Bio-Mechanical behaviour of artificial intervertebral disc in lumbar spine

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Abstract. Total Disc replacement has the higher success rate for reducing the lower back pain and increased mobility in intervertebral disc in lumbar spine region. An Artificial disc replacement, the method is designed to bring about pain relief by eliminating the painful disc, then the motion at that spinal section is kept with the use of a prosthetic implant. This creates a need for studies to be conducted to examine these failures. The main aim of this study is to develop and designing an artificial intervertebral lumbar disc based on literature and validates its function using finite element analysis. A finite element model of L4 to L5 section of lumbar spine model was created by using computer tomography scan images of a person. From that a surface model of the L4 to L5 lumbar section model was developed. From that, Different components were added to complete the intact L4-L5 lumbar section model and concerned properties were attributed to each of the component model. This intact spine model was then validated with reported literature. To analyse the range of motion variation and also compared to the validated intact spine analysis results with the reported literature. Thus, a biomechanical behavior study of the lumbar spine was conducted to analyse the range of motion where a semi-constrained artificial lumbar disc is designed and checked for the normal motion by comparing intact model spine and artificial disc implanted spine results using finite element analysis.

1. Introduction

Nowadays a very common problem is chronic back pain is the intervertebral disc (IVD) related degenerative disc disease (DDD). Today 90% of the persons above the age of 60 years are having the disc degenerative problem. For DDD, Many techniques and instruments are developed [1]. The human spine is a biomechanical structure that allows complex motion while providing stability and protection for the spinal cord during a variety of loading conditions. Spine is a very complicated and vulnerable part of our skeleton [2]. The important portion in the human body is spine which supports our whole body and creating all possible range of motions. Lower back pain is caused due to several variations that will occur to the human lumbar vertebrae. Many experimental and theoretical studies have been carried out to better understand the biomechanics of the lumbar spine in order to reduce the risk of disc injury or degeneration. Compared to experimental testing, theoretical models using the Finite Element (FE) method are a relatively inexpensive and fast way to accomplish the mechanical analysis of the human spine. In addition, theoretical simulations allow investigating the behaviour of the lumbar spine.
The lumbar spine consists of two layers of bones named as cancellous and cortical bone. They are structured one on top of the other bone to make a compact structure. Medical treatments for degenerative disc disease (DDD) is to conventional measures include spinal lumbar fusion, discectomy, and total disc replacement. Artificial Disc replacement has the higher success rate to reduce the lower back pain and increased mobility in the artificial disc replacement can be used. There are two methods is there. One is lumbar fusion and another one is disc replacement. Posterior Lumbar inter body fusion is an effective method for treating the degenerative spinal instability. Fusion primarily modifies the biomechanics of human spine, often resulting is to reduce the range of motion in the segments adjacent to the lumbar vertebra fusion. Lumbar fusion surgery is to eliminate the motion in between one vertebral to another vertebral by fusing together to that the spinal inter body fusion cage is lesser, porous, hollow implant, either cylinder-shaped or nearly cuboid in shape. The degenerative disc and the intervertebral disc can be replaced, and thus returning functional of disc height to the vertebra. The behaviour of human spine healthy, diseased and damaged spine has several methods to study and calculate the treatment process. The total disc replacement is the alternative for spinal fusion. The procedure of designing the artificial replacement is to bring the motion in spinal segment of lumbar vertebra and to reduce the stress motion in the artificial disc implant and by removing the painful disc in the lumbar spine vertebra. Spine has many physiological conditions. The prosthetic implant design is to validate and verify with standard technique process. To analyse the bio-mechanical problems of human lumbar spine, finite element method is used. Then, the finite element analysis (FEA) is used to study the behaviour of intact lumbar spine model. The main medical considerations that were measured from the range of motion (ROM) Finite element simulations essentially depends on the choice of mechanical approach and the development of proper finite model. Generally, mechanical FE simulations are aimed to calculate variations of mechanical stress and strain fields while evaluation of strength, fracture risk and others synonymous parameters is performed in secondary part of simulation. The purpose of the study is to determine the three-dimensional psychological movements of the lumbar spine. The finite element models of the lumbar spine is applied for mechanical analysis.

2. Materials and Methods
The human spine model was constructed by using the three dimensional (3D) spine from digitization. The L4 to L5 section of lumbar spine was created by using computer tomography scan images of a person. From that, CT Computer tomography scan image data to create 3D model of the vertebra L4 to L5 using segmentation software. A flowchart of methodology as shown in figure 1.
Figure 1. Flow chart of methodology.

