Simulation of Child Cervical Spine Injury in Frontal Crash

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Abstract. Computer simulations using Finite Element (FE) models, including full-body models and tissue models are widely performed in biomechanical studies. However, child models are very rare mainly because of the difficulty of child data collection. A child cervical spine (C0-T1) FE model was developed in this study. The geometrical data was collected from clinical Computed Tomography (CT) images of a 6-year-old child volunteer. The mechanical properties were defined based on the results from previous studies. A frontal crash simulation was performed using this model. The mechanism of the cervical spinal injury was simulated. The protection for the child cervical spine was also discussed. Results showed that the maximum stress occurred in pediatric upper cervical spine during the impact. Proper use of Child Restraint System (CRS) could protect the child cervical spine from injury in motor vehicle crashes. This study could help to understand the injury mechanisms of child cervical spine and better protect children from motor vehicle crashes.

Keywords: Finite Element model, simulation, child cervical spine, child protection.

1. Introduction

Studies on pediatric cervical spine (C-spine) are relatively few. However, injuries related to C-spine may be associated with severe disability and mortality [1-3]. Younger children usually sustain C-spine injuries during motor vehicle crashes. Adolescents commonly injured during sporting activities [4-5]. Biomechanical studies on C-spine injuries during motor vehicle crashes are very common in adult population, especially with three-dimensional Finite Element (FE) methods, studies on pediatric population are far from enough [6].

In this study, the geometrical data of the pediatric C-spine from cranial base to the first thoracic vertebrae was acquired from a healthy 6-year-old child using Computed Tomography (CT) scan. The stereo lithography (STL) model of C-spine was generated after visual assembling. The whole model was developed after repairing and optimization using FE methods. The mechanical properties of the C-spine were defined according to the result from literature. With the model developed in this study, the mechanisms of the C-spine injury during motor vehicle crashes for the child population was simulated.

2. Methods

2.1 Population

A 6-year-old child volunteer (male, stature of 118 cm and weight of 20 kg) participated in this study. The volunteer does not have neck pains or cervical trauma. Clinical CT (Siemens Soma tom Sensation 64, Siemens, Germany) examination scan was performed on the volunteer to exclude C-spine degenerative disorders, vertebral destruction or cervical instability. Scan was performed with slice thickness of 0.6 mm, 80 KVp. CT images were collected in DICOM format. This scan was approved by the ethical committee and the volunteer’s guardian approved this examination.

2.2 C-spine FE model

The collected images were imported into Simple ware (Simple ware Ltd, UK). The stereo lithography (STL) triangle mesh model was developed from cranial base to the first thoracic vertebrae.

Reverse reconstruction was performed to create a smooth NURBS (Non-Uniform Rational B-Splines) model. The anterior arch of child C1 vertebrae was not fused with the neural archer but linked by two cartilages [7], as shown in Fig.1.

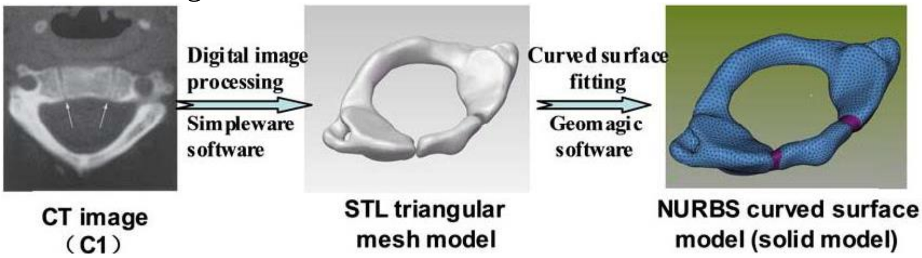


Fig.1. Geometrical model of pediatric C1 vertebrae

Based on the previous studies on pediatric C-spine anatomy, the start point and the end point of pediatric C-spine ligament were determined. Twelve critical ligaments were established using 2 nodes nonlinear spring unit, which includes AAOM, PAOM, CLV, AP , AL, TM, TL, ALL, PLL, FL, FC, ISL and SSL11. Non-linear contact relation was used to simulate interactions among those joints, as shown in Fig. 2.

