Evolution in Electrical and Electronic Engineering Vol. 1 No. 1 (2020) 247 - 252
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Homepage: http://penerbit.uthm.edu.my/proceeding/index.php/eeee
e-ISSN : 2756-8458

Biomechanical Analysis of Posterior Lumbar Interbody Fusion Cages with Various Infill Pattern Designs

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DOI: https://doi.org/10.30880/eeee.2020.01.01.029
Received 31 July 2020; Accepted 06 September 2020; Available online 30 October 2020

Abstract: Degenerative disc disease (DDD) is a spinal condition when intervertebral disc that can help to protect the nerves and increase the flexibility of the spine begin to collapse. One of the treatment techniques is Posterior Lumbar Interbody Fusion (PLIF) surgery. However, many unresolvable clinical implications such as cage deformation, mechanical cage failure and stress shielding effects. This project aim to develop various infill pattern of interbody cage design to suit bones' compatibility's order to reduce the consequences of PLIF technique by using Finite Element Analysis (FEA). Material used was Polylactic Acid (PLA) and Solidworks software was used to design the interbody cages. The designed interbody cage was implanted between first lumbar (L1) and second lumbar (L2) vertebra which was extracted from CT scan images in 3D Slicer software. The implanted model was analysed in Ansys Workbench Software to determine the structural strength of the designed interbody. The implanted model analysed in terms of Von Mises Stress and Maximum Principal Stress values on the conditions of the motions such as flexion, extension, axial rotation, lateral bending and compression force. From the results, the interbody cage of honeycomb infill pattern is the most reliable biomechanical construct by showing the minimal value of Von Mises Stress and Maximum Principal Stress. In conclusion, the interbody cage with honeycomb infil pattern exhibited higher dimensional accuracy and higher compressive properties than rectilinear infill pattern structures.

Keywords: Degenerative Disc Diseases, Finite Element Analysis, Von Mises Stress

1. Introduction

The anatomy of humans comprises the cervical spine, thoracic spine, lumbar spine and sacral bones. The whole spine was called vertebrae, which was made up of 24 bones. The central joint between two vertebrae is called an intervertebral disc, these two sections of the disc function together to enable movement of the spine and to provide shock absorption [1]. Lumbar osteoarthritis, disc degeneration, degenerative disc disease, and spondylosis are terms used to describe functional changes in the vertebral bodies and intervertebral disc spaces that may be associated with chronic pain syndromes [2].

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Degenerative changes in the intervertebral disc, facet joint degeneration and deep soft tissues around the spine cause low back pain [3]. Age, body weight, body height, body mass index (BMI), knee prevalence and low back pain, smoking and osteoporosis are potential risk factors for the progression of narrowing disc height which included severity of narrowing disc height at all lumbar disc levels [4].

Cage subsidence and cage failure are irresolvable clinical consequences related to posterior lumbar interbody fusion (PLIF) procedures. According to the American Society for Testing and Materials (ASTM) standard, the mechanical properties of a printed component from Polylactic Acid (PLA) such as tensile strength and flexural strength were determined [5]. In current techniques, it could not achieve cage individualisation to customise the host bone's mechanical properties and demand high production costs. Moreover, the model used in the current practice posed several weaknesses which did not take into account the geometrical perspective [6]. To solve this problem, the design of the interbody cage will be emphasized by the cage's geometric structure and this individualization can be accomplished by the introduction of three-dimensional (3D) printing technology, where manufacturing costs and material printing can be reduced, and the process can speed up [7].

This project propose to develop 3D vertebral model from CT scan images. Then, interbody cage with two different types of infill patterns namely as honeycomb pattern and rectilinear pattern using Polylactic Acid (PLA) material will be designed and analyzed.

