Development and initial evaluation of a finite element model of the pediatric craniocervical junction

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OBJECTIVE There is a significant deficiency in understanding the biomechanics of the pediatric craniocervical junction (CCJ) (occiput–C2), primarily because of a lack of human pediatric cadaveric tissue and the relatively small number of treated patients. To overcome this deficiency, a finite element model (FEM) of the pediatric CCJ was created using pediatric geometry and parameterized adult material properties. The model was evaluated under the physiological range of motion (ROM) for flexion-extension, axial rotation, and lateral bending and under tensile loading.

METHODS This research utilizes the FEM method, which is a numerical solution technique for discretizing and analyzing systems. The FEM method has been widely used in the field of biomechanics. A CT scan of a 13-month-old female patient was used to create the 3D geometry and surfaces of the FEM model, and an open-source FEM software suite was used to apply the material properties and boundary and loading conditions and analyze the model. The published adult ligament properties were reduced to 50%, 25%, and 10% of the original stiffness in various iterations of the model, and the resulting ROMs for flexion-extension, axial rotation, and lateral bending were compared. The flexion-extension ROMs and tensile stiffness that were predicted by the model were evaluated using previously published experimental measurements from pediatric cadaveric tissues.

RESULTS The model predicted a ROM within 1 standard deviation of the published pediatric ROM data for flexion-extension at 10% of adult ligament stiffness. The model's response in terms of axial tension also coincided well with published experimental tension characterization data. The model behaved relatively stiffer in extension than in flexion. The axial rotation and lateral bending results showed symmetric ROM, but there are currently no published pediatric experimental data available for comparison. The model predicts a relatively stiffer ROM in both axial rotation and lateral bending in comparison with flexion-extension. As expected, the flexion-extension, axial rotation, and lateral bending ROMs increased with the decrease in ligament stiffness.

CONCLUSIONS An FEM of the pediatric CCJ was created that accurately predicts flexion-extension ROM and axial force displacement of occiput–C2 when the ligament material properties are reduced to 10% of the published adult ligament properties. This model gives a reasonable prediction of pediatric cervical spine ligament stiffness, the relationship between flexion-extension ROM, and ligament stiffness at the CCJ. The creation of this model using open-source software means that other researchers will be able to use the model as a starting point for research.

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KEY WORDS pediatric; craniocervical junction; finite element modeling; spinal biomechanics; spine

BIOMECHANICAL analysis is the foundation upon which modern spine surgery rests. Without it, clinicians are left to speculate about what injuries or interventions destabilize the spine, as well as what maneuvers are required to correct instability. Fortunately, there is a wealth of knowledge regarding this topic, and most of it was acquired from adult human cadaveric testing and failure analysis.^{9,10,17,19} This knowledge has given us a rich

understanding of the determinants of stability at all levels of the adult spine. Unfortunately, the same cannot be said about the pediatric counterpart. Primarily because of a lack of human pediatric cadaveric tissue, but also because of the relatively small number of treated patients, this is a significantly understudied area in spinal biomechanics. This fact is especially true of the most complex region of the pediatric spine: the craniocervical junction (CCJ). This

ABBREVIATIONS CCJ = craniocervical junction; FEM = finite element model; ROM = range of motion; TL = transverse atlantal ligament; TM = tectorial membrane.

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region includes the bony elements of the occiput, atlas (C-1), and axis (C-2), as well as the supporting ligamentous and soft-tissue structures. Our current biomechanical knowledge is based mostly on clinical experience^{29,30} and a few cadaveric studies.^{23–25,28}

One way to overcome this deficiency is to create a finite element model (FEM) of the pediatric CCJ. Robust FEMs give an accurate representation of the complex geometrical structures that contain dissimilar material properties by discretizing the larger structure into numerous smaller pieces for evaluation. Recent advances in computational power have allowed researchers to use FEMs to examine the biomechanical behaviors of a wide variety of skeletal structures, including the spine.^{4,7,21,22,32,33,36} The FEM must also be evaluated with cadaveric biomechanical test results, which, as discussed above, are very difficult to obtain for the pediatric population.

