A biomechanical study of cervical disc degeneration in C4-C6 using finite element analysis

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Abstract. The C4-C6 region of the cervical spine is a common area of injury in the spinal column. Most of the injuries are caused due to accidents, sports etc. These injuries with increase in age can lead to slight, moderate and severe disc degeneration. As technology has advanced over the years, biomechanical finite element models are used instead of cadavers to study effects of progressive degeneration on the stress distribution. This study was conducted to develop a three dimensional finite element model of the C4-C6 human cervical spine structure using computed tomography scans and was validated against experimental data published earlier. The model was then used to produce progressive disc degeneration at the C4-C6 region by varying the material properties. Slight degeneration and moderate degeneration is obtained by modifying the material properties of nucleus pulposus and annulus fibrosus respectively. Severe degeneration was achieved by taking the material properties for maximum degeneration. The degenerated models were subjected to flexion, extension and lateral bending and the stress distribution on the anterior and posterior region were determined and compared with the intact model. Based on this study, the anterior region showed more increase in stress as compared to the posterior region with progressive degeneration.

1. Introduction

The cervical spine forms the neck and consists of seven vertebrae C1-C7. It is greatly responsible for movement and stability of the neck. The cervical spine is more prone to movements in terms of flexion,
extension and rotation. As compared to lumbar vertebrae, cervical vertebrae is much smaller. Each of the seven vertebrae has a disc in between them that acts as a cushion and helps in shock absorbing and also prevents vertebrae from brushing against each other. Disc degeneration develops when the cushioning discs between the cervical vertebrae starts to break down due to wear and tear which are caused by accidents or sports related activities [1]. As age increases, the wear and tear does not heal leading to a decrease in disc height. Reduction in disc height leads to bone spurs and pinging of the spinal nerve that causes neck and arm pain. Finite element analysis is used as it is less expensive and not laborious like in-vitro studies. The earlier studies conducted by Kumaresan et al. [2, 3] found that soft tissues has more influence on the responses as compared to hard tissue. The study conducted by Hong-Wan et al. showed that the stiffness of cervical spine depends on its material properties and geometry [4]. The finite element details for developing C4-C6 model were obtained from literature [4]. Hong-Wan et al. found that spinal components have important role in maintaining spinal stability [11]. For this study, C4-C6 region was selected because of its high chance for injury. The study conducted by Kumaresan et al. showed that segmental stiffness at degenerated level increased with severity of degeneration [10]. The flexion plus extension and lateral bending values were validated against values obtained from White and Panjabi [6]. The material properties of different levels of degeneration was obtained from previous published literature [8, 9, and 10]. The present study was conducted to study the stress distribution on the anterior and posterior region of C4-C6 model with progressive degeneration which was achieved by altering the material properties of annulus fibrosus and nucleus pulposus.

2. Materials and Methods

2.1. Materials
This project is carried out with the help of some essential software and patient specific CT scan data in standard Digital Imaging and Communications in medicine (DICOM) format. The software used are MIMICS to create a surface model of the cervical region (C4-C6). Meshing the model was done using HYPERMESH and analysis was done in ANSYS. For this study, the finite element model was obtained from the cervical spine geometry developed from a 35-year-old adult which was free from spinal disease, metastasis and trauma were collected from SRM Institute for Medical Science, Vadapalani.

2.2. Methodology
2.2.1. CT image processing using MIMICS

To process data in Mimics, patient images (CT scans) are first imported. The quality of the 3D images that Mimics can create directly correlates to the slice thickness and pixel size of the 2D images. The MIMICS screen is broken up into four main views; coronal, axial, sagittal, and 3D. Engineers can think of coronal as a front view, axial as a top down view, and sagittal as a right view. The axial view comes from the imported stack of images. To obtain the coronal and sagittal views, MIMICS transposes the axial images into their respective positions. The 3D pane is where 3D models are visualized. The CT scans imported to MIMICS undergoes image segmentation through region growing and thresholding. Then the required region (C4-C6) which was smoothened and cavity filled so that it is compatible for the next step i.e. the meshing procedure. The 3D model developed in MIMICS is saved as .cdb file to be transferred to HYPERMESH software for finite element meshing and insertion of intervertebral disc. Figure 2 shows a 3D model of cervical spine C4-C6 after extraction of surface model.

Figure 1. Overall workflow

Collection of CT scan in standard DICOM format

Import the CT scans to MIMICS 14.0 to extract surface model

Meshing using HYPERMESH software

FE Analysis using ANSYS 18.1 software.

Model Validation

Comparison of stress distribution on slight, moderate and severe degenerated cervical models
2.2.2. Meshing of the C4-C6 model using HYPERMESH
The model has been properly meshed and undergone quality checking like warpage, skew, aspect ratio etc. The intervertebral disc have been modelled using HYPERMESH. The Finite Element Method (FEM) helps in predicting the behaviour of the entire model by combining the information obtained from all elements making up the model. Now the 3D meshed model is ready to be validated with existing literature. Once the model is validated, the model is now ready for the FE analysis in ANSYS.

