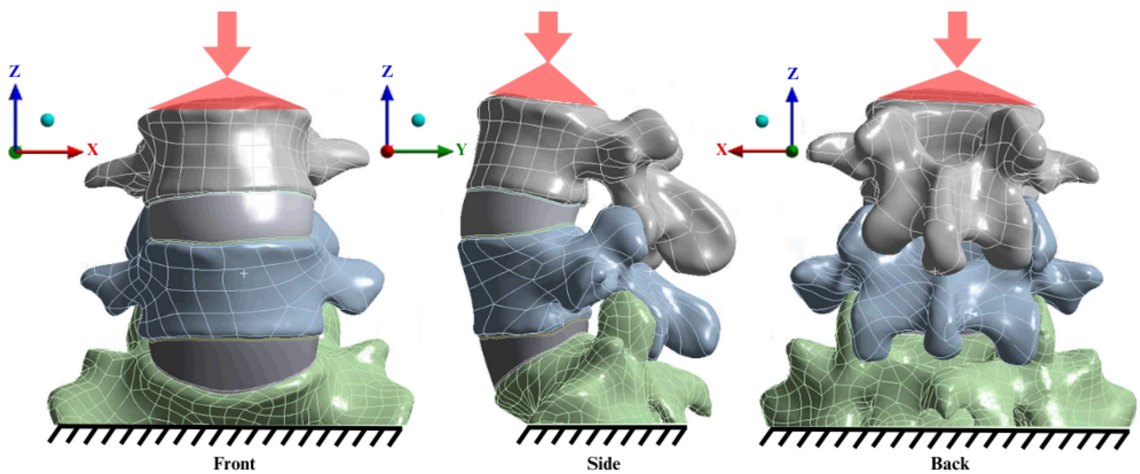

Figure 1: FE model of the lumbar spine including L4 to S1 (the model receives a vertical load on the top surface while the bottom surface is fully constrained).

3.0 RESULTS AND DISCUSSION

The study was validated by comparing the range of motion values from this research with those obtained by Shi et al. (Shi et al., 2021) as shown in Table 2 and Figure 2. The validation refers to the comparison of ROM values from the current study with those from previous research, with the testing results showing an error value of less than 10%.

Table 2: The validation of simulation results.

	ROM (Range of Motion)	
	Present Study	**Previous Study (Shi et al., 2021)**
Flexion-Extension	11.26	12.19 ± 2.61
Lateral Flexion	10.32	11.46 ± 1.53
Lateral Rotation	6.04	5.09 ± 1.22

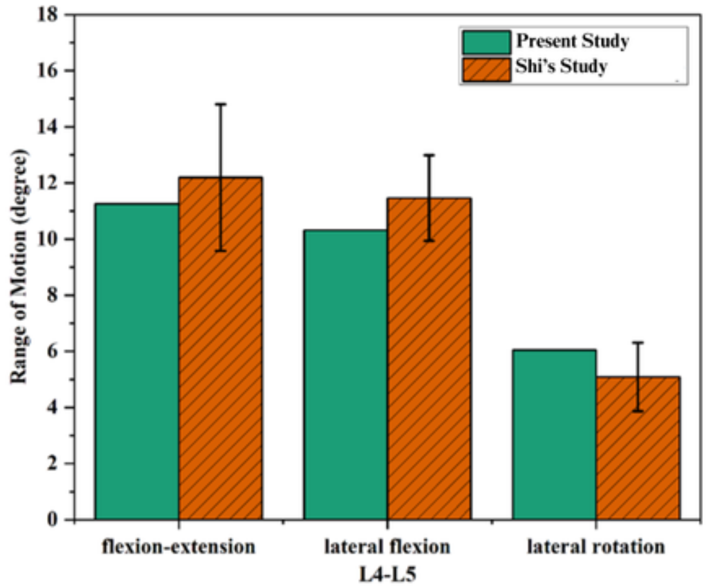

Figure 2: Validation range of motion compared with Shi's study (Shi et al., 2021).

The von Mises stress in spinal studies allows for a more detailed analysis of load distribution, facilitating an understanding of stress distribution in the spine and aiding in the prediction of potential risks. The von Mises analysis has been applied in numerous bioengineering studies, including research on the spine (Eremina et al., 2022; Shi et al., 2021). The von Mises stress occurring in the intervertebral disc area shows a significant increase in each BMI category and occurs in each segment of both L4-L5 and L5-S1 vertebrae, with an average of 16.13% for the L4-L5 segment and 15.65% for the L5-S1 segment in the annulus fibrosus. Additionally, increases are also observed in the nucleus pulposus, averaging 15.19% for the L4-L5 segment and 16.05% for the L5-S1 segment. For a clearer understanding of how BMI affects the condition of the lumbosacral spine, refer to Figure 3.

