Development and Tensile Investigation of a 3-year-old Cervical Spine Finite Element Model

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Abstract. A 3-year-old cervical spine finite element (FE) model with detailed anatomical and material properties was developed and validated against cadaver tests under dynamic loadings. First, the bone geometry was reconstructed based on high-resolution computed tomography (CT) scans, and the elastic-plastic material was defined to simulate the cortical and cancellous bones. Second, to simulate various ligament tears during dynamic tensile, ligaments failure were defined using force versus displacement curves, which had a sigmoidal shape governed by three control point. To better represent complicated structure of disc, such as nucleus pulposus, annulus fibrosus substrate and four pairs of reinforced fiber lamina, the intervertebral discs were defined using composite materials which combined by viscoelastic material, hill foam material and four pairs of reinforced fiber lamina, respectively. Finally, dynamic tensile experiments in C4-C5 and C0-C7 were used to validate the dynamic ultimate force and displacement of the 3-year-old cervical FE model, revealing that this FE model is capable of predicting intervertebral disc injury and ligament tear. This FE model will contribute to a better understanding of the mechanisms underlying pediatric cervical injuries.

Introduction

As the number of people using modern transportation continues to increase, the number of traffic accidents also increases each year, and it is widely accepted that traffic accidents are a major cause of human fatalities[1]. Recently, considerable attention has been paid to the pediatric cervical spine due to its increased vulnerability to injury. It has been shown that upper spinal injuries caused by sudden deceleration resulting from vehicle crash or direct impact in the case of pedestrians frequently occur in the 0-6 year age group [2]. Three years of age is an important growth period for the pediatric cervical spine. The fusion of the posterior synchondrosis first occurs at this age, and the anterior and posterior ossification centers join at this age as well [3]. These unique anatomical characters might cause more common pediatric upper cervical injury to 3 year-old children include occipitoaxial joint dislocation, atlantoaxial joint dislocation, atlantoaxial rotatory subluxation, and spinal injury without radiological abnormalities [4-6]. To better understand the cervical spine injury mechanism for 3-year-old children, it is necessary to develop finite element model with more anatomical and mechanical biofidelity.

Among all the existing 3-year-old cervical spine FE models, Meyer, Roth and Willinger [9] developed the most detailed pediatric cervical spine morphology using 3-dimensional (3-D) reconstruction based on computed tomography (CT) scans. However, the cortical and cancellous bones in Meyer’s FE model were simulated using linear elastic materials. Furthermore, in the validation described in Meyer’s study, the dynamic response was compared to the global response of the head, which might not accurately represent the segmental partial response of the cervical spine.

In this study, the objective was to develop a 3-year-old cervical spine FE model with both nonlinear material properties and extensive validation. Because it involves all of these methods, our
proposed FE model might contribute to a better understanding of the mechanism underlying pediatric cervical injury, allowing better prediction of the injury response in a wide variety of accident scenarios and the development of better protection for 3-year-old children.

**Method and Material**

The images of vertebrae shown in Figure 1a were obtained from a 3-year-old boy (the cause of death was aplastic anemia and infection) with a height (93 cm) and weight (16 kg) similar to the average of 3-year-old children via CT (Brilliance CT, Philips Medical Systems, Best, The Netherlands). The CT scan was performed with 1-mm slice thickness and a screen resolution of 512×512 pixels following guidelines approved by Central South University Xiangya 3rd hospital Ethics Committee. The 3-D geometry data for the osseous structures were reconstructed in 3-D using MIMICS (Version 12, Materialise Inc., Leuven, Belgium), as shown in Figure 1b. The geometries of the ligaments, cartilage, and intervertebral discs not visible in the CT images were filled in between the bony segments based on pediatric cervical anatomy [3, 12-14] and pediatric spinal models [7-9, 15]. In our study, we adopted a multi-block approach to generate vertebral body meshes efficiently (ANSYS ICEM CFD/HEXA 12.0, Ansys, Canonsburg, PA, USA). Hypermesh 10.0 (Altair, Troy, MI) was used to generate the remaining meshes. The coordinate system of the entire model was defined with the positive x-axis pointing in the anterior direction, the y-axis pointing to the left, and the z-axis pointing in the superior direction, as shown in Figure 2a. All the simulations were conducted using LS-DYNA version 971 solver (LSTC, Livermore, CA).

