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Biomechanical Analysis of Spinal Fusion Cage for Lumbar Vertebrae

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Abstract: ***Lumbar spinal fusion or lumbar interbody fusion is a surgical procedure done by putting the cages implant between the lumbar vertebra supported by rods and screws to hold the vertebra. This procedure is commonly used to treat disc degeneration diseases and other medical conditions. However, failure of the subcutaneous vertebral endplate has been identified to increase the possibility of biomechanical instability. There are broad range of designs and material types of the spinal implant cages that can be used in spinal fusion. Posterior lumbar interbody fusion (PLIF) cage is used to preserve stability and stimulate fusion between vertebrae. There are four different types of biomaterials that can be used to produce the cage namely as metal, ceramic, polymer and composite. The objective of this project is to examine the interbody fusion effects of a several type of cage's materials. A 3D finite element model of third (L3) and fourth lumbar (L4) vertebrae with interbody fusion made up of different types of cage's materials namely as Polyether ether ketone (PEEK), poly lactic acid (PLA), Cobalt Chromium, Titanium Alloy and Stainless Steel were developed and analysed. A fusion model developed based on the respective surgical protocols. The resulting stress and displacement within the cage at the vertebra were measured under different types of compressive loadings and motions. The results indicated an important effects of the material properties on flexibility in extension, axial rotation and lateral bending. Titanium Alloy have been identified as a good material for the metal categories, while for the composite categories PLA (Polylactic acid) has also been simulated as the best alternative material with cheaper material and lower production costs.***

Keywords ***: Spinal Fusion, PLIF, Posterior Instrument (PI), PLA.***

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I. INTRODUCTION

A rapid rate of living and a heavy workload in modern society, leads to some clinical problems. The back pain of the body is the most frequent disease that affects people at some point in their lives. Back pain often arises from injury, spinal instability or spinal deformity that causes minor cartilage damage in the spine, called Intervertebral Disc. Intervertebral

discs can withstand body loads as in the case of lying or standing upright, where the disk holds close to 450-600N. However, aging affects its function when it comes to daily activities or worse when lifting something heavy. The disk becomes drier then the possibility of losing flexibility in your back will be high. This can have an impact on the neural structure that will cause pain, numbness and weakness. In addition, changes may occur in the vertebrae and mechanical properties of the disc. Unfortunately, for chronic lower back pain patients, physiotherapy treatment is inadequate; therefore, surgery is inevitable to replace damaged discs with certain implant disks that can help spinal patients.

The spine is a structure that withstands loads that are applied with the help of ligaments, tendons, muscles, bones and intervertebral discs that work in various movements while protecting the root of the spinal cord. The vertebrae structure contains two bilateral facet joints in the posterior part and is separated in each bone segment by the cartilaginous intervertebral disc. Factors such as trauma, tumors, infections, degenerative disorders can contribute to spinal instability and can affect bones, discs, joints, or ligaments. Two of the most common clinical problems are degeneration and herniation. Degenerative changes can affect vertebrae and intervertebral discs. Intervertebral discs work as shock absorbers to the spine. As the disk deteriorates, the ability to handle the pressure also changes. In addition, the fibers of the peripheral collagen disc are emphasized to cause the disc herniation of the material out and compress the root of the nerve or spinal cord.

Spinal fusion surgery is a proven surgical procedure to correct defects and achieve nerve root decompression through the recovery of disk space discs with interbody cages implantation [1]. The procedure of this surgery is by using the interbody fusion technique which the cages implant will be inserted between the vertebra bones to fill the disk space with supported by rods and screws to hold the vertebra bones.

There are many types of cage implant designs and are available in the market for use by the United States Food and Drug Administration (FDA) [2].

II. BACKGROUND

Different type of cages implant design can be determined by their shape and geometry itself and presents different effects on the spinal fusion (Fig. 1). The cages implant designs come with risks and complications if used without knowing the effects. Examples of issues that can arise are cage migration, cage subsidence, injury to spine and nerve and infection [3]. So, the type of cages used must be suitable with the condition.