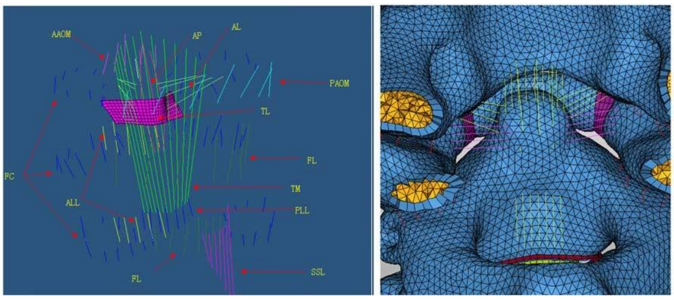


Fig. 2. The distribution and location of pediatric C-spine ligament

The C3D6 unit was used for cortical bones, with an average thickness of 1 mm. The C3D4 unit was used for cancellous bones. Three-dimensional reducing integral shell element S4R was used for TL transverse ligaments. The enhanced hourglass control of three-dimensional hexahedral reducing integral C3D8R was used for C2-C7 intervertebral discs (including nucleus gelatinous and fiber ring) and endplate. Hourglass control can reduce volumetric locking which is caused by large deformation.

Using the topologically partitioning and meshing of Hyper mesh (Altair Hyper works 10.0, Troy, MI, USA), the Jacobian mesh quality was controlled to be above 0.6.

2.3 Material Properties

The material properties are introduced from previous studies, as shown in Table 1 and Table 2. Isotropic material properties were used for cortical bone and cancellous bone [8]. The transverse ligament was modeled as anisotropic material [9], as shown in Table 1. The intervertebral discs (including nucleus pulpous and annulus fibrosis) adopts incompressible hyperplastic material: Mooney-Reviling (C10, C01), as shown in Table 2.

Table 1: C-spine Material properties

		Modulus	Poisson's ratio
Vertebra	Cortical bone	15GPa	0.2
	Trabecular bone	500MPa	0.3
Ligament	Transverse	86MPa	0.016
	Lengthways	6MPa	

Table 2: The material properties of the intervertebral discs

Material properties	Nucleus pulpous	Annulus fibrosis	Collagenous fibers
Density (kg/mm3)	1.000E-06	1.200E-06	Nonlinear elastic curve
Poisson's ratio	0.495	0.450	
C10	0.120	0.180	
C01	0.030	0.045	

2.4 Loading and boundary conditions

The C-spine injuries during frontal impact were simulated using Madymo (Tass, The Netherlands), with a 6-year-old child dummy (TNO P6). The simulation was performed using two impact conditions: with Child Restraint System (CRS) and without CRS seated in the back row, as shown in Fig. 3. The output parameters from the simulation are the speed, acceleration, displacement and other dynamics relevant parameters of the dummy’s head and chest, providing data for finite element analysis of pediatric cervical spine. From the simulation, the displacement-time curve of dummy’s skull to the chest was obtained.

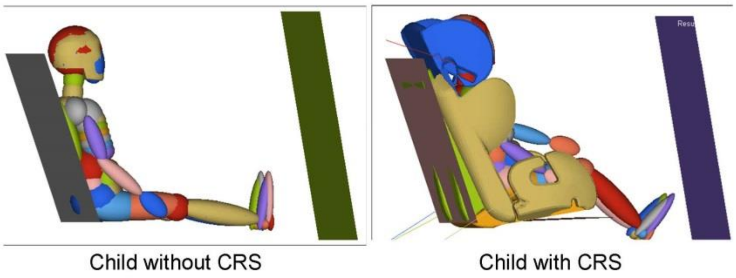


Fig. 3. The simulation of the injuries using Madymo and a P6 dummy

The loading condition of the C-spine FE model was shown in Fig. 4. The acceleration of the skull from multibody dummy simulation was loaded on MASS point from X and Y direction. The C0 displacement-time curve in the FE model simulation was similar to the one of dummy’s skull to the chest apex from multibody dummy simulation. It showed that The FE C-spine model had the similar dynamic response as the multibody dummy under the same loading and boundary conditions. The 6-year-old child C-Spine FE model developed in this study is reasonable and reliable.