2. Materials and Methods

Figure 1 illustrates the whole process used to develop the findings of this project that involves the process of developing interbody cages using rectilinear and honeycomb infill pattern as well as its corresponding Finite Element Analysis (FEA) approach for analysis purposes. Basically there were four stages to be accomplished in order to achieve the objectives of the study [5]. It consists of CT data acquisition, 3D model development of interbody cages, Finite Element Analysis (FEA) of the constructed cages and conclusion. Firstly, the lumbar L1 and L2 were extracted from CT scan image using 3D Slicer Software. After the lumbar model has been generated by the 3D Slicer software, then interbody cage were developed using the Solidworks software.

Interbody cages were designed based on two different types of infill patterns which are rectilinear pattern and honeycomb pattern. Next, the interbody cage were implanted and attached in between L1 and L2. In fourth step, the cage models are analyzed using software. The analysis is consider on basic physiological motions of L1 and L2 which are compression, flexion, extension, axial rotation and lateral bending. Lastly, from the data obtained by the Ansys Workbench software, conclusion were made on which infill pattern design of interbody cage was more suitable to be implanted in the lumbar vertebrae, without jeopardizing the structural integrity of the lumbar segment.

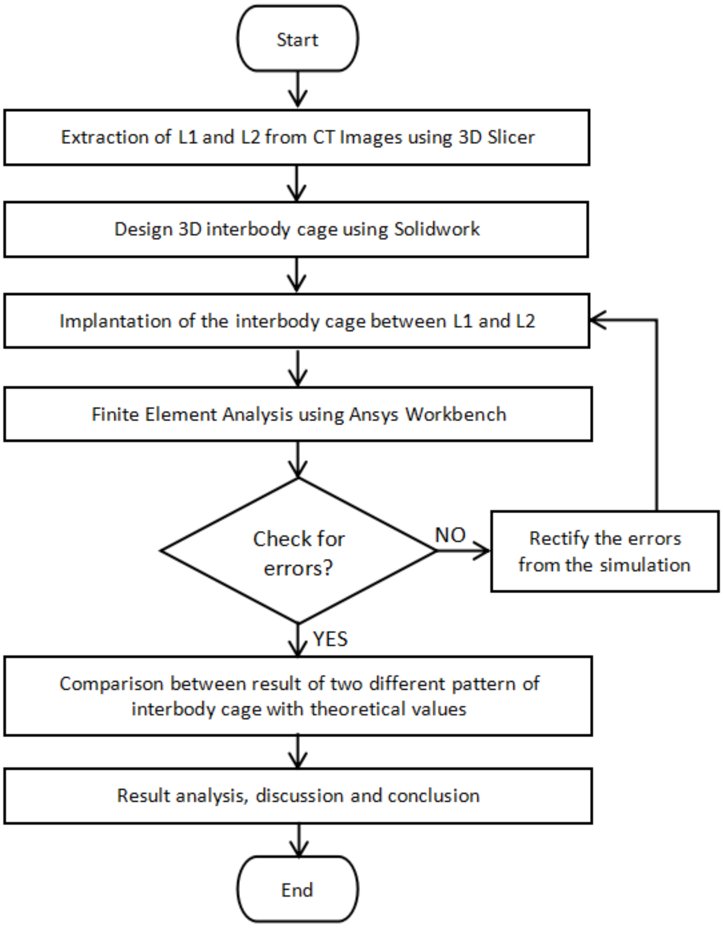

Figure 1: Flowchart of the project

3. Results and Discussion

3.1 Results

The whole strength of the developed interbody cage was evaluated based on Von Mises stress and Maximum Principal Stress. These values are essentially reflected in the Yield strength and Ultimate Tensile strength of the cages. Von Mises stress was used to compare with the material yield strength. Von Mises Stress can be used as an index in biomechanical research to measure the impact of loading on the tissue. Thus, the higher the stress value of Von Mises Stress as compared to the Yield Strength of the materials, the higher the risk of failures the structure. Table 1 shows the results of the Von Mises Stress of honeycomb infill pattern and rectilinear infill pattern cage design during compression, flexion, extension, axial rotation and lateral bending motions. The value of Von Mises Stress for rectilinear infill pattern is higher than the yield strength of Polylactic Acid (PLA).