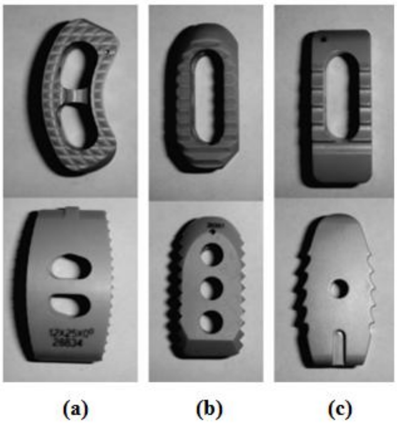

Fig. 1: Three type of cages (a) banana shape (b) flat and straight shape (c) Biconvex and straight shape [2]

All lumbar spinal fusion surgery adds a bone graft to set up biological response between the two vertebral elements thereby stabilizing that segment via cage instrumentation [4]. There are many type of spinal fusion surgery options. The most commonly utilized methods are posterior lumbar vertebral interbody fusion (PLIF), anterior lumbar interbody fusion (ALIF), Transforaminal lumbar interbody fusion (TLIF) and extreme lateral interbody fusion (XLIF) (Fig. 2).

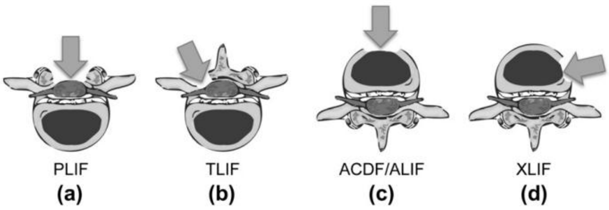

Fig. 2: Type of spinal surgery option [4]

Interbody implants or cages, are developed for a rigid axial mechanical support to improve the initial stability [5]. The cages are designed to restore normal disc height, improve construct stiffness and thus reduce posterior instrumentation failure. Cages also have several type of material which is silicon nitride (Si_3N_4), PEEK, Titanium and trabecular metal. Various material, including titanium, silicon nitride (Si_3N_4), femoral cortical allograft and polyetheretherketone (PEEK) have been used to fabricating cages [6]. PEEK based cages is the most reliable material or tool of interbody fusion surgery due to Young's modulus of 3.6 GPa [7]. Different cages have been used in interbody fusion procedures to simplify surgical implantation and improve biomechanical performance. There are many different type of cage designs in inter-body fusion [6].

Many materials have been used in literature for spinal therapy as it has been analysed. For this case study, the next biomaterials selected are Stainless Steel, Titanium Alloys (Ti), Cobalt-Cromium Alloys (Co-Cr), Polylactic Acid (PLA) and Polyetherether ketone (PEEK). The biomechanical characterization and biocompatibility, was previously examined by Guibert et al. [8] and Marti [9]. In addition, CoCr rods demonstrated significantly larger fatigue lifespan compared to Ti rods during cyclic loading testing [10].

III. MATERIALS AND METHODS

Computed tomography (CT) images of intact lumbar spine with interval of 0.7 mm were obtained from a 29-year-old man. A total of 663 computed tomography images were imported into Mimics Software. In Mimics, the 3D geometry structure was constructed, which consists of vertebrae, intervertebral disc, and cartilage end plate. The geometric structure was meshed using CATIA. Finally, the mesh model was imported into CATIA to perform FE analysis. The CT scan data of vertebra bone of the patient is transferred into a 3D model. The CT scan data of lumbar vertebra cutting process is performed by MIMICS and 3-Matic software. The part of lumbar vertebra that needs to develop is L3 and L4. So, the vertebrae need to be sliced by each CT scan data to ensure it is not connected to pelvis and the upper part of lumbar vertebra bones. The other part of vertebra bones and pelvis will be deleted by slices of CT scan data. After all the parts that are connected to L3 and L4 lumbar vertebra bone have been deleted by edit 3D mask of the model, the part left will be import to 3-MATIC software to edit the surfaces and shells of the model (Fig. 3). Finally, it will be imported back to MIMICS software to get the model of L3 and L4 vertebra bones completely edited and export it to igs written files.