![Figure 1](image_url)

**Figure 1.** (a) This is the Images of vertebrae obtained via CT scanning, (b) The geometry of the 3-year-old pediatric FE model reconstructed in 3-D using MIMICS.
The 3-year-old cervical spine FE model has 278,492 elements and 243,901 nodes, including 1,384 1-D beam elements, 84,066 2-D shell elements, 192,940 3-D hexahedral elements, and 102 triangular prism elements, in which the element size ranges from 0.5 to 1.0 mm. The head was simulated as a rigid body element. The settings adopted in our simulations were the same as the dynamic boundary conditions used in Luck’s study [32]. A velocity of 230 mm/s was simulated via prescribed motion control, as shown in Figure IIb. The failure force, failure displacement, and tensile stiffness under 20%-80% and 20%-50% loading were validated against the experimental curves estimated by the logistic regression method for the 3-year-old C4-C5 segmental cervical spine.

Ouyang, Zhu, Zhao, Xu, Chen and Zhong [38] reported dynamic tensile failure data for 1-year-old to 10-year-old pediatric whole cervical specimens. In Ouyang’s experiment, the T2 vertebrae was constrained, and a rigid rod threaded the CG of the head and controlled the motion of the head, including up-down and anterior-posterior translational motion, axial rotation, and lateral rotation. In our study, the C7 vertebrae was constrained, the tensile motion was simulated with a velocity of 5 mm/s until failure occurred, and the failure force of each ligament was recorded. Compared to the experimental data in Ouyang’s study [38], the force versus displacement curve was evaluated for 3-year-old whole cervical dynamic tensile validation.

**Result**

The simulated C4-C5 dynamic tensile force versus displacement curve was compared with experimental data collected from a 22-month-old specimen, as shown in Figure 3. In the simulation, the disc injury occurred when the displacement was 1.75 mm. The PLL failed when the displacement was 5.08 mm, and the ALL failed when the force achieved a maximum value of 795.9 N, as shown in Table 1 Compared with the experimental data, the deviations of the initial failure force, the ultimate failure force and the ultimate failure displacement were -17.5%, -6.1%, and -13.3%, respectively.
Luck et al. (2008) quasi-static tensile stiffness

Power-Law curve fitting

Figure 3. The age versus C4-C5 quasi-static tensile stiffness curve for children across all age ranges.

Table 1. Comparison of the C4-C5 segmental dynamic tensile simulation with the experimental data reported by Luck et al. [32]

|                        | Experimental data | Interpolation | Simulation |
|------------------------|-------------------|---------------|------------|
| Initial failure force (N) | 466.8             | -             | 397.3      |
| Ultimate failure force (N) | 844.8             | 698.2         | 795.9      |
| Failure displacement (mm) | 5.76              | 4.94          | 5.08       |
| 20%-80% Stiffness (N/mm) | -                 | 244.3         | 128.1      |
| 20%-50% Stiffness (N/mm) | -                 | 265.3         | 158.2      |

The simulated ultimate failure displacement and the ultimate failure force of the C0-C7 FE model for the 3-year-old pediatric cervical spine were compared to the tensile experimental data reported by Ouyang et al. [38], as shown in Figure 4b. The ultimate failure force in the 2.5-year-old and the 3-year-old experiment were 530.5 N and 569.5 N, respectively, and the ultimate displacement in the 2.5-year-old and the 3-year-old tensile experiment were 19.45 mm and 22.48 mm, respectively. The simulated ultimate failure displacement and the ultimate failure force were 17.91 mm and 451.4 N, respectively. Compared to these two experimental values, the deviations in ultimate failure displacement were 8.6% and 25.5%, whereas deviations in ultimate failure force were 17.5% and 26.1%. We observed that failure occurred in the upper surface of the C3 endplate and the growth plate, similar to the locations predicted by Dong based on dynamic tensile simulations from a 10-year-old [15].