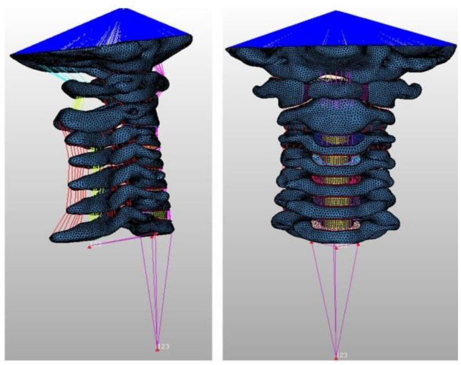


Fig. 4: Loading locations on the child cervical spine

3. Results

It showed that the acceleration, displacement and stress on child passenger's C-spine were changed during the frontal impact. The upper cervical spine suffered larger stress and displacement than the lower part. With a CRS, the stress of the C-spine was reduced, as shown in Fig. 5 and Fig. 6.

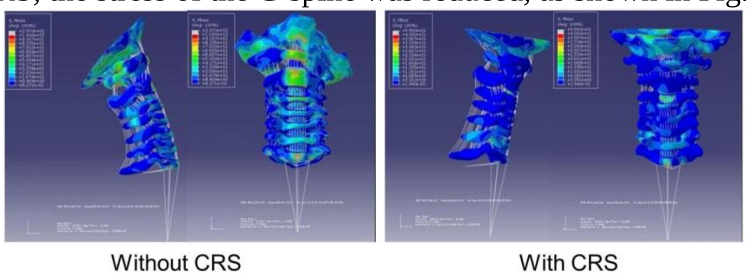
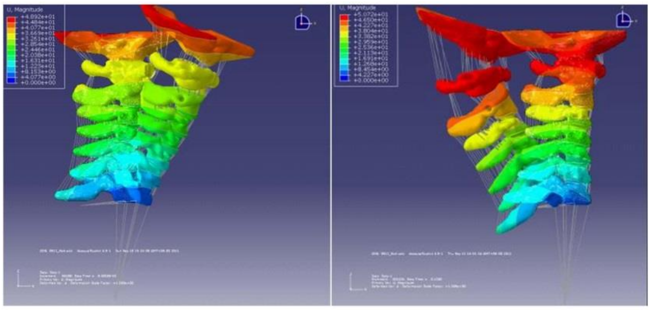


Fig. 5: The stress map of C-spine

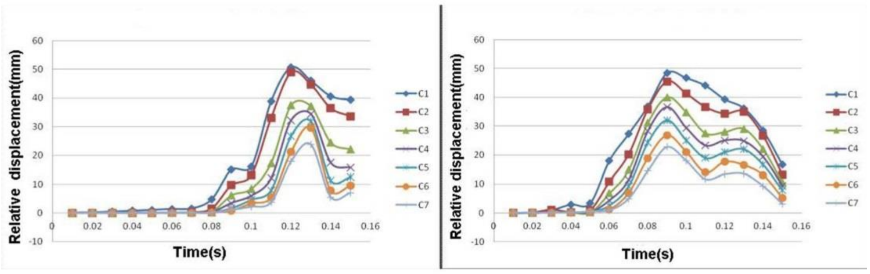


Without CRS With CRS

Fig. 6: The maximum displacement of C-spine

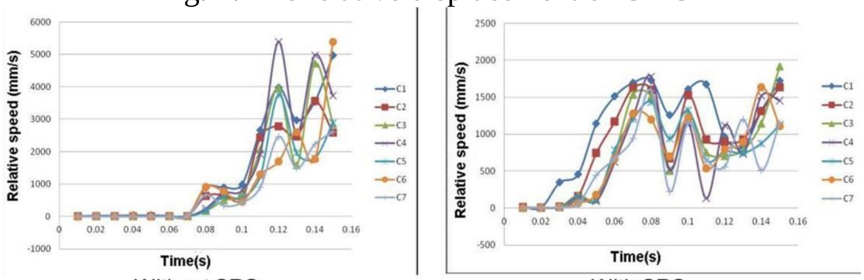
In case of a crash, if the child was not restrained in a CRS, the simulation showed that the head and body moved forward within 0.08s. In this period, the speed, relative displacement, and the stress of the cervical vertebrae were relatively small. However, the head and body impacted the faceplate or seat. In this case, the speed, relative displacement and the stress of the C-spine increased very fast. The instantaneous impact energy would produce devastating injuries to the cervical spine.