Figure 2. Schematic flowchart model of L4 to L5. a) Segmented model, b) Meshed model without intervertebral disc and, c) Meshed model with intervertebral disc.
Figure 3. Meshed model of L4-L5 with intervertebral disc with ligaments.

Figure 4. Meshed model of L4-L5 Artificial Disc with ligaments.

After the segmentation the model is converted into STL file format. From that, segmented STL file format is imported into GEOMAGIC DESIGNX software to create surface model L4-L5 vertebra. The created surface model is to convert into IGES file format. The created surface model is used for meshing to create the intact spine model L4-L5. The L4-L5 vertebrae is meshed using tetramesh to create the cancellous bone cortical bone, end plate. The natural intervertebral disc in between each vertebra, annulus and nucleus portion of the intervertebral disc were created. After that, ligaments were added in order to create the functional spine unit of the intact spine model of L4-L5 vertebra with natural disc. The ligaments were combined into the model in the form of tension only spring elements, including luanterior-longitudinal ligament (ALL), posterior-longitudinal ligament (PLL), supra-spinal ligament (SL), ligament flavum (LF), intertransverse ligament (ITL), interspinal ligament (ISL) and
The total number of elements and nodes is 1038446 and 260519 respectively. Thirteen components were created and the material properties were assigned for the human lumbar spine intact models shown in table 1.

| Material properties | Young's Modulus (Mpa) | Poisson Ratio | Crosssection Area (mm²) | Element Type |
|---------------------|-----------------------|---------------|-------------------------|--------------|
| Cancellous bone     | 100                   | 0.2           | -                       | Solid 45     |
| Cortical bone       | 12000                 | 0.3           | -                       | Solid 45     |
| Nucleus             | 1                     | 0.499         | -                       | Solid 45     |
| Annulus             | 8.4                   | 0.45          | -                       | Solid 45     |
| Vertebra Endplate   | 24                    | 0.4           | -                       | Solid 45     |
| Anterior longitudinal ligament | 7.8     | -            | 63.7                    | Link180      |
| Posterior longitudinal ligament | 1.0      | -            | 20                      | Link180      |
| Flavum ligament     | 1.5                   | -             | 40                      | Link180      |
| Inter transverse ligament | 10       | -             | 1.8                     | Link180      |
| Capsular ligament   | 7.5                   | -             | 30                      | Link180      |
| Inter spinal ligament | 1.0       | -             | 40                      | Link180      |
| Supra spinal ligament | 3.0       | -             | 30                      | Link180      |

According to previously published experiments, the cross-section area was defined for every ligament to check the reaction in different vertebral loading conditions.

2.1 Loading and Boundary Conditions
The degrees of freedom was completely constrained for all nodes on the lower surface of vertebra. The boundary conditions will be apply a direction of the force in x direction is clockwise extension and anticlockwise flexion, y direction is clockwise right lateral bending, and anticlockwise left lateral bending, z direction is clockwise left axial rotation and anticlockwise right axial rotation. The range of motion were determined for 6 loading conditions, (a) Flexion load of 10000N, (b) Extension load of -10000N, (c) Right lateral bending of 10000N, (d) Left lateral bending of -10000N, (e) Left axial of 10000N and (f) Right axial of -10000N. The following figures represent the various physiological conditions.

3. Results and discussion
The L4-L5 intact model was constrained in the bottom to prevent movement. The model was loaded with the moment of 10 N·m in the sagittal plane to get the axial rotation, in the coronal plane to get the flexion and extension, and in the transverse plane to get the lateral bending. The model was solved and the range of motion of the intact model is shown in figure 5.
The L4-L5 instrumental model was loaded similar to the intact spine model and the range of motion is shown in figure 6. The obtained range of motion of the intact and instrumented spine model was compared against the Yamamoto IS [9] and the same has been plotted and shown in figure 7.

**Figure 5.** Range of motion of the intact spine model with load of 10 N-m.

**Figure 6.** Range of motion of the instrumented spine model with load of 10 N-m.
4. Conclusion
The intact model and artificial disc model in lumbar region were developed as per the from literature. Analysis carried out with load application, yielded results of angular range of motion of the entire model. These values were verified and validated so that they could be further used for analysis with insertion of an artificial disc implant. Upon analysis, artificial disc implant inserted spine was able to achieve closer results in few categories of human motion with an exception of slightly higher angular range of motion for lateral bending. Further optimization and modification of artificial disc design could be carried out in future, to achieve optimum results.

5. References
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