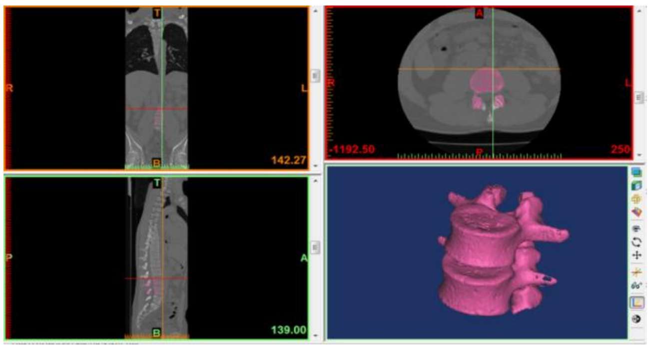

Fig. 3: The pink region of L3-L4 vertebrae

The spinal implant will be placed at the L3 and L4 lumbar vertebra to complete the spinal fusion model which will be imported to CATIA software to perform analysis steps. The screws will be implanted bilateral at each lumbar vertebra bone and the rods will be placed at each two screws to connect it together. The cages implant will be inserted between lumbar vertebrae with same spot.

CATIA is a modelling tool used for both 2D and 3D modelling. In our case study, a spinal model was developed from 3D scan data of healthy spine of male subject. However, this model contains the whole spine, the spine model was hollow and each intervertebral disc was model as one hollow part. The modelling and graphic tools use these kinds of algorithms to represent lines and surface. Therefore, modifications of the model were necessary. Having modelled these parts, the surfaces of the vertebral bodies and the disc were joined and transformed into solid parts (Fig. 4).

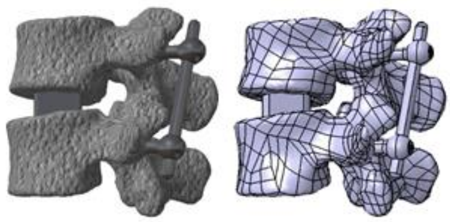

Fig. 4: Reconstructed model of spinal fusion on lumbar vertebra (a) shading with material and (b) shading edge

The simulations of our model carried out in CATIA V5. This methodology divides a continuous structure into finite regions in one, two or three-dimensional spaces and are called elements. These elements are connected by points, referred as nodes and the resulting geometry is called mesh. The simulation of the FEM also requires the boundary and the loading conditions, i.e. the displacement/ rotation and/ or the forces/ moments. The spinal fusion on lumbar vertebra model of L3 and L4 will be imported to CATIA software to perform the analysis on it with the applying distributed loading of compressive force at the top of the lumbar vertebra bones. The loading of compressive force will be applied with 2 different value which are 1000N and 2000N for each material properties of cages implant. The result of FE analysis for each cages implant on spinal fusion will be compared each other to get the different effect on using different material properties of cages implant.

The mechanical properties of the bone model were assigned as Young's modulus (12,000MPa) and Poisson's ratio (0.3) for Cortical Bone and for Cancellous Bone, the value of Young's modulus (350MPa) and Poisson's ratio (0.25) were obtained for the heterogeneous bone model and biomaterial of cage implant as shown in Table 1.

Table 1: Material properties specified in the finite element models

Material	Young's Modulus (MPa)	Poisson ratio	Yield's Strength (MPa)
Poly lactic acid (PLA)	3.620 x 10^3	0.39	130
polyetheretherketone (PEEK)	1.459 x 10^3	0.4	231.2
Titanium Alloy (Ti-6Al-4V)	105x10^5	0.34	795
Stainless Steel	210 x 10^5	0.29	190
Cobalt Chromium (CoCr)	200x10^5	0.3	450

The spinal fusion on lumbar vertebra model of L3 and L4 will be imported to the CATIA software to perform the analysis on it with the applying distributed loading of compressive force at the top of the lumbar vertebra bone. Loading and boundary condition were applied in this study to represent the load during normal physiological activities of the spine. The FE models were loaded with two compressive loads of 1000N and 2000N, and four rotational loads, namely as flexion, extension, lateral bending and axial rotation. The result of Finite Element analysis for each material properties of cages implant on spinal fusion will be compared with each other to get the different effects on using different types of material properties cages implant. Observation on the predicted maximum von Mises stress distribution in the cage bodies was done to understand the effect of different materials and loading activities on the cage itself [11].

