Influence of loading in cervical spine motion segment and stress distribution

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Abstract: The aim of this study is to create a three-dimensional model of a cervical spine motion segment and to confirm it by inspecting the model with similar FE method. Initially a model was created by extracting CT scan images and the mesh was generated. FEM models of the lower cervical spine are derived from a CT scan with dissimilar elements and then quality of these models is evaluated with the help of mesh element-related metrics. Different material properties were assigned for each part of the model and then the analysis was carried out. Finite element analysis is used to find the effect of variations in morphology of spine, intervertebral disc height, slope of facet joint, process height of articular facet joint and segment size was parameterized. Ligament forces and vertebral rotation variations was also done as part of the FE study. The individual components of spine are subjected to different types of loading situations and the stresses developed on them need to studied. Some of the most important morphological variations found in the anatomy were disc segmental size & stress developed in the superior and inferior endplates and also the stress developed in the disc were analysed. The results obtained were collated with some external references and after validation of the model; the model could be used for extended similar studies.

1. Introduction

The cervical spine is an important part of the spinal column as it plays a vital role in the functioning of the human body [1]. It consists of seven vertebrae which are connected together by paired facet joints and these vertebral joints help in the movement of the neck [2]. The first two vertebrae, the atlas and the axis are ring like structures and are responsible for the rotation of the skull and the neck [3].

The cervical spine segment is always prone to injuries because of the stresses acting on them on a daily basis. The everyday bending, lifting, turning and twisting causes wear and tear in the discs present between these cervical vertebrae [3]. They are particularly open to injuries because of its functional and structural complexities especially as it relates to multiplanar ROM [4]. DDD is one such medical condition that deteriorates the discs and causes pain. Height variations in the intervertebral disc along with age factors can be the reasons for DDD [5]. In-vivo and In-vitro studies can be conducted to study about the degenerated discs and to understand about their biomechanics [7].

The vertebrae are generally connected by ligaments and discs modelled as springs for dynamic study model [5]. The primary methods for assessing the reliability and precision of an FE model are validation and verification [6]. In-vivo and In-vitro tests have been conducted theoretically and
experimentally to understand the biomechanics of the degenerated cervical spine, but over the years various studies highlight only a specific degree of DDD or combination of one-disc degeneration[8].

Vertebral morphology is distinct and for the input of FE models fixed input is only considered so instead of considering fixed input we can consider morphology as the input[9]. The studies conducted over the years gives an insight of the mechanics of disc degeneration, but not a detailed view about the specific degenerative change related to the mechanical alteration of the spine [10]. So, the progression of the degenerative disc disease is due to the mechanical causes based on overall view of the degenerative condition.

The purpose of this study is to determine the morphological variations influence in loading under lateral bending and axial rotation, the ROM using FEM as the sections of spine are subjected to various loading conditions which may affect the disc height of the intervertebral column.

2. Materials and methods

2.1 Imaging and modelling the C5-C6 spine.
The modelling and analysis of the spine is done by obtaining the CT scan. A solid model was created by importing the CT scan into Mimics Software version 10.0.1 and was later converted into a surface model by segmentation. A CT scanner was used for 419 slices with 1mm slice increment. The fusion of facet joints and separation of individual vertebrae can be carried out by segmentation [11].

2.2 Finite Element Model of C5-C6 spine.
The surface model was exported to Hypermesh 13.0 for meshing. A hexahedral mesh was used to differentiate the anterior side, intervertebral disc and endplates from the rest of the vertebrae [12]. The posterior side was meshed using tetrahedral elements. The mesh size used was 0.5 mm in order to avoid failure of models. The meshed model was tested with various loads of 1Nm, 2Nm,3Nm respectively. The finite element model of C5-C6 cervical spine is shown in figure 1.

The modelling of the soft tissues is done once the modelling of vertebrae of the cervical spine is completed as these are the elements which act like connectors between the vertebrae [13]. The width of the disc is decided upon the gap present between the superior and inferior endplates of the C5-C6 vertebrae [14]. Non-linear spring elements have been allocated for all the ligaments as they do not have any effect during compression. Five main ligaments, Anterior Longitudinal Ligament (ALL), Posterior Longitudinal Ligament (PLL), Ligamentum flavum (FL), Capsular Ligament (CL) and Interspinous Ligament (ISL) have been considered [15] as shown in figure 2. Table.2 show the force and displacement values of ligaments in cervical spine.
Three-dimensional model of C5 and C6 was developed by assembling their sagittal and coronal images sequentially [9]. By approximation of solid model, the FE mesh was acquired. The input material property was varied individually from the base model values for each loading conditions to do the sensitivity analysis[11]. The properties used in FE model are cortical elastic modulus, cancellous core modulus, intervertebral disc modulus, bony posterior elements modulus and end plate modulus[15]. Table 1 includes the material properties used in the FE model.