Table 1: The results of the von mises stress

Physiological motions of L1 and L2 vertebra	Yield Strength of Polylactic Acid (MPa)	Von Mises Stress values (MPa) of honeycomb infill pattern	Von Mises Stress values (MPa) of rectilinear infill pattern
Compression	70	18.46	182.98
Flexion	70	28.18	594.04
Extension	70	8.57	87.62
Axial Rotation	70	31.65	355.07
Lateral Bending	70	20.18	360.24

Theoretically, the failure of any material occurs when the Principal Stress of the material was exceeded the Ultimate Tensile Strength of the material when the load is applied. According to the Table 2 it can be observed that all the values of Maximum Principal Stress that applied on honeycomb and rectilinear infill pattern with physiological movements L1 and L2. The Maximum Principal Stress of rectilinear infill pattern are higher than the actual Yield Strength of Polylactic Acid (PLA).

Table 2: The results of the maximum principal stress

Physiological motions of L1 and L2 vertebra	Yield Strength of Polylactic Acid (MPa)	Maximum Principal Stress values (MPa) of honeycomb infill pattern	Maximum Principal Stress values (MPa) of rectilinear infill pattern
Compression	73	25.26	41.97
Flexion	73	32.07	196.12
Extension	73	8.11	30.04
Axial Rotation	73	37.11	283.39
Lateral Bending	73	21.81	148.21

3.2 Discussions

Honeycomb infill pattern with hexagonal cells has the best standard structure between cellular materials, and successfully developed a number of technologies and materials. The main characteristic of honeycomb structures is high mechanical strength. Besides, honeycomb structures have been shown to allow load transfer between layers, thus providing greater mechanical strength, failure reliability and fatigue resistance [6]. In addition, the honeycomb function also includes bending resistance, energy absorption, and shock resistance in other mechanical properties. The structures of the honeycomb show improved mechanical properties, including shear strength, resistance to indentation and stiffness of fractures [8].

Figure 2 shows the bar chart graph, which summarizes the values of Von Mises Stress for two types of interbody cages infill pattern, namely as honeycomb and rectilinear infill pattern used in this project. The results of the study show that honeycomb infill pattern implanted cage spine model gained the lowest Von Mises Stress values compared to the rectilinear infill pattern interbody cage. This indicated that the honeycomb infill pattern structures typically outperform than rectilinear structures in terms of stiffness and compressive strength or shear [6].

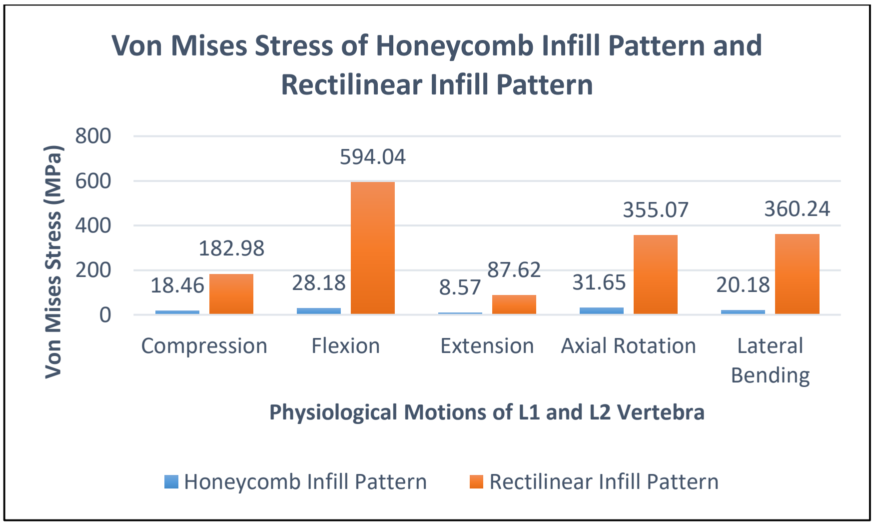

Figure 2: Bar chart of von mises satress versus physiological motions of L1 and L2 vertebra for two types of infill pattern