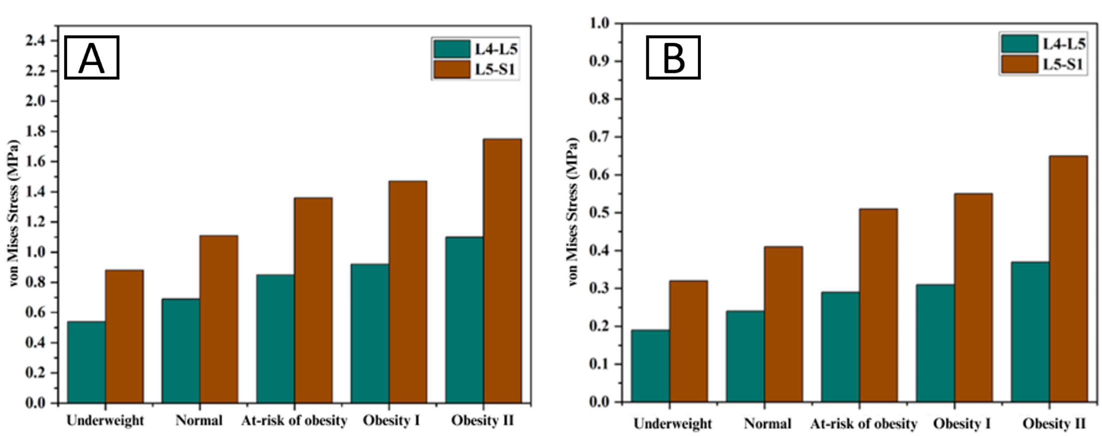

Figure 3: Von Mises stress of (A) annulus fibrosus, (B) nucleus pulposus in each BMI category.

Based on Figure 3, it is evident that the von Mises stress in the intervertebral disc area experiences a significant increase, especially in the L5-S1 segment. Furthermore, in Figure 4 and Figure 5, the distribution of von Mises stress is depicted for each BMI category. It can be observed that as the von Mises stress value increases, the distribution of von Mises stress becomes more pronounced and extends forward from the lumbosacral spine with increasing BMI. The sequence of von Mises stress distribution from smallest to largest is underweight, normal, at-risk of obesity, obesity I, and obesity II.

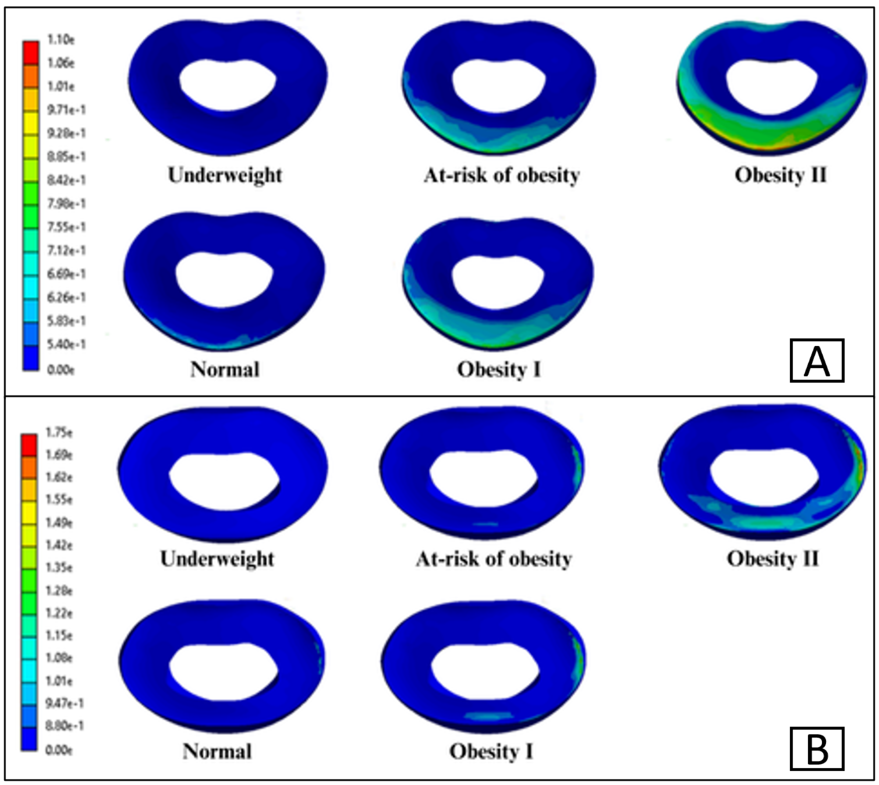

Figure 4: Distribution of von Mises stress in (A) annulus fibrosus L4-L5, (B) annulus fibrosus L5-S1 in each BMI category.

Based on the results above, it can be seen that individuals in the obesity categories I-II BMI are at higher risk of experiencing future health complaints. This is supported by several articles (Lucha-López et al., 2023; Maharty, 2012; Soiza et al., 2018) which mention that individuals with higher BMI have a significantly greater chance of experiencing failures.