To date, only 1 group has reported biomechanical tests of human cadaveric pediatric craniocervical tissue that is appropriate for evaluating predictions from a pediatric craniocervical FEM.^{23–25} Luck et al. reported both flexion-extension range of motion (ROM) data and axial tension structural stiffness data for cadaveric pediatric cervical spine tissue.^{23,24} These data were used previously to evaluate an FEM of the entire pediatric cervical spine, which consisted of a dynamic/explicit model created to simulate automobile-related crash scenarios.⁶ Because the data sets also include flexion-extension ROM and axial tensile stiffness for the CCJ that were separately reported from data on the rest of the spine, the data may also be useful for evaluating regions of the spine.

The aim of this study was to describe the development of an FEM of the pediatric CCJ based on CT scans of a patient and complete an initial evaluation of the model using the experimental data available from pediatric cadaveric tissue. The knowledge gained from this study has direct clinical applications and will become the gateway through which a variety of spinal disorders may be studied.

Methods

Introduction to FEM

This research utilizes the FEM method, which is a numerical solution technique for discretizing a larger problem³⁹ into smaller pieces comprising finite elements. The FEM method is very powerful and has been widely used in the field of biomechanics to evaluate complex structures, including the adult CCJ.^{1,5,8,11–16,20,21,27,34} Several factors must be considered to apply the FEM method correctly. Spine models include complicated 3D geometry, nonlinear and/or inhomogeneous material properties, and complex boundary and loading conditions. To ensure that predictions from the model are accurate enough for their intended use, appropriate verification and validation methods must be used, including mesh convergence studies (described below) and subsequent evaluations of the model's predictions with the appropriate experimental measurements.

An FEM of the pediatric CCJ was created, and all simulations were run using FEBio open-source software (<http://febio.org/>). The model's anatomical osseous structure was based on a healthy pediatric human patient, and

the material properties of the cartilage and ligaments were assigned using published experimental data, when available. Parameter studies were performed using the model in order to compare the biomechanical responses to changes in ligament stiffness. Details regarding model development and testing are described below.

Patient

After we received approval from the institutional review board, a patient with a radiographically normal cervical spine was selected for this study. The patient was a healthy 13-month-old, 9-kg female who had undergone diagnostic CT angiography for a soft-tissue injury to her neck, which revealed no evidence of bony, ligamentous, or vascular injury.

Surfaces

The initial step in creating an accurate FEM is the generation of surfaces that can then be discretized into finite elements. Volumetric image data were acquired using CT with a field of view encompassing a 240-mm, 512 × 512 acquisition matrix and 0.5-mm slice thickness. Next, each slice of the CT data was segmented (the process of drawing contours around the structures of interest) using a combination of thresholding and manual techniques and Amira (Visage Imaging, Inc.). To ensure accurate surface generation, cross-sectional contours of the bones and cartilage were extracted in the axial, coronal, and sagittal planes. The articular cartilage surfaces of the occiput–C1 and C1–2 joints, which are difficult to distinguish on CT images, were manually segmented with a nearly constant 1-mm thickness. The boundaries of the cartilage were based on the bony landmarks.

To create ligamentous structures appropriate for pediatric FEM, the transverse atlantal ligament (TL) and tectorial membrane (TM) surfaces from a validated adult FEM²¹ were imported into FEBio's preprocessor, PreView (<http://febio.org/>). This step is important because it allowed the scaling and rotation of these critical structures. The TL and TM surfaces were uniformly decreased in size until the ends were approximately aligned with their insertion sites on the pediatric model. The insertions of the TL and TM were then reshaped to better match the bony surfaces of the insertion sites. A closed volume was generated from the segmentations of all surfaces, including bone, articular cartilage, TL, and TM, and the surfaces were smoothed (which removes the artifacts created by manual segmentation). The bony surfaces were converted directly to shell elements and represented as rigid bodies.

Meshing

The surfaces of the articular cartilage, TL, and TM were discretized (i.e., meshed) with tetrahedral finite elements using ANSA (BETA CAE Systems USA, Inc.). To assure FEM accuracy, a sufficient number of finite elements must be used to discretize the surfaces and avoid creating a model that is too "stiff." In other words, if not enough elements are used, the ROMs predicted by the model are less accurate. The original edge length of 0.8 mm was based on the lead analyst's (B.J.E.) experience.

To ensure that our model was sufficiently discretized, a mesh convergence study was conducted, during which the element's edge lengths were reduced from 0.8 mm to 0.3 mm. Decreasing the edge length to 0.3 mm substantially increased the number of elements, but when the model was tested it predicted a change in flexion/extension ROM of only approximately 1%. Thus, the original model with 0.8-mm edge lengths satisfactorily predicted accurate ROMs.