Figure 3 indicate the Maximum Principal Stress of honeycomb infill pattern and rectilinear infill pattern design cage, which generated specifically during compression, flexion, extension, axial rotation and lateral bending motions. It may be observed that the Maximum Principal Stresses for the rectilinear infill pattern cage tend to produce higher stress when compared with the honeycomb infill pattern cage. More significantly, some of the stresses exceeded the cage material's Ultimate Tensile Stress. This condition could increase the risk of cage failures considerably. This condition can be observed when the cage has been exposed to the motion of flexion, extension, lateral bending, and axial rotation. The honeycomb infill pattern cage displays better structural integrity that can withstand the stress generated on the cage without posing any risk of cage failure when compared with the rectilinear infill pattern cage [8].

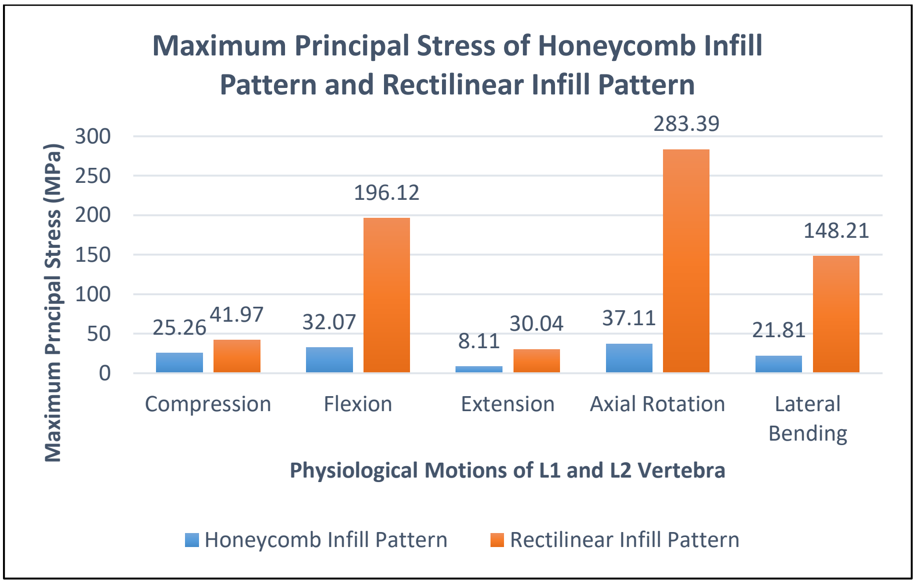

Figure 3: Bar chart of maximum principal stress versus physiological motions of L1 and L2 vertebra for two types of infill pattern

4. Conclusion

In conclusion, this research has successfully achieved all its objectives. Result analysis obtained has found that the interbody cage honeycomb infill pattern is more reliable than interbody cage rectilinear infill pattern. This is due to the value of Von mises stress, and maximum principal stress on the interbody cage honeycomb infill pattern is lower than the value of yield strength and ultimate tensile strength of polylactic acid. The value of von mises stress, and maximum principal stress for interbody cage rectilinear pattern is very high from the value of yield strength and ultimate tensile strength of polylactic acid material. This has caused the rectilinear interbody infill pattern cage to deform and rupture. Some recommendations that can be taken into consideration for future works are; (i) using the full version of Ansys Workbench software to produce more accurate results, (ii) making 3 dimensional (3D) printing using the Polylactic Acid (PLA) material to advance the research into a higher level, (iii) design various infill patterns and (iv) investigate the filling pattern by involving honeycomb infill pattern density.

Acknowledgement

The author would like to thank the Faculty of Electrical and Electronic Engineering, Universiti Tun Hussein Onn Malaysia (UTHM) for its support.

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