Contrary, if the child was proper restrained in a CRS, the speed, relative displacement, and the stress were changed gradually, and maximum values or the dynamic response parameters were significantly lower than that without a CRS. The gradual changes in the C-spine might be more conducive to protect children's cervical spine from injury in case of a crash. As shown in Fig. 7, Fig. 8 and Fig. 9.



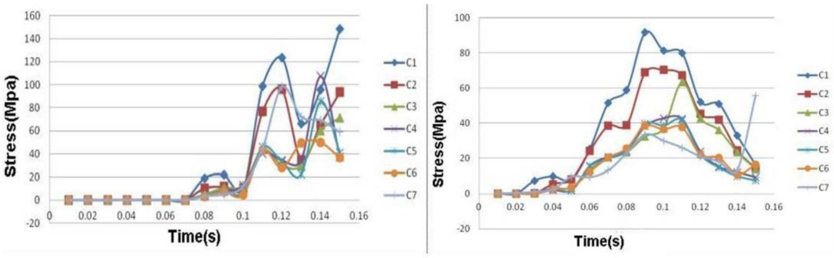
Without CRS With CRS

Fig. 7: The relative displacement of C1-C7



Without CRS With CRS

Fig. 8: The relative speed of C1-C7



Without CRS With CRS

Fig. 9: The stress of C1-C7

4. Discussion

Children are also frequent vehicle users and are increasing in China. However, the child passenger's safety is not optimistic, as children are often involved in motor vehicle crashes.

According to a subjective survey from the parents, less than 40 percent of children were retrained in vehicles [11]. Another objective investigation in highways showed that the rate of the CRS usage is only 2.2% in China [10]. Motor vehicle crashes are one of the main reasons of pediatric cervical spine injuries, with about 48-61% of all injuries [12, 13]. Also, the anatomical structure and tissue mechanical properties of children’s head and neck are different from adults. Comparing to adults, children’s head is relatively heavier compared to their body structures. The geometry of the head and neck are relatively larger compared to their statures. Therefore, the injury mechanism of children’s head and neck is quite different from adults. The upper cervical spine (C1-C4) is the most common injured part in children, accounting for about 66-68% of all cervical spine injuries, which very different from adult cervical injuries [14]. Biomechanics studies on pediatric cervical spine injuries during vehicle crashes are quite necessary.

Currently, different models have been developed to study the biomechanics of cervical spine injuries, using cadaver or animal cervical spine and computer simulations. The cadaver experiment is under pressure of ethical controversy. Also, there are no physiological characteristics of cadaveric cervical organization. For animals used in bio-collision experiment, the anatomical differences between animals and human beings are not well known. Computer simulation experiments provide support for biomechanical mechanism of cervical spine injuries much easier. Developing FE models of human cervical spine and using it in biomechanical studies on cervical spine injuries have become a commonly used research tools.

Although the biomechanical mechanisms of cervical spine injuries in traffic accidents has been widely studied in adult population using FE models, fewer researches have been carried out on biomechanics mechanisms of pediatric cervical injuries. In China, only few groups have conducted the quasi-static biomechanical test for pediatric cervical movement [15]. In Europe, The project CHILD conducted dimensional FE analysis for pediatric cervical spine. However, it is unsure to apply European pediatric cervical FE model to study the biomechanical mechanisms of Chinese pediatric cervical spine injuries. Therefore, developing Chinese pediatric cervical spine FE model in this study is precise.