The remaining supportive ligaments, including the alar ligaments, anterior and posterior longitudinal ligaments, anterior and posterior atlantooccipital membranes, anterior and posterior atlantoaxial membranes, apical ligament, and joint capsular ligaments, were represented with tension-only, discrete elements (springs), similar to other adult FEMs.

Material Properties

To match the material representations used for previous adult FEMs, the cartilage, TM, and TL were computationally/mathematically modeled as computationally/mathematically neo-Hookean materials. This type of material representation, using the appropriate coefficients, accurately captures the response of the tissues during material testing and has been used previously for FEMs of the CCJ.^{2,3,5,20,21,31,37} The initial adult material properties used for the articular cartilage, TL, and TM were obtained from published data (Table 1).^{20,21} The initial adult stiffness values assigned to the springs were also taken from a previous study (Table 2).²¹

Boundary and Loading Conditions

Flexion-extension, lateral bending, axial rotation, and axial tension were simulated for this study. For all simulations, the occiput and C-1 were free of all constraints, while C-2 and C-3 were fixed in all degrees of freedom. For flexion-extension, lateral bending, and axial rotation, a torque of 0.1 Nxm was applied to the center of mass of the occiput, and the rotational ROMs were predicted. For axial tension, a vertical axial displacement of 10 mm was applied to the occiput, and the rigid body force on the occiput was predicted. Contact algorithms in FEBio were used to enforce the interfaces between the surfaces of the articulating cartilages, TM, and TL and between the TL and the odontoid. These algorithms use the penalty method for enforcement, thus ensuring that surfaces in contact with each other did not penetrate through one another. All analyses were performed with FEBio, a nonlinear, open-source, FEM software suite.²⁶

TABLE 1. Material properties used in FEM*

Authors & Year	Components	Adult Young's Modulus (MPa)	Model Young's Modulus (MPa)	Poisson's Ratio
Leahy, 2012	TL	8.3–24.7	10	0.4
Leahy, 2012	TM	4.3–12.5	5	0.4
Kumaresan, 2000	Articulating cartilage	10.4	14.9	0.4

* Ranges or finite values are shown.

TABLE 2. Adult ligament stiffness and the scaled values used in the pediatric model

Ligament	Adult Stiffness (N/mm)*	Proportionally Reduced Stiffness (N/mm)		
		50%	25%	10%
Apical	35	17.5	8.75	3.5
Alar	17.8	8.9	4.45	1.78
Anterior atlantooccipital membrane	20	10	5	2
Posterior atlantooccipital membrane	7.3	3.65	1.825	0.73
Anterior longitudinal	38.5	19.25	9.625	3.85
Facet capsule	29.4	14.7	7.35	2.94
Posterior atlantoaxial	4.2	2.1	1.05	0.42

* Adult stiffness values were obtained from the dissertation by Leahy (2012).

Material Parameter Study and Model Evaluation

The material properties of the ligaments of the pediatric CCJ have not been published. Thus, a parametric approach for scaling the ligament properties of the adult cervical spine was implemented to represent the material properties of a child. Given the age of the patient and the senior author's clinical experience, the stiffness of adult ligaments (Table 2) was reduced to 50%, 25%, and 10% of the original adult properties in order to simulate the higher laxity of the pediatric spine. FEM simulations of all loading conditions were created for each reduction in ligament stiffness. The predicted ROMs from the flexion-extension simulations were compared with published ROM data obtained by testing pediatric cadavers.²³ The model with 10% of the adult ligament properties was also evaluated using experimental axial tension data from the CCJ of a 9-year-old cadaveric specimen.²⁴ The predicted ROMs in axial rotation and lateral bending are presented without comparison because of the lack of published pediatric experimental data.