Based on Figures 4 and 5, the highest distribution of von Mises stress consistently moves forward towards the intervertebral disc. This can potentially lead to a condition known as HNP caused by high stress in the anterior area of the spine (Azharuddin, 2014). This condition can affect anyone under any conditions, depending on their habits, but it can worsen significantly when someone has a high BMI, particularly in the obesity categories (classes I-II) (Lucha-López et al., 2023; Maharty, 2012; Soiza et al., 2018). The ideal weight to prevent HNP falls within the 'Normal' BMI category, as a lower body weight (without malnutrition) helps maintain spinal pressure at a safe level, thus slowing down disc degeneration and reducing the risk of HNP. There are several ways to prevent this condition, such as maintaining a healthy diet to reduce body weight and lower BMI, engaging in regular exercise, improving body posture during activities, and reducing heavy lifting in daily activities (Kılıç, 2015). Additionally, prevention efforts can include raising awareness about LBP and HNP among the public to promote spinal health awareness. For the treatment of HNP, consulting with a doctor for physiotherapy sessions is recommended (Delauche-Cavallier et al., 1992; Kanayama et al., 2005; Seo et al., 2023; Taylor Paziuk et al., 2019).

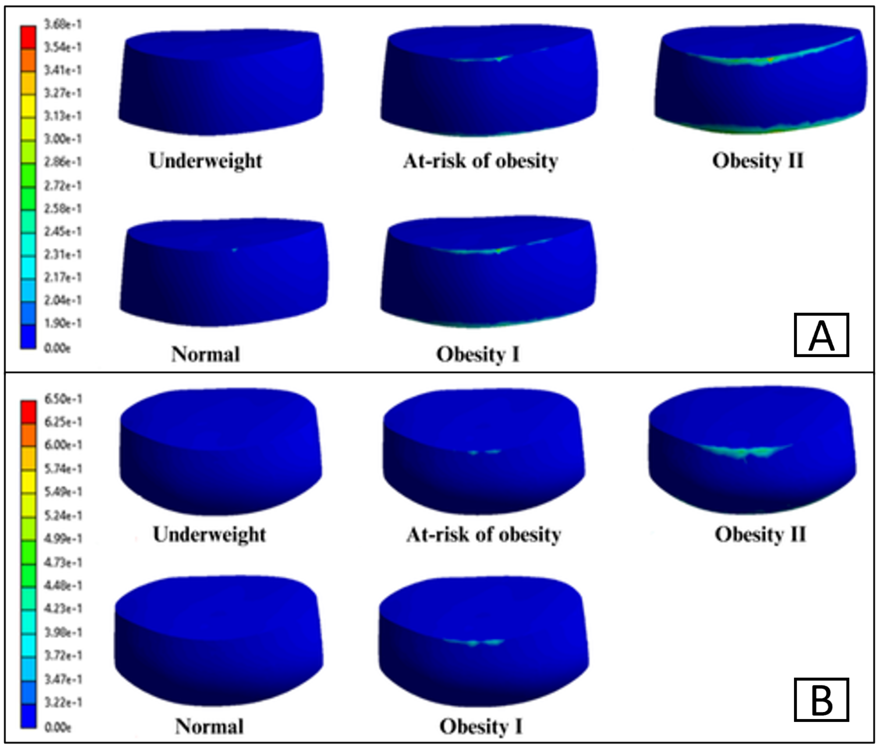

Figure 5: Distribution of von Mises stress in (A) annulus fibrosus L4-L5, (B) annulus fibrosus L5-S1 in each BMI category.

This study has several limitations that may affect the obtained results, and it's important to clarify the integrity of the research conducted. First, the present study only presents computational simulation data that require validation. Additionally, the current model for the nucleus pulposus uses solid material, caused the increase in heterochromatinization in elderly individuals, which is a thickening of chromatin structure that becomes denser(McMorran & Gregory, 2021; Soto-Palma et al., 2022). Lastly, the model does not include all components of the spine such as ligaments and muscles. These shortcomings in our research will be addressed in future studies.

CONCLUSIONS

This study found that the von Mises stress values increase and the distribution of von Mises stress widens with increasing BMI. High stress in the front side of the spine can force the nucleus pulposus to back side, then through the layers of the annulus fibrosis. The 'Normal' BMI category is the ideal weight to prevent HNP. This is because a lower body weight (without starvation) helps maintain spinal pressure at a healthy level, which slows down disc degeneration and lowers the risk of HNP. This research is expected to serve as a reference in the healthcare field to assist healthcare professionals in providing appropriate treatment and to guide the development of implants around the lumbosacral area, taking into account BMI considerations. In this study, the elderly patient had good bone health, which would have been different if the patient had suffered from scoliosis and had an altered bone structure, presenting a challenge for our future research.

ACKNOWLEDGEMENTS

This study was granted by Diponegoro University in the scheme of RPIBT No. 609-122/UN7.D2/PP/VIII/2023-2024. The authors express their gratitude to all laboratory partners at the Biomechanics Research and Engineering Center (UBM-ERC) of Diponegoro University for their encouragement and valuable discussions regarding this research.

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