A study of cervical spine morphology variation influence in loading and range of motions using finite element analysis

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Abstract. The most commonly found disease in aged people which can be dangerous and which affects the condition of an individual’s life is disc degenerative disease. The shift in the anterior load-bearing column was caused by the disc height changes in posterior side which could have adverse effects on posterior column. The lack of symptoms at early stages makes the identification of disc degenerative disease difficult but once identified, the treatment actions should be taken at right time. Biomechanical literature gives a static morphology of the FE models of cervical spine. An upcoming tendency in the current day medical practice is the use of personalized medicines and the predicting capabilities of this trend gets affected by not taking into account morphology as a model parameter. 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 parametrized. Finite element study was done on vertebral rotation variations and ligamental forces. Some of the most important morphological variations found in the anatomy were disc segmental size & height and body depth. The estimation of ROM and calculation of impact loads were found to be the key elements in the examination of degeneration of discs. Nonetheless there are risks involved in the extensive use of instruments for direct measurement of range of motion. 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. The range of motion values are then compared with the literature studies and the model with good mesh standard are used for future examination process. The individual components of spine are subjected to different types of loading situations and the stresses developed on them need to studied. The results gained from the finite element model helps us to plot stresses of subjects obtained from the respective lifestyles can benefit surgeons to suggest treatment actions.

1. Introduction
The cervical spine is designed in a robust manner that it plays a vital role in the structure & function of the human body. Each spinal region is distinct as they are not identical in many aspects [1]. Vertebra generally share identical structures except the caudal and cranial extremes. Lumber and thorax parts of the spine differ from the cervical segments as they exhibit difference in size, shape etc. of facet joints and transverse & posterior process [2]. Cervical spine is injury prone due to its structural and
functional complications and multiplanar ROM. Height variations in the intervertebral disc leads to DDD and is the main cause for injury [3].

DDD usually causes pain in the lower back i.e. lumbar region of the spine [4]. It is due to the changes in the disc of the spine. Disc degeneration may get accelerated due to the abnormal loads and motion patterns [5]. The morphological changes of the intervertebral disc and its adjacent structures are associated with the disc degenerative process [6]. Discs usually act as shock absorbers between vertebrae [7]. When these discs are subject to improper mechanical loading and nutrient deficiency DDD occurs. Over a period of 30 years numerous tests have been conducted in order to understand the mechanisms involved in the injury and trauma of the cervical spine [8]. 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 [9]. 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 [10]. 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 [11]. So, the progression of the degenerative disc disease is due to the mechanical causes based on overall view of the degenerative condition.

In patient specific models in order to identify the spine responses, it is mandatory to understand the influential variations in morphology [12]. The purpose of this study is to determine the morphological variations influence in loading and the ROM using the finite element analysis as the sections of spine are subjected to various loading type conditions which may affect the disc height of the intervertebral column. This work traverses through the appeal of the model for the examination of degenerative cervical spine disease under various conditions.

2. Methods and Materials

Three-dimensional FEM of intact cervical spine was created using CT scan. The CT scan was collected from 35-year-old male. The data of basic geometry of intervertebral disc and others spinal components were taken for modelling [13]. The total number of 424179 elements and 141102 nodes are present in the model of C5-C6. Almost all the ligaments using 2-node nonlinear link elements, which permit tensile axial force transmission. Nature of head and spine components were taken as linear elastic, homogenous & isotropic. In order to obtain the different movements of head & spine under F-E, AR and LB contableuerations pure moment loading of 1.0Nm is applied.

2.1 Imaging and modelling the C5-C6 spine.

CT scan is necessary to bring the image of the spine for the modelling and analysis. The CT scan was imported into Mimics Software version 10.0 to generate a surface model. A CT scanner was used for 419 slices with 1mm slice increment. To obtain a surface model for C5-C6 segmentation was done. Further segmentation was carried out to separate the individual vertebra and remove the fusion of facet joints resulting from segmentation. A surface model of a C5-C6 spine segment was generated from the scan, where the surface represents the bone.

2.2 Finite Element Model of C5-C6 spine.

A FEM of C5-C6 spine was developed using the surface model to be used as a baseline model. The surface model was exported Hypermesh 13.0 for meshing. The anterior side which constitutes vertebra, intervertebral disc and endplate is meshed using hexahedral mesh and the posterior side due to the irregular surface a tetrahedral mesh was done. The surface model was meshed using various mesh sizes such as 1mm the meshed model was tested using various load of 1Nm, 2Nm, 3Nm respectively. The loads were gradually increased till the failure limit. The FEM of C5-C6 cervical spine is shown in Fig.1.
The basic FEM was validated and with three material properties. The intervertebral disc was modelled and was attached with the C5-C6 vertebral bodies. The variation of loads in various material models varies the disc height between the vertebral bodies which may cause DDD [14]. This may affect the discrete components of the spine when different types of loading conditions are applied and the stresses developed on them are studied using the FE model of the spine [15]. The testing was carried out in three different material properties subjected to various loading conditions as stated above.