Results

At 10% of adult ligament stiffness, the model predicted a ROM within 1 standard deviation of published pediatric ROM data for flexion-extension (Figs. 1 and 2A).²³ In flexion-extension, the ROM increased from 8.36° with adult ligament properties to 39.72° with 10% of the adult properties. The model with 10% of the adult ligament properties also predicted a force displacement in axial tension that showed good agreement with experimental tensile characterization data (Fig. 2B).²⁴ The structural stiffness of the 10% model, in terms of axial tension, was 150 N/mm. All of the axial rotation simulations illustrated a symmetric ROM (Figs. 1 and 2C). In terms of axial rotation, the ROM increased from 10.42° with adult ligament properties to 26.15° with 10% of the adult properties. The lateral bending simulations also showed a symmetric ROM (Figs. 1 and 2D). In terms of lateral bending, the ROM increased from 2.09° with adult ligament properties to 8.63° with 10% of the adult properties. The models predicted a relatively stiffer ROM in both axial rotation and lateral bending in comparison with flexion-extension (Fig. 2 and Table 3). As expected, the models for each ROM

FIG. 1. Upper: FEM of flexion (A) and extension (B). Center: Left (C) and right (D) axial rotation. Lower: Left (E) and right (F) lateral bending at 10% ligament stiffness.

showed increased laxity with a decrease in ligament stiffness. Video 1 demonstrates the results of the FEM and comparison with the experimental data.

VIDEO 1. Video summary of experimental findings. Copyright University of Utah, Department of Neurosurgery. Published with permission. [Click here to view.](#)

Discussion

We have developed a pediatric craniocervical FEM that accurately predicts flexion-extension ROM and axial force displacement of occiput–C2 when the ligament's material properties are reduced to 10% of the published adult ligament properties. This model gives a reasonable prediction

of pediatric cervical spine ligament stiffness and the relationship between flexion-extension ROM and ligament stiffness at the CCJ.

Previous work has shown that FEM analysis is a useful tool for investigating biomechanical questions that may otherwise be unfeasible for direct laboratory testing. This is especially relevant when investigating the biomechanical properties of the pediatric spinal column. To date, only a few studies have focused on this topic, with the existing research limited primarily by small sample sizes and wide age ranges. Luck et al. published the only experimental data appropriate for evaluating predictions from an FEM of pediatric CCJ.^{23–25} The flexion-extension ROM data from this thesis were first used to evaluate our model.²³ The liga-

FIG. 2. A: Model flexion-extension ROM at varying amounts of ligament stiffness in comparison with that reported by Luck et al.²³ **B:** Model (occiput–C2) tensile response compared with the force-displacement response of the upper cervical spine (occiput–C2) of a 9-year-old specimen. **C:** Model axial rotation ROM at varying ligament stiffness. **D:** Model lateral bending ROM at varying amounts of ligament stiffness.

ment stiffness values in our model were decreased until the model-predicted ROM was within a standard deviation of their experimental measurements. As a second evaluation, we simulated axial tension after decreasing the ligament stiffness to 10% of an adult and then compared our model results with published force-displacement predictions.^{23,24} With a stiffness of 150 N/mm, our model's stiffness was well within the range of 7.1 to 199.0 N/mm measured by Luck et al.,^{23,24} and our model force-displacement response compared very well with the specimen highlighted in Fig. 5 of their 2008 paper.²⁴ Although Luck et al. have provided

the only data available for evaluating an FEM of the pediatric CCJ, the data are not perfect as they are derived from a cadaveric population with a large range of ages and relatively few specimens. In other work, Luck et al. tested stiffness-to-failure at occiput–C2 in 24 human specimens obtained from individuals between the ages of 20 weeks and 24 years.²⁵ This specimen population exhibited an even wider range of stiffness, ranging from 22 ± 7 N/mm for neonates to 504 N/mm for an 18-year-old individual, showing that greater ligamentous laxity occurred at younger ages.

Ouyang et al.²⁸ also tested the biomechanical responses of 10 human whole cervical spine specimens between the ages of 2 and 12 years under tensile loading to failure.²⁸ Their data are not directly comparable because the authors did not isolate and only test the CCJ. It is also harder to interpret smaller torques, but it appears that they reported approximately 10° ROM in flexion/extension for a ± 0.1 Nxm torque applied to a 2-year-old specimen. The flexion-extension ROM predictions from our model were significantly higher than those reported by Ouyang et al., which is not unexpected given the large range of flexion-extension ROMs reported in both experimental studies for

TABLE 3. Model-predicted ROM at 10% of adult ligament stiffness at the applied moment of ± 0.1 Nxm

Simulation	ROM
Flexion	23.5°
Extension	16.4°
Left axial rotation	13.4°
Right axial rotation	12.7°
Left lateral bending	4.15°
Right lateral bending	4.48°

the pediatric population and the large range of stiffness values reported by Luck et al.