Discussion

The pediatric cervical spine is significantly different from the adult spine with regard to its anatomical and material properties [2, 10, 15, 31]. In this study, the C2-C7 cervical segmental response was first validated under the dynamic tensile response and the dynamic extension-flexion response were then compared with both segmental and global experimental data. However, the muscles were not included in this model because accurate muscle force is dependent on the physiological cross-section area (PCSA), the muscle activation level and muscle fiber length [39], which were unavailable in the 3-year-old pediatric cervical spine [40].
In the dynamic validations, the simulated force versus displacement curves for the 3-year-old pediatric C4-C5 cervical spine was in good agreement with the tensile experimental data obtained using a 22-month-old pediatric cervical spine. However, the differences in the anatomical and material properties of 3-year-old and 22-month-old pediatric cervical spines should not be ignored. Compared with the conditions of actual cervical spinal injuries, the disc and ligaments in the experiments were ruptured gradually. In this study, the disc, ALL and PLL failed in the same sequence as observed experimentally. Still, most of the FE model dynamic tensile simulations exhibited the following limitations: all of the elements in the discs and ligaments failed immediately when the failure thresholds were reached, which caused the tensile force to suddenly decrease in these simulations, typically under 20%-80% and 20%-50% loading, as shown in Figure 4 a. A similar problem was reported by DeWit and Cronin [29] in adult C4-C5 segmental tensile failure simulations. For the reasons described above, the tensile stiffness in the simulations, which is represented by the linear slope of the dynamic tensile curve obtained via linear regression, was substantially lower than that of the experimental dynamic tensile curve.

In the C0-C7 dynamic tensile validations, the simulated ultimate displacement was less than the experimental values reported by Ouyang, Zhu, Zhao, Xu, Chen and Zhong [38] for the following reasons. First, the specimen in Ouyang’s experiment was C0-T2, and the C7-T2 cervical spine might experience greater displacement. Second, the specimen in Ouyang’s experiment included all of the ligaments and muscles, whereas the supraspinous ligament, ligamentum nuchae and intertransverse ligament were not included in the 3-year-old pediatric FE model in this study. The absence of these
elements could cause this FE model to exhibit lower stiffness and ultimate tensile force than the experimental specimen.

Luck, Nightingale, Loyd, Prange, Dibb, Song, Fronheiser and Myers [32] reported failure force and displacement data for cadaver spines subjected to impacts dynamic tensile loading, which represent an important addition to our knowledge of the osteoligamentous mechanical properties of the pediatric cervical spine. To the best of our knowledge, this important experimental work has not yet been applied to develop numerical models for the 3-year-old pediatric cervical spine and should be adopted to enhance the biofidelity of FE models of cervical spines.

In this study, a 3-year-old cervical spine FE model was developed which includes the C0-C7 cervical vertebra, the intervertebral discs, cartilages and ligaments, which exhibited good biofidelity under dynamic tensile loading. The elastic-plastic material was defined to simulate the cortical and cancellous bones, the nucleus pulposus and annulus fibrosus were defined using composite materials which combined by viscoelastic material, hill foam material and four pairs of reinforced fiber lamina, respectively. The ligaments were defined using different experimental curves to simulate various failure sequences in dynamic tensile simulations. This FE model are good agreement with experiment data under flexion, extension, lateral bending and axial rotation conditions which scaled from the adult experiments in five motion segments (C2–C3, C3-C4, C4–C5, C5-C6 and C6–C7). Then the dynamic tensile experiments in C4-C5 and C0-C7 were used to validate the dynamic ultimate force and displacement of the 3-year-old cervical FE model, revealing that this FE model is capable of predicting intervertebral disc injury and ligament tear. However, this FE model could be further improved by performing additional experiments involving 3-year-old cervical spine muscles to obtain more accurate material parameters and geometry data.

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