5. Conclusions

A 6-year-old pediatric cervical spine FE model was developed based on a healthy child's cervical spine using CT images in this study. It showed that the maximum stress occurred in pediatric upper cervical spine during a vehicle crash, which matches results from previous epidemiological studies on child cervical spine injuries. Using CRS in the right way could reduce the acceleration, speed, displacement and the stress of the C-spine. The press on the pediatric cervical spine was significantly reduced when children were seated in CRS. Proper use of CRS could protect the child passenger's cervical spine from injury during motor vehicle crashes.

Acknowledgment

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References

[1] D. M. Ja_e, H. Binns, M. A. Radkowski, M. J. Barthel, H. H. Engelhard, Developing a clinical algorithm for early management of cervical spine injury in child trauma victims. Annals of emergency medicine, 1987, 16(3), pp. 270-276.

[2] I. Rachesky, W. T. Boyce, B. Duncan, J. Bjelland, B. Sibley, Clinical prediction of cervical spine injuries in children: radiographic abnormalities. Archives of Pediatrics and Adolescent Medicine, 1987, 141(2), pp. 199.

[3] D. Bohn, D. Armstrong, L. Becker, R. Humphreys, Cervical spine injuries in children. J Trauma, 30 (1990) 463-469.

[4] J. C. Patel, J. J. Tepas, D. L. Mollitt, P. Pieper, Pediatric cervical spine injuries: de_ning the disease, Journal of pediatric surgery, 2001, 36(2), pp. 373-376.

[5] R. L. Brown, M. A. Brunn, V. F. Garcia, Cervical spine injuries in children: a review of 103 patients treated consecutively at a level 1 pediatric trauma center, Journal of pediatric surgery, 2001, 36(8), pp. 1107-1114.

[6] K. Mizuno, K. Iwata, T. Deguchi, T. Ikami, M. Kubota, Development of a three-year-old child FE model, Tra_c injury prevention, 2005, 6(4), pp. 361-371.

[7] E. S. Lustrin, S. P. Karakas, A. O. Ortiz, J. Cinnamon, M. Castillo, K. Vaheesan, S. Singh, Pediatric Cervical Spine: Normal Anatomy, Variants, and Trauma 1. Radiographics, 2003, 23(3), pp. 539-560.

[8] K. Brolin, P. Halldin, Development of a _nite element model of the upper cervical spine and a parameter study of ligament characteristics, Spine, 2004, 29(4), pp. 376-385.

[9] M. El-Rich, P. J. Arnoux, E. Wagnac, C. Brunet, C. E. Aubin, Finite element investigation of the loading rate e_ect on the spinal load-sharing changes under impact conditions, Journal of biomechanics, 2009, 42(9), pp. 1252-1262.

[10] S. Pan, W. Du, F. Jiang, L. Bilston, J. Brown, X. Shen, Restraint use and seating position among child car passengers: An observational study in Shanghai, Accident Analysis & Prevention, 2011, 43(6), pp. 2195-2199.

[11] S. Pan, W. Du, F. Jiang, L. E. Bilston, J. Brown, & X. Shen, Exploring child car passenger safety practices in China: experience from a parental survey in Shanghai, 2012, Injury prevention, 18(2), pp. 133-137.

[12] J. T. Wilcox, D. Cadotte, & M. G. Fehlings, Spinal cord clinical trials and the role for bioengineering, Neuroscience letters, 2012, 519(2), pp. 93-102.

[13] M. A. Eleraky, N. Theodore, M. Adams, H. L. Rekate, & V. K. Sonntag, Pediatric cervical spine injuries: report of 102 cases and review of the literature, Journal of Neurosurgery: Spine, 2012, 92(1), pp. 12-17.

[14] M. Mortazavi, P. A. Gore, S. Chang, R. S. Tubbs, & N. Theodore, Pediatric cervical spine injuries: a comprehensive review, Child's Nervous System, 2011, 27(5), pp. 705-717.

[15] J. Ouyang, Q. Zhu, W. Zhao, Y. Xu, W. Chen, & S. Zhong, Biomechanical assessment of the pediatric cervical spine under bending and tensile loading, Spine, 2005, 30(24), E716-E723.