The results from our model are corroborated by the only other pediatric FEM reported in the literature.⁶ The model developed by Dong et al.⁶ had a ROM for flexion-extension of 35° to 40°, which is close to the ROM (~40°) of our model.^{18,35} In the current study, we also simulated lateral bending and axial rotation. Although there are currently no experimental or computational results to evaluate those predictions, we do have some confidence in them because they are symmetric and reasonable in comparison with the differences seen between pediatric and adult flexion-extension ROMs.

In light of previous research and in order to improve the understanding of the biomechanical properties of the pediatric CCJ, our work focused on creating a validated FEM using open-source software that can be widely disseminated for collaborative research. It is well known that a robust FEM can evaluate the role of material properties, perform parameter studies, and determine responses to physiological loads. It is also known that FEMs have been developed for the adult CCJ,^{5,32,33,38} but unfortunately they cannot be generalized to the pediatric population. Similarly, the problems investigated by adult FEMs, such as odontoid fractures, rheumatoid arthritis, and the effects of posterior instrumentation, are not commonly demonstrated in children.^{5,32,33,38}

The pediatric CCJ differs from the adult CCJ in many important ways. Greater ligamentous laxity, different joint angles and relationships, a greater ratio of head mass to body size, and the presence of immature cartilage all play a part in differentiating the pediatric CCJ from its adult counterpart. All of these differences must be taken into account when creating a pediatric spinal FEM.²⁰ To the best of our knowledge, only 1 previous study managed to successfully do this,⁶ but the study targeted the subaxial cervical spine and its response to motor vehicle accidents and therefore was not applicable to our work.⁶

Future studies will involve comparisons between the adult and pediatric CCJ geometry and its effects on segmental ROM when the material properties are the same. This will shed light on the relationship between anatomical geometry and its resulting impact on ROM. We also aim to identify the specific underlying ligamentous injuries present in atlantooccipital dislocation. This area has not been adequately studied using either experimental or computational methods, and, at this point, it is not precisely known which craniocervical ligamentous structures must be injured to create significant CCJ instability. These questions may be addressed using FEM.

We recognize that there are limitations to our study. The primary limitation is the use of linear discrete elements to represent most of the ligaments in the model. The stress-strain response of adult cervical spine ligaments is nonlinear, and the original linear stiffness used for our “adult” model was derived from nonlinear force-displacement curves.²¹ It is also very likely that the ligaments of the pediatric CCJ exhibit a nonlinear stress-strain response. That said, the material properties of the ligaments of the pediatric CCJ have not been published, and this method of using linear springs provides the first estimate of pediatric

CCJ ligament stiffness compared with that of adults. The use of nonlinear springs would not have produced such a clear estimate of the increased laxity in the pediatric population. Another limitation of this study is that only 1 model was constructed based on the bony anatomy of 1 patient. It is likely that ligament stiffness, bone structure, and the contacting cartilage surfaces affect the resulting ROMs. It is possible that another patient’s bone and cartilage structures could have demonstrated different predicted ROMs as the ligament stiffness decreased, but we believe these changes would be minor in comparison with the effects of the decreased ligament stiffness. The role of the bone and cartilage structures on CCJ mechanics will be investigated in future studies. It should also be noted that it is typical to report the results from a single model because of the time and expense needed to create accurate FEMs of the spine.^{6,7,21,33,38}

Conclusions

An FEM of the normal pediatric CCJ has been created that accurately predicts ROM in both flexion-extension and axial force displacement when the published adult material properties were reduced to 10% of their original values. This provides a reasonable prediction of how flexion-extension ROM increases with reduced cervical spine ligament stiffness in the pediatric population. By using open-source software, we hope that other researchers may benefit from our work.

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Disclosures

The authors report no conflict of interest concerning the materials or methods used in this study or the findings specified in this paper.

Supplemental Information

Videos

Video 1. <https://vimeo.com/146907592>.

Author Contributions

Conception and design: Brockmeyer, Mazur, Ellis. Acquisition of data: Phuntsok, Mazur, Ravindra. Analysis and interpretation of data: all authors. Drafting the article: Brockmeyer, Phuntsok, Mazur, Ellis. Critically revising the article: Brockmeyer, Ellis. Reviewed submitted version of manuscript: all authors. Approved the final version of the manuscript on behalf of all authors: Brockmeyer. Study supervision: Brockmeyer, Ellis.

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