Development and validation of a C0-C7 cervical spine finite element model

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Abstract. A finite element model (FEM) of human C0-C7 cervical spine has been developed as a baseline to study the biomechanical factors in spinal surgical intervention. To accurately simulate the anisotropic properties, the intervertebral disc was divided into nucleus, annulus matrix and annulus fiber, and it was simulated with viscoelastic and fabric material models. The nonlinear force-displacement curves of ligament experiments were implemented to simulate the elastic zone and neutral zone at low loads. The model was validated with experimental data on range of motion (ROM) for normal, non-degenerated cervical spines tested in flexion and extension, lateral bending, and axial rotation at loads of 0.33, 0.5, 1.0, 1.5, and 2.0 Nm, and intra-discal pressure (IDP) was validated against experiment data at loads of 2Nm and 5Nm. For lateral bending and axial rotation, the model was well within in vitro experimental standard deviation corridors for the whole load range. For extension and flexion, however, the error index of C3-C4, C4-C5, C5-C6 flexion were 0.268, 0.03, 0.124 and the C6-C7 extension was 0.046 respectively. The IDP result was in well agreement with the experiments. These results indicated the C0-C7 cervical spine model was biofidelic for static simulation of these motions.

1 Introduction

With advancement of clinical and experimental studies on the pathogenesis of cervical spine diseases and injuries, biomechanical factors have been found to play an essential role as a series of parameters were found to change in injury and degeneration[1]. Comparing to the limited availability of specimen and poor repeatability of experiment in clinical and laboratory study, mathematical modeling, especially finite element modeling, is an important complement method in spine biomechanics study as it could quantify both internal and external response of cervical spine under various loading scenarios, which may hopefully improve our understanding of the mechanism of cervical spine diseases and injury, as well as prevention or treatments.

As the spinal degeneration and surgical treatment are in a quasi-static condition and under this condition, accurate geometry and reliable soft tissue response are of primary concern in investigating the biomechanical responses of cervical spine. In the last two decades, finite element modeling for static cervical spine diseases has made great progress. On the basis of segmental models[2][3] in the early time, occipito-atlanto-axial joint was included to simulate whole head and neck, as structure integrity of whole cervical spine is highly important for accurate prediction made by FEM. Minor soft tissues structures,

such as cartilage endplate and facet joint cartilages, which were also not included.

Despite the improvement mentioned above, validation of FEMs response against experimental data is essential for model bio-fidelity as it defines the conditions under which the model can be applied and the confidence of the prediction results is guaranteed. For model validation, the computer model should produce similar results as that of experiment under identical boundary and load conditions. The level of validation is assessed by the degree to which computer model response matches experimental response and the quality of experimental data. However, not all finite element models (FEMs) of the human cervical spine have been subjected to rigorous validation and therefore have limited application to the study of normal and abnormal cervical conditions. In this study, a FE model of C0-C7 human cervical spine was developed and extensively validated with segmental ROM of flexion, extension, lateral bending and axial rotation, as well as inter-vertebral disc pressure at various momentum loading condition. Hopefully, this FE model may be used for patient-specific adjustment in spinal degeneration and surgical intervention studies.

2 Method

The geometry was defined by CT and MRI image information of a 24-year-old healthy male with average height and weight. After three dimensional osseous structure of cervical spine was reconstructed with MIMICS (Version 12, Materialise Inc., Leuven, Belgium), the elements were meshed with HYPERMESH (Version 10, Altair, Troy, MI). Soft tissues including intervertebral disc, ligaments and articular cartilage were then incorporated into the model. The entire model consisted of 86,286 nodes, 106,311 elements, including 64,926 solid elements and 40,564 shell/membrane elements, 821 beam elements. The length, width, and height of most of the elements ranged from 0.75 to 1.25mm, as shown in Figure 1.
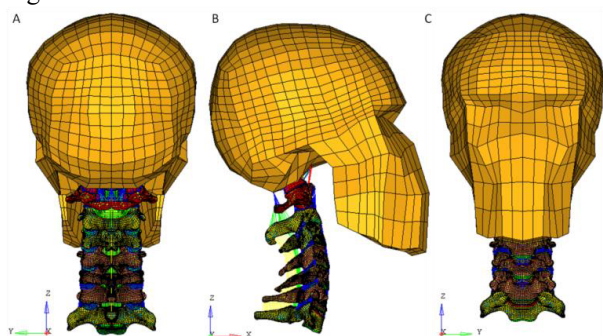

Figure 1. The head-neck model in Cartesian coordinate system

The material type and properties of this model were listed in Table 1. adjust the margins to those shown in Table 1.