| Material                  | Young’s modulus (MPa) | Poisson’s ratio |
|---------------------------|-----------------------|-----------------|
| Cortical elastic modulus  | 12000                 | 0.29            |
| Cancellous core modulus   | 125                   | 0.29            |
Annulus disc modulus & 5 & 0.40 \\
Nucleus disc modulus & 5 & 0.49 \\
Bony posterior elements modulus & 2500 & 0.29 \\
Endplate modulus & 500 & 0.40 \\

Table 2. Ligament properties.

| ALL | PLL | LF | ISL | CL |
|-----|-----|----|-----|----|
| F   | dl  | F  | dl  | F  | dl  | F  | dl  | F  | dl  |
| 5.5 | 1.2 | 4.5| 1.2 | 1.5| 1.8 | 1.5| 1.3 | 1.5| 3.6 |
| 10  | 2.5 | 8.5| 2.2 | 3  | 3.5 | 2  | 2.8 | 2.6| 5   |
| 13.5| 3.7 | 11 | 3.2 | 3.5| 5.1 | 4  | 4.1 | 4.3| 7.5 |
| 16.5| 4.8 | 13.5| 4.3| 5  | 6.9 | 5  | 5.5 | 5.2| 9.5 |
| 19.5| 6   | 15 | 5   | 5.5| 8   | 5.5| 7   | 5.4| 9.9 |
| 54.5| 20 | 47 | 20  | 11 | 20  | 9.8| 20  | 10.5| 20 |

2.3 Validation.
The validation of the FE model was done using the ROM of different materials and for various loading conditions. The FEA study for ROM was conducted as shown in figure 3(a),3(b),3(c),3(d). ROM was found largest for F-E followed by LB and AR. The values obtained for the various range of motion were compared with the literature results available [6]. The lateral bending and axial rotation values were obtained by summing up the values obtained for both left and right siderations [12]. Most of the projected values of ROM fell within the range of experimental data [13]. However, under lateral moment loading, the model predicted some inconsistency against experimental data, as shown in figure 4.
Figure 3. (a) FEA study for ROM under flexion, (b) FEA study for ROM under extension, (c) FEA study for ROM under lateral bending and (d) FEA study for ROM under axial rotation.

Figure 4. Model validation under 1Nm moment and comparison of ROM experimental values against the values of literature.

3. Result and discussion
The disc height variation is tested for 3 loads of 1Nm, 2Nm and 3Nm as shown in figure 5 and figure 6. The disc height variation was found to be more during axial rotation rather than lateral bending. The disc height was found to vary between 0.5-1.7mm during lateral bending and between 1.2-3.6mm during axial rotation.
Figure 5. Disc height variation – Lateral bending under different loading conditions.

Figure 6. Disc height variation – Axial rotation under different loading conditions.

Figure 7. Stress distribution in the disc – Lateral bending under different loading conditions.
The stress distributions in the discs were also found out for loads of 1 Nm, 2 Nm and 3 Nm as shown in figure 7 and figure 8. The stress distribution was also more during axial rotation rather than lateral bending and the stress appeared to be concentrated more on the nucleus of the disc. The stress value was found to vary between 1.2-3.5 MPa for lateral bending and between 2-6 MPa for axial rotation. The stress distributions in the superior endplates were also found out for loads of 1 Nm, 2 Nm and 3 Nm as shown in figure 9 and figure 10. Here also the stress distribution was found more during axial rotation. The stress value was found to be varying between 1.5-4.5 MPa during lateral bending and between 2-5.5 MPa during axial rotation.
Figure 10. Stress distribution in the superior endplate – Axial rotation under different loading conditions.

Figure 11. Stress distribution in the inferior endplate – Lateral bending under different loading condition.

Figure 12. Stress distribution in the inferior endplate – Axial rotation under different loading conditions.
Almost the same results were obtained for the stress distribution on the inferior endplates during lateral bending and axial rotation as shown in figure 11 and figure 12.

4. Conclusion
In conclusion, this study presents a subject-specific FEM model for analysis of cervical spine for the degenerative disc disease. The disc height and stress distribution in the disc during axial rotation and lateral bending were found to have influence on the spine biomechanics especially in the cervical spine segments. The experimental data and results from existing study was compared and validated with the stress converged models of present study based on ROM. After the analysis of the result, it was found that the disc height variation and the stress distribution was more during axial rotation. The results also showed that the medial and lateral areas of the disc and the endplates were the most affected by the application of loads and hence these areas are critical for the occurrence of disc degenerative disease. This study can be used by doctors for the treatment of disc degenerative diseases as the calculation of range of motion of the specimen can help in understanding the improvement of his condition during the course of treatment.

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