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

Rinchen Phuntsok, BS,1 Marcus D. Mazur, MD,2 Benjamin J. Ellis, PhD,1 Vijay M. Ravindra, MD, MSPH,2 and Douglas L. Brockmeyer, MD2

1Department of Bioengineering and Scientific Computing and Imaging Institute, University of Utah; and 2Department of Neurosurgery, Division of Pediatric Neurosurgery, University of Utah, Primary Children’s Hospital, Salt Lake City, Utah

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.

http://thejns.org/doi/abs/10.3171/2015.8.PEDS15334

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
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 and a few cadaveric studies.

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. 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. Luck et al. reported both flexion-extension range of motion (ROM) data and axial tension structural stiffness data for cadaveric pediatric cervical spine tissue. 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. 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 problem 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. 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 x 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 FEM 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 atlantoaxial membranes, anterior and posterior atlantooccipital 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 N⋅mm 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 a 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.\(^26\)

### 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

### Table 1. Material properties used in FEM

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Components</th>
<th>Adult Young's Modulus (MPa)</th>
<th>Model Young’s Modulus (MPa)</th>
<th>Poisson’s Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leahy, 2012</td>
<td>TL</td>
<td>8.3–24.7</td>
<td>10</td>
<td>0.4</td>
</tr>
<tr>
<td>Leahy, 2012</td>
<td>TM</td>
<td>4.3–12.5</td>
<td>5</td>
<td>0.4</td>
</tr>
<tr>
<td>Kumaresan, 2000</td>
<td>Articulating cartilage</td>
<td>10.4</td>
<td>14.9</td>
<td>0.4</td>
</tr>
</tbody>
</table>

* Ranges or finite values are shown.

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

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

* Adult stiffness values were obtained from the dissertation by Leahy (2012).
showed increased laxity with a decrease in ligament stiffness. Video 1 demonstrates the results of the FEM and comparison with the experimental data.

**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. The flexion-extension ROM data from this thesis were first used to evaluate our model. The liga-
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. 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., and our model force-displacement response compared very well with the specimen highlighted in Fig. 5 of their 2008 paper. 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. 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. tested the biomechanical responses of 10 human whole cervical spine specimens between the ages of 2 and 12 years under tensile loading to failure. 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 N·m 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 N·m

<table>
<thead>
<tr>
<th>Simulation</th>
<th>ROM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexion</td>
<td>23.5°</td>
</tr>
<tr>
<td>Extension</td>
<td>16.4°</td>
</tr>
<tr>
<td>Left axial rotation</td>
<td>13.4°</td>
</tr>
<tr>
<td>Right axial rotation</td>
<td>12.7°</td>
</tr>
<tr>
<td>Left lateral bending</td>
<td>4.15°</td>
</tr>
<tr>
<td>Right lateral bending</td>
<td>4.48°</td>
</tr>
</tbody>
</table>
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. The model developed by Dong et al. had a ROM for flexion-extension of 35° to 40°, which is close to the ROM (~ 40°) of our model. 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 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.

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. To the best of our knowledge, only 1 previous study managed to successfully do this, but the study targeted the subaxial cervical spine and its response to motor vehicle accidents and therefore was not applicable to our work.

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 craniovertebral 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. 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.

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.

Acknowledgments

We thank Kristin Kraus, MSc, for editorial assistance with this paper and Vance Mortimer for his assistance with the preparation of the accompanying video.