IV. RESULTS AND DISCUSSION

A. Effects of Different Material of Cage in Lumbar Vertebrae at Compressive Load

The element models of spinal implant on lumbar vertebra was developed and analyzed using several commercial biomedical and design software. A well-presented FEM of the intervertebral and adjacent vertebra bodies (L3-L4) was structured and simulated under two values of compressive load, axial rotation, flexion, extension and lateral bending for five different types of material properties; mainly metal and composite.

The result of FE analysis using CATIA software was compared to get the effects of using different types of cage's materials on spinal fusion. The first analysis was conducted to see the effect of different cage's material in lumbar vertebrae at two different values of compressive load, and for the second analysis is to see the effect of different types of cage's material under four different vertebral physiological motions. All the effects are discussed based on the von Mises stress and the displacement of the vertebrae bodies.

The von Mises stress of the different material properties of the cage under the two different values of compressive loads (1000N and 2000N) were shown in Fig. 5. In most of the cases, the maximal von Mises stress were detected and concentrated on the interface between the cage and endplate of L3 and L4.

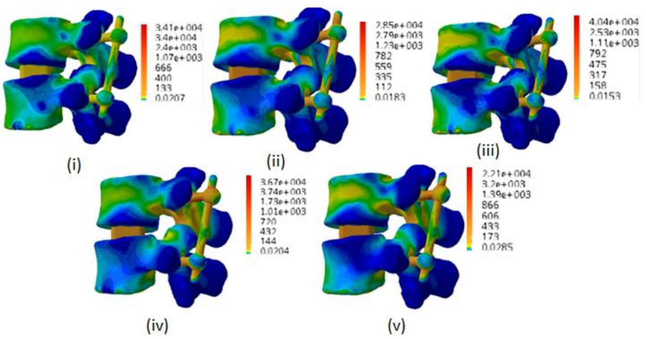

Fig. 5: Von Mises Stress distributions (Nm^2) under two different compressive loads for i) Titanium Alloy, ii) Cobalt Chromium, iii) Stainless Steel, iv) PEEK and v) PLA

Fig. 6 shows the translational displacement in mm of the model for the load case of 1000N. It shows that the relation between spinal fusion with posterior instrument (PI) and L3-L4 vertebrae are not much affected on the displacement. The cage and vertebrae are very stable in the position.

The results indicated that PLA cage construct showed the most affected on the displacement when the material applied on L3-L4 vertebral level. However, these material is cheaper and possess high quality of biomaterial implant. Cage from this category must be implanted with PI to provide more stability. Usually, PI accessories such as pedicle screws and rodes are made from metal categories such as Titanium Alloy.

Spinal interbody fusion is a sophisticated method of surgery for treatment of intervertebral disc degeneration.

The inserted cage acts as an artificial load bearing element between the two adjacent vertebrae and supports the bony fusion of the spinal segment. From this simulation study, it showed that appropriate cage's material selection is very important in order to get better stability and induce less stress at the bone when doing physiology activity such as walking, climbing or walking.

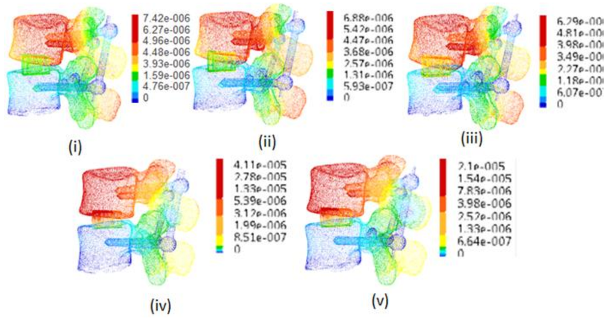

Fig. 6: Translational displacement (mm) for i) Titanium Alloy, ii) Cobalt Chromium, iii) Stainless Steel, iv) PEEK and v) PLA

B. Effects of different vertebral physiological loading in lumbar vertebrae

Fig. 7 shows the maximal von Mises stress generated at the cage-endplate interface under the compressive load of 1000N and 2000N. The highest stress generated was detected at stainless steel cage. This material posse the highest Young's Modulus (210 x 10^5) and it has the greatest ability to withstand changes in length when under tension or compression. Obviously, stainless steel cage construct is not affected by the compressive load in which the stress generated is transferred immediately on the vertebral bones and subsequently increased the risks of subsidence effects. Thus, Titanium Alloy from metal categories and PLA from composite categories can be considered more flexible material which has a low Young's modulus and changes its shape considerably.