![Finite element model of C5-C6 cervical spine.](image)

**Figure 1.** Finite element model of C5-C6 cervical spine.

Three-dimensional model of C5 and C6 was developed by assembling their sagittal and coronal images sequentially. 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 [16]. The elastic modulus of the cortical vertebrae was 8000, 12000 and 16000MPa; the cancellous vertebrae modulus was 50, 125 and 200MPa; the intervertebral disc modulus was 1, 5 and 10MPa; the posterior elements modulus was 1000, 2500 and 5000MPa; the modulus for endplates was 20, 500 and 1000MPa respectively for the low, medium and high loading conditions. The properties used in FE model are cortical elastic modulus, cancellous core modulus, intervertebral disc modulus, bony posterior elements modulus and end plate modulus [17]. Table 1 includes the material properties used in the FE model.

| Material                        | Model – 1 MPa | Model – 2 MPa | Model – 3 MPa | Poisson’s ratio |
|---------------------------------|---------------|---------------|---------------|----------------|
| Cortical elastic modulus        | 8000          | 12000         | 16000         | 0.29           |
| Cancellous core modulus         | 50            | 125           | 200           | 0.29           |
| Annulus disc modulus            | 1             | 5             | 10            | 0.40           |
| Nucleus disc modulus            | 1             | 5             | 10            | 0.49           |
| Bony posterior elements modulus | 1000          | 2500          | 5000          | 0.29           |
| Endplate modulus                | 20            | 500           | 1000          | 0.40           |
Table 2 includes the ligament force-displacement behavior used in the FE model. The levels of 1Nm, 2Nm and 3Nm was the loading condition used to get different outputs under different conditions like F-E, LB and AR. Under all degree of freedom, the inferior most vertebrae were fully constrained according to the boundary conditions [11]. To accept the external load, factor the superior most vertebrae was unconstrained.

**Table 2.** Ligament force-displacement behavior, F considered as N and dl as mm.

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

The posterior longitudinal ligament (PLL), anterior longitudinal ligament (ALL), capsular ligament (CL), ligamentum flavum (LF), and interspinous ligament (ISL) were defined as combin 39 spring elements. The force and displacement values of these ligaments were given as the material properties of the ligament [17]. The anterior and posterior ligaments were placed on the anterior and posterior surface of the vertebral body. The ligamentum flavum was attached between the laminae and the capsular ligament between the articular processes [15].

2.3 Validation
The FE model of the C5-C6 spine was validated using the ROM of different material and loading conditions. The ROM was measured using various experiments and was compared with the FE model. ROM was found largest for F-E followed by LB and AR. The FE model of C5-C6 vertebral section was compared for different motions of the cervical segments with those obtained by literature results as shown in Fig.2. The left and right angular motions were summed up for the values of AR and LB [14]. Most of the projected values of ROM’s fell within the range of experimental data. However, under lateral moment loading, the model predicted some inconsistency against experimental data, as shown in Fig.2. Keeping range of motion as standard, the chosen model was validated successfully and compared with past studies. Under load of 1000N, 2000N and 3000N compressive forces validation was derived from disc bulge of 1.1mm, within the literature range of 0.4 to 1.2mm. Further for validating the model, the prevalent FE study showed the maximum deflection for flexion which was similar to results obtained from literature.
Figure 2. Model validation under 1Nm moment and comparison of ROM experimental values against the values of literatures.

Morphological parameters were varied in three generated models as the first step of analysis. In the next step, taking F-E into consideration stress distribution and disc height variation was identified. The regression coefficients of the parameters in the first level screening are taken as references from literature study. The F-E responses of these models with morphological property variations can be seen in the graph given. The changes in vertebral rotation due to these variations was 2.7 degree in flexion and 1.7 degree in extension.

3. Result and discussion
As the force increases from 1Nm-3Nm, the disc height shows notable increase from 0.2-1.2 mm. The correlation coefficients were evaluated for vertebral rotations at 1 Nm, 2 Nm, and 3 Nm. In flexion, the disc height was the most influential parameter, followed by the scale factors of stress distribution. While the influence of most parameters was independent of the moment magnitude, the influence of stress scale factor increased with an increase in moment, while the influence of stress reduced with various loads. In extension, the disc height variations were the most influential, followed by smaller contributions from the stress distribution. In flexion there is a constant increase in disc for model-2 and model-3 as the load is increased. There is not much significant change in model-1 for disc height as shown in Fig.3.
Figure 3. Disc height variation - Flexion for different models under various loading conditions. The values of literatures.

Figure 4. Disc height variation - Extension for different models under various loading conditions.
During extension there is an increase in disc height for model-2 and model-3 whereas model-1 does not show much significance as shown in Fig.4. The suggested method for experimentation gave remarkable output when compared to literature with lower risk and less instruments. As there was only small standard error between trials and consistency was high. During F-E high ROM is obtained when two studies are compared, they produce high stress levels on the spine. Stress was induced on the spine during movements. The maximum stress was endured by the cortical & cancellous tissues. When the spine is subjected to abnormal conditions for a longer duration it would cause harm to the disc and facet joint thus causing DDD. In flexion there is a constant increase in stress distribution for model-2 and 3 as the load is increased. There is not much significant change in model-1 for stress distribution as shown in Fig.5. During extension there is an increase in stress distribution for model-2 and 3 whereas model-1 does not show much significance as shown in Fig.6.

![Stress Distribution - Flexion](image)

**Figure 5.** Stress Distribution under flexion for different models under various loading conditions.
Figure 6. Stress Distribution under Extension for different model under various loading conditions.

4. Conclusion

In conclusion, this study presents a subject-specific FEM model for analysis of cervical spine for the DDD. The disc height and stress distribution in the disc were found to have influence on the spine biomechanics especially in the cervical spine segments. An insight about possible variation range of simulation results were given by the variation in material properties. The experimental data and results from existing study was compared and validated with the stress converged models of present study based on ROM. Out of the 3 models validated, model 1 did not show much variation in disc height or stress distribution. Model-2 & Model-3 showed notable variations in both the properties were the maximum variation in disc height was found to be in model-2 whereas stress distribution was more in model-3. The simulation results in present study were generally uniform with the experimental values and other literature results but analysis of DDD could not be assessed with the present models. Further developments will concern the inclusion on the models of other common degenerative features such as tears, osteophytes and facet joint degeneration. Combinations of different degenerative changes that are found in clinical cases will be also taken into account.

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