References

alytical diagnostics of the rotary instability of upper cervical
spine. 1. An experimental study on cadavers. Spine (Phila Pa
10. Dvorak J, Schneider E, Saldinger P, Rahn B: Biomechanics of the
cranio cervical region: the alar and transverse ligaments. J
Orthop Res 6:452–461, 1988
11. Elkins JM, Stroud NJ, Rudert MJ, Tochigi Y, Pedersen DR,
Ellis BJ, et al: The capsule’s contribution to total hip con-
stuct stability—a finite element analysis. J Orthop Res
29:1642–1648, 2011
12. Ellis BJ, Debski RE, Moore SM, McMahon PJ, Weiss JA;
Methodological and sensitivity studies for finite element mod-
ing of the inferior glenohumeral ligament complex. J Bio-
mech 40:603–612, 2007
13. Ellis BJ, Drury NJ, Moore SM, McMahon PJ, Weiss JA, Deb-
ski RE: Finite element modelling of the glenohumeral cap-
sule can help assess the tested region during a clinical exam.
14. Ellis BJ, Lujan TJ, Dalton MS, Weiss JA: Medial collateral
ligament insertion site and contact forces in the ACL-defi-
15. Henak CR, Abraham CL, Anderson AE, Maas SA, Ellis BJ,
Peters CL, et al: Patient-specific analysis of cartilage and
labrum mechanics in human hips with acetabular dysplasia.
16. Henak CR, Kapron AL, Anderson AE, Ellis BJ, Maas SA,
Weiss JA: Specimen-specific predictions of contact stress under
physiological loading in the human hip: validation and sensi-
400, 2014
17. Hurlbert RJ, Crawford NR, Choi WG, Dickman CA: A bio-
mechanical evaluation of occipitocervical instrumentation: screw
compared with wire fixation. J Neurosurg 90 (1 Supp):
84–90, 1999
18. Kallieris D, Barz J, Schmidt G, Heess G, Tzochi Y, Pedersen DR,
Ellis BJ, et al: The capsule’s contribution to total hip con-
stuct stability—a finite element analysis. J Orthop Res
29:1642–1648, 2011
the cervical spine and pediatric PMHS osteoligamentous cervical
spine. 1. An experimental study on cadavers. Spine (Phila Pa
20. Kumaresan S, Yoganandan N, Pintar FA, Maiman DJ, Kuppa
S: Biomechanical study of pediatric human cervical spine: a
21. Leahy PD: Assessment of the Effects of Ligamentous
Injury in the Human Cervical Spine [PhD dissertation].
Fort Collins, CO: Colorado State University, 2012
22. Leahy PD, Puttlitz CM: The effects of ligamentous injury in
the human lower cervical spine. J Biomech 45:2668–2672,
2012
23. Luck JF: The Biomechanics of the Perinatal, Neonatal
and Pediatric Cervical Spine: Investigation of the Tensile,
Bending and Viscoelastic Response [PhD Dissertation].
Durham, NC: Duke University, 2012
24. Luck JF, Nightingale RW, Loyd AM, Prange MT, Dobb AT,
Song Y, et al: Tensile mechanical properties of the perinatal
and pediatric PMHS osteoligamentous cervical spine. Stapp
25. Luck JF, Nightingale RW, Song Y, Kair JT, Loyd AM, Myers
BS, et al: Tensile failure properties of the perinatal, neonatal,
and pediatric cadaveric cervical spine. Spine (Phila Pa
26. Maas SA, Ellis BJ, Ateshian GA, Weiss JA: FEbio: finite ele-
G: Muscle connective tissue controls development of the dia-
phragm and is a source of congenital diaphragmatic hernias.
Nat Genet 47:496–504, 2015
mechanical assessment of the pediatric cervical spine
under bending and tensile loading. Spine (Phila Pa 1976)
30:E716–E723, 2005
29. Pang D, Li V: Atlantoaxial rotatory fixation: Part 1—Biome-
chanics of normal rotation at the atlantoaxial joint in chil-
30. Pang D, Nemzek WR, Zovickian J: Atlanto-occipital disloca-
tion: part 1—normal occipital condyle-CI interval in 89 chil-
31. Panjabi MM, Crisco JJ III, Lydon C, Dvorak J: The mechanici-
properties of human alar and transverse ligaments at slow and
fast extension rates. Clin Biomech (Bristol, Avon)
13:112–120, 1998
32. Puttlitz CM, Goel VK, Clark CR, Traylor VS, Scifert JL,
Grosland NM: Biomechanical rationale for the pathology of
rheumatoid arthritis in the craniovertebral junction. Spine
33. Puttlitz CM, Goel VK, Traylor VS, Clark CR: A finite ele-
ment investigation of upper cervical instrumentation. Spine
34. Reese SP, Ellis BJ, Weiss JA: Micromechanical model of a
surrogate for collagenous soft tissues: development, valida-
tion and analysis of mesoscale size effects. Biomech Model
Mechanobiol 12:1195–1204, 2013
35. Wismans J, Maitla J, Melvin J, Stallnam R: Child Restraint
Evaluation by Experimental and Mathematical Simula-
tion. SAE Technical Paper 791017. Warrendale, PA: SAE
International, 1979
modeling of kinematic and load transmission alterations due
to cervical intervertebral disc replacement. Spine (Phila Pa
37. Yoganandan N, Kumaresan S, Pintar FA: Biomechanics of the
cervical spine part 2. Cervical spine soft tissue responses
and biomechanical modeling. Clin Biomech (Bristol, Avon)
16:1–27, 2001
38. Zhang H, Bai J: Development and validation of a finite ele-
ment model of the occipito-atlantoaxial complex under physi-
39. Zienkiewicz OC, Taylor RL: The Finite Element Method,
Volume 1: Basic Formulation and Linear Problems. Lon-

Disclosures
The authors report no conflict of interest concerning the materi-
als or methods used in this study or the findings specified in this
paper.

Supplemental Information

Videos

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.

Correspondence
Douglas Brockmeyer, Department of Neurosurgery, Division of
Pediatric Neurosurgery, University of Utah, Primary Children’s
Hospital, 100 Mario Capecchi Dr., Salt Lake City, UT 84113.
email: douglas.brockmeyer@hsc.utah.edu.