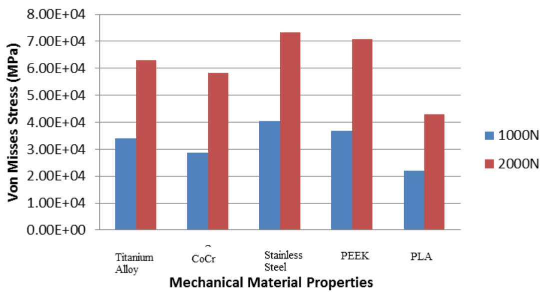

Fig. 7: Maximal Von Misses stress distribution at cage-endplate interface

The maximal von Mises stress is identified on the region with the red colour appreences. The areas such as at the cage-endplate and pedicle screw-bone interface indicte the areas with the highest sress generation. In this study, the result focuses on the bone that is in contact with the cage (Figure 8). The color contour of the vertebrae gives different value of the stress distribution. The blue colour represents the least stress generation and red represents the highest stress generation.

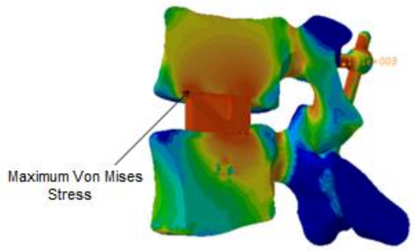

Fig. 8: The region of the maximal von Mises stress were identified

Fig. 9 demonstrates the maximal von Mises stress generated on the vertebral body under the influenced of four different spine physiological motions, namely as axial rotation, flexion, extension, and lateral bending. These results showed a good slip behaviour for all of the cage's materials under the spine physiological motions. The PEEK cage experienced the highest stress during flexion that shows the suitability of the material to be used as cage materials if the strength of the material is considered. However, PEEK cage experienced the lowest stress during lateral bending to make it compliment to the highest stress produced during flexion. Basically, for other spine motions, the stress generated did not show any significant difference for the all types of cage's materials. This condition indicates that all the biomaterials used are compatible to the human bone and anatomy.

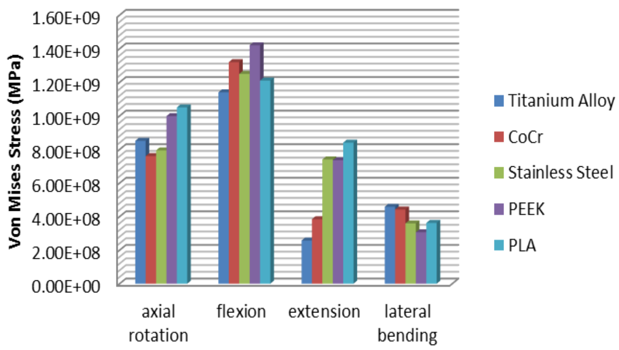

Fig. 9: The maximal von mises stress distribution on the vertebral body under the influenced of five different vertebral physiological motions : (a) axial rotation; (b) flexion, (c) extension, and (d) lateral bending

V. CONCLUSION

The aim of the current research work is to analyse the stress distribution and displacement of five different material properties of cages on spinal fusion of lumbar vertebrae (L3-L4). A well-presented FEM of the intervertebral and adjacent vertebra bodies (L3-L4) was structured and simulated under compression, axial rotation, flexion, extension and lateral bending. The spinal model produced from a healthy subject data using CATIA modelling tool. Therefore, a highly accurate geometry has been developed.

A computational modelling study was conducted to evaluate the effect of material properties for different cage material with PI.

However, the results of this study demonstrated that the posterior lumbar interbody fusion (PLIF) with different categories of implant material is very important in order to improve the biocompatibility of the implant. Stabilization system with low stiffness not only produced desirable stabilization but also allowed near-intact motion. Finite Element study has predicted changes in stress due to flexibility of stabilization systems. Five different materials, mainly metal and polymers, were simulated under the same loading conditions to select the ones that generate almost the same behaviour with the parts with the higher stresses than expected.

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