Table 1. Material Properties of Cervical Spine Finite Element Modeling[4].

Tissue names	Element type	Material type	Material Parameters
Cortical bone	Shell	power-law plasticity	ρ=1.61e-9 t/mm^3, E=16700 MPa, μ=0.3, K=354.8 MPa, N=0.2772
Cancellous bone	hexahedron	power-law plasticity	ρ=8.77e-10 t/mm^3, E=291 MPa, μ=0.3 K=5.7 MPa, N=0.2741
Endplate	Shell	power-law plasticity	ρ=1.61e-9 t/mm^3, E=5600 MPa, μ=0.3, K=153.2 MPa, N=0.2772
Matrix of annulus fibrosus	hexahedron	Hill Foam	m=3, n=2, C1=2.1857 MPa, b1=1, C2=-2.36 MPa, b2=2, C3=0.891 MPa, b3=3
Annulus fibrosus fibres	Shell	Fabric	Strain-Stress Curve
Nucleus	hexahedron	General viscoelastic	N=4, K=1.72 GPa
			G_1=0.5930 kPa, β_1=0.001477 1/s, G_2=0.6763 kPa, β_2=0.061524 1/s, G_3=0.9516 kPa, β_3=1.017893 1/s, G_4=2.0384 kPa, β_4=13.20041 1/s,
Cartilage endplate	hexahedron	Isotropic elastic	ρ=1.36e-9 t/mm^3, E=25 MPa, μ=0.4
Facet articular cartilages	Hexahedron	Isotropic elastic	ρ=1.36e-9 t/mm^3, E=10.4 MPa, μ=0.4
Ligaments	Beam	Non-linear	Displacement-Force Curve

For each motion segment, the model is validated in flexion, extension, lateral bending and axial rotation under quasi-static tensile loading with moments of 0.33, 0.5, 1.0, 1.5, and 2.0 Nm. The flexion and extension responses of this model were compared with previous cadaveric studies reported by Nightingale et al.[5] and Wheeldon et al.[6]. In addition, the inter-vertebral disc pressures(IDP) were compared to 2Nm flexion/extension quasi-static experiment in C2-C3, C6-C7 segments reported by Dmitriev[7] and the 5Nm axial rotation and lateral bending quasi-static experiment in C4-C5, C5-C6 segments reported by Kretzer[8].

To evaluate the accuracy of the model, the evaluation index on ROM response for all loadings was calculated in gross correlation index (GCI)[9] equation(1).

$$F(E) = \frac{1}{6}\sum_{n=1}^{m}\left[\left(\frac{F_i^m - F_i^0}{F_i^m}\right)^2\right] \qquad (1)$$

The goodness of fit (or correlation) between the simulated results and test data was evaluated using a GCI developed by Deb et al.[9]. Here F_i^m presents the mean value of experiment data, while F_i^0 was the predicted simulation value. This algorithm was utilized to assess the accuracy of FE models simulations in previous literatures [10][11].

3 Result

The ROM of each segment from C0 to C7 in this model were compared to the studies from Nightingale et al.[5] and Wheeldon et al.[6] of flexion/extension, as shown in Figure 2. According to the gross correlation index (GCI) equation, the error index of C3-C4, C4-C5, C5-C6 flexion were 0.268, 0.03, 0.124 and the C6-C7 extension was 0.046 respectively. The extension of C0-C2, C2-C3,

C3-C4, C4-C5, and the flexion of C0-C2, C2-C3, C6-C7 agreed well with the experimental data.