The C4-C6 model imported to HYPERMESH is firstly 2D meshed and it undergoes mesh quality checking to ensure that there are no edges. Edges present can cause errors and can affect the quality of the mesh. Now it is converted to 3D using tetra mesh and again undergoes quality checking say skewness, aspect ratio etc. Before it is converted to 3D, all the components are saved separately using solid map. The anterior side is meshed using hexamesh and the posterior side of the model is meshed using tetra mesh. The mesh style varies depending upon the complexity of the model. Figure 3 shows the meshed 3D model of C4-C6 after it has undergone mesh quality check. The element type for all the components is Solid 45.

The material properties are assigned for each components with the help of component manager in HYPERMESH where Young’s Modulus and Poisson ratio are specified (refer table 1) [8] [9]. After the assigning the properties, the C4-C6 model is exported to ANSYS using the export command.

| Components          | Element type | Young’s Modulus(MPa) | Poisson Ratio | Reference                              |
|---------------------|--------------|----------------------|---------------|----------------------------------------|
| Cortical shell      | SOLID 45     | 10000                | 0.29          | Hong–Wan Ng et.al(2000)                |
| Cancellous core     | SOLID 45     | 100                  | 0.29          | Hong–Wan Ng et.al(2000)                |
2.2.3. FE Analysis
Model validation and the variation in stress distribution on the anterior and posterior region of the C4-C6 model is carried out in ANSYS as seen in figure 4. The material properties for slight, moderate and severe degeneration are assigned using this software.

| Component     | Element Type | Properties | Reference         |
|---------------|--------------|------------|-------------------|
| Endplate      | SOLID 45     | 500        | Hong–Wan Ng et.al(2000) |
| Disc annulus  | SOLID 45     | 3.4        | Hong–Wan Ng et.al(2000) |
| Disc nucleus  | SOLID 45     | 1          | Hong–Wan Ng et.al(2000) |

Figure 4. C4-C6 viewed in ANSYS

3. Results
3.1. Validation
The present model was validated under lateral bending, flexion and extension load configuration as seen in figure 5. The predicted values are compared with published base papers under the same load configurations. The material properties of the spinal components were taken to be linear, homogeneous and isotropic. The boundary condition was taken such a way that the vertebra C6 of the cervical spine was constrained fully under all degrees of freedom. The load 1.8Nm was applied on the C4 vertebra. The initial and final position were noted and their coordinates were plotted to get two intersecting lines that gave the degree of rotation. The obtained range of motion (ROM) values falls in the range given by White and Panjabi [6] which is shown in figure 6.
Figure 5. Model validation under 1.8Nm moment a) flexion b) extension c) lateral bending

Figure 6. Model validation under 1.8Nm for flexion plus extension and lateral bending.

3.2. Stress distribution under 1.8Nm moment on anterior side and posterior of the slight, moderate and severe degenerated models.

The levels of degeneration was obtained by modifying the material properties of annulus and nucleus pulposus of the cervical disc. The inferior region of the cervical vertebrae (C6) is constrained from all degrees of freedom. The load is applied on the C4 vertebrae. A 1.8Nm moment is applied to slight, moderate and severe degenerated models under three physiologic loading modes i.e. flexion, extension and lateral bending. According to figure 7, the stress distribution on the anterior region is more as compared to posterior region in slight, moderate and severe degenerated models. The anterior part of C6 vertebrae shows maximum stress with increase in degeneration as compared to C4 and C5. Stress due to progressive degeneration is less on the posterior region when compared to anterior region of C4-C6 which can be seen in figure 8.
Figure 7. Stress distribution on anterior side of C4-C6 under 1.8Nm moment of (a) flexion (b) extension (c) lateral bending.
4. Discussion
The present study was conducted to study the stress distribution on the anterior and posterior region of slight, moderate and severe degenerated models. The analysis was carried out in linear, static and steady state in ANSYS 18.1. The model was validated against ROM values published earlier. The flexion plus extension and lateral bending values fell in the range given by White and Panjabi [6]. After validation, the material properties of nucleus pulposus and annulus fibrosus were altered to achieve slight, moderate

Figure 8. Stress distribution on posterior side of C4-C6 under 1.8Nm moment of (a) flexion (b) extension (c) lateral bending.
and severe degeneration. Furthermore, the material properties used as input for representing the various levels of degeneration was obtained from finite element modelling literature [10]. The material property changes was only done to the Young’s modulus of the annulus and nucleus but the Poisson ration was not changed [2]. The flexion, extension and lateral bending load was applied to three degenerated models to study the stress distribution with increase in disc degeneration. The load applied is 1.8Nm force moment on the superior side (C4) and the inferior part of the model (C6) was fixed by constraining all degrees of freedom.

This study showed that the stress distribution in the anterior region of C4-C6 cervical vertebrae under flexion, extension and lateral bending is more than the posterior region with increase in degeneration. The stress distribution on various parts of the disc calculated with different loads can throw some light on the materials to be chosen for the development of disc implants.

5. Conclusion
In summary, a FE model of C4-C6 cervical vertebrae was developed successfully and validated against 1.8 Nm flexion, extension and lateral bending. The validated model was used to study the effects of progressive degeneration on the anterior and posterior side of the C4-C6 model. The increase in von misses stress in the discs was high for severe model as compared to slight and moderate. The C6 vertebrae disc showed more stress in all the cases when compared to C4 and C5. Due to disc degeneration, the anterior region experiences more stress as compared to the posterior region of C4-C6 model. This suggests that progressive degeneration can affect the movement and stability of cervical spine and stress appears to be more distributed to the anterior region as compared to posterior.

6. References
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