As cadaveric research on the IDP was quite scarce, IDP of the single segment models was validated with corridors obtained from a pure moment study of Dmitriev 2005[7] on 2Nm flexion/extension, and the study of Kretzer 2012[8] on 5Nm axial rotation and lateral bending. The model also matched very well with results obtained in these literatures, as shown in Figure 3.
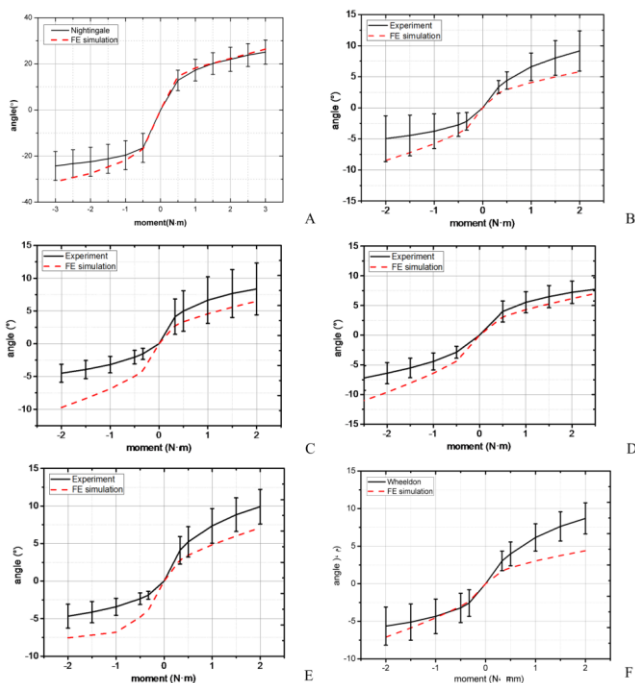

Figure 2. Flexion-extension response of each segments (A. C0-C2, B. C2-C3, C. C3-C4, D. C4-C5, E. C5-C6, F. C6-C7) for inter-segment models under a range of quasi-static flexion and extension moments. For sub-axial segment validation, the simulation results were compared to experiment of Nightingale et al, 2007(A. C0-C2) and Wheeldon et al, 2004(B. C2-C3, C. C3-C4, D. C4-C5, E. C5-C6, F. C6-C7).
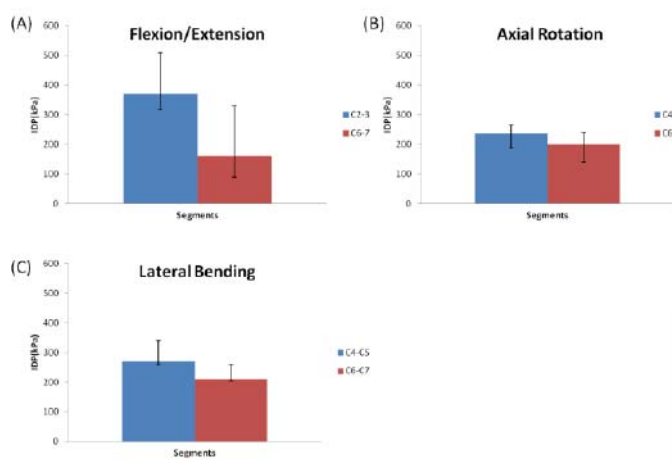

Figure 3. IDP response for inter-segment model in different motion compare to literatures (A. Flexion in moment 2Nm. B. Axial rotation in moment 5Nm. C. Lateral bending in moment 5Nm).

4 Discussion

Several quasi-static C0-C7 cervical FE models were developed and validated in last few years. Del Palomer et al.[12] developed a C0-C7 cervical spine model for quasi-static simulations, but only flexion-extension moment-rotation curves were validated with previous cadaveric experimental literatures; similarly, Panzer et al.[4] developed a C0-C7 cervical spine model for frontal impact injury, while only the flexion and extension quasi-static experiments reported by Nightingale et al.[5] and Wheeldon et al.[6], 2004 were utilized in validation. Toosizadeh et al.[13] also developed a C0-C7 cervical spine with muscle for the study of neck pain, and only single torque responses in 1Nm loading were validated with all the motions. To our knowledge this is the only C0-C7 FE model that was accurately validated against quasi-static ROM and IDP experimental data of normal specimens.

In this study, an FE cervical model is developed as a baseline to investigate the tissue-level biomechanical change in static simulation of various motions including flexion/extension and IDP. The C0-C7 FE model of human cervical spine without any adjustments was exercised in 24 loading cases without numerical difficulties to ensure its precision in multiple cervical motion simulations. Based on the model developed in this study, patient-specific FE models could be developed to further investigate the biomechanical response induced by structural change during surgical intervention and/or degeneration. As a matter of fact, the baseline model is being used for patient-specific modeling of patients after surgical intervention and hopefully more accurate biomechanical data might be obtained to investigate the cervical spine response after surgery.

Acknowledgement

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