Which Geometric Variations in the Cervical Spine influence Vertebral Rotations under Combined Loading?

Jobin D. John, Gurunathan Saravana Kumar, Mike W J. Arun, Narayan Yoganandan

Abstract Non-physiological loadings on the cervical spine usually act in a combination of moment, axial and shear forces. Geometric variations can influence the responses of a spine segment. This study used a parametric cervical spine segment (C5-C6) to study the influence of geometric variations. Fifty finite element models with variations in disc height, facet angle, facet height, antero-posterior vertebral depth, uncinate processes slope and segment size were generated. The influence of these geometric parameters on vertebral rotation in flexion-compression, flexion-distraction, extension-compression, extension-distraction coupled with anterior/posterior shear was investigated. Sixteen load-cases on the fifty parametric models were simulated for response-surface based sensitivity analysis of the geometric parameters. The variation due to the geometric parameters were on an average 30% of mean vertebral rotation in each load case. The sensitivity analysis showed that disc height, vertebral depth and segmental size influence the vertebral rotation in most loading cases. This may have implications in gender-based variations observed in inertial loading scenarios. Vertebral depth and size are gender-dependent, female dimensions being smaller compared to males. The influential geometric variations identified in this study will be implemented in whole cervical spine parametric model for detailed analysis.

Keywords cervical spine, combined loading, finite element analysis, sensitivity analysis, vertebral morphology

I. INTRODUCTION

A combined loading of moments, axial force and shear force act on cervical spine segments under most inertial loading scenarios. For instance, a combination of extension moment, axial compressive force and posterior shear force act in the lower cervical spine during rear impact whiplash, while it would be a combination of flexion moment and axial distractive force during a frontal crash. Similarly, various sports and military inertial and contact loading scenarios result in flexion/extension loading coupled with the axial compression of the segments [1-2].

Geometric variations in the cervical spine are reported in literature from dissection and radiographic studies. These variations include that of disc height [3], facet joints [4–7], and vertebral dimensions [8–10]. Some of these, such as vertebral depth and size are shown to be gender dependent, while few others such as facet slope has been shown to be age dependent [8]. With very limited experimental data available on the influence of these geometric variations on spinal responses, finite element (FE) modelling is a useful approach to study such variations. Laville et al. used a parametric FE model of the cervical spine to show the influence of geometry on moment-rotation characteristic of motion segments [11]. Parametric FE models were also used to show that facet joint influence coupled motion especially in lateral bending [12]. These parametric models were used mainly for clinical studies, simulating low-magnitude moment loads. Experiments performed by Przybyla et al. reported that bending strength and compressive of male cervical motion segments were more than that of female segments [13]. Variations in motion between male and female cervical spine segments in whiplash motion were reported by Stemper et al., with female segments exhibiting more flexibility [14].

FE analysis has been widely used to construct models that predict responses of the human body under non-physiological loading conditions [15]. FE models of the cervical spine with deformable bone tissues, hyperelastic intervertebral disc and non-linear rate dependent ligaments have been used in isolated head-neck and integrated human body studies under various inertial loading conditions [16–18]. All these studies, however,

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used a single representative geometry and hence did not study the influence of geometry variations of the cervical spine. The objective of this study was to use parametric FE models of cervical spine to investigate the influence of above mentioned geometric variations on the relative rotation between two adjacent vertebrae under the influence of various cases of combined loading. Vertebral rotation is an output measure used in experiments (both post-mortem human subjects(PMHS) [14,19] and volunteers [20]) to evaluate the influence of inertial loads on cervical spine motion segments as it gives an overall indication of the deformation that constituent spinal components like facet joint capsules, annulus fibres and ligaments undergo.

II. METHODS

Finite Element Model of Cervical Spine Segment

A non-linear validated FE model of the cervical spine constructed using hexahedral/quadrilateral mesh was used in this study [15-16]. The model consisted of C5 and C6 vertebrae, and the intervening soft tissues. The cortical and cancellous bones were defined using linear elastic definitions with E=16.8 GPa and E= 400 MPa respectively. The disc annulus ground material was defined using Hill-foam strain energy function (C_1=0.115 MPa, C_2=2.101 MPa, C_3=-0.893 MPa, b_1= 4, b_2= -1, b_3= -2) and the annulus fibres were defined using non-linear orthotropic elastic definition. The disc nucleus was defined as viscoelastic solid (G_0=17.8 kPa, G_1=7.1kPa, β=1.0/s, K =1720 MPa). The spine ligaments were defined using orthotropic non-linear elastic definitions on membrane elements with no resistance to compressive forces. Non-linear force-displacements relationships reported for low and high rate loading reported by Mattucci et al. 2015 was used for ligament definitions [23]. The model was validated separately in flexion, extension, compression, distraction, anterior and posterior shear [24]

The relative rotation of one vertebra with respect to other was measured from the simulations. This was obtained by measuring the change in Cobb angle (angle between the intervertebral disc endplates about the sagittal plane). An axis system based on C5 vertebra orientation was used to define the forces and moments. Posterior-anterior direction was defined as the positive x-axis, superior-inferior direction was defined as the z-axis, and y-axis as the normal to these axes.

Geometry Parameterisation and Sensitivity Analysis

Variations in vertebral geometry reported in literature were implemented using mesh morphing method. A mapping-block based mesh morphing was used to parameterise the geometry of the vertebrae and intervening soft tissues. In this method, the FE mesh of the spine segment was encapsulated in hexahedral mapping-blocks. Changes in shape of the vertebral components were achieved using transformations of the shape of mapping-blocks, which in turn controlled the shape of the FE mesh contained with the respective mapping-blocks [25-26]. The variations studied in this paper were: disc height variations of 0.8 mm [3], facet articular processes height variation of 2 mm and facet angle variation of 10° [4,5,27], uncinate slope variation of 5° [28], vertebral antero-posterior depth variation of 1.5 mm [10] and the size variation of ±5% in the whole segment (Figure 1). Latin-Hypercube sampling of the geometric variations was used as the experimental design to generate 50 models with geometric variations mentioned above. A global sensitivity analysis of these variations was performed on response surfaces constructed for the different loading cases described below. Response surfaces were constructed using quadratic polynomial functions. Variance-based Sobol's indices were used to evaluate on the polynomial response surface the influence of the geometric variations [29]. Influential geometric parameters were identified by the percentage contribution with respect to total variation in the output (i.e. vertebral rotation).

Combined Load Cases

Four combinations of moment-axial force were considered: Flexion-Compression, Flexion-Distraction, Extension-Compression, Extension-Distraction. The magnitude of the moment was 5Nm and axial force was 300N. For each of the moment-axial force combinations, two directions of shear load- anterior and posterior- were considered. Shear forces were considered at two load levels: 300N and 150N. These load combinations resulted in a total of 16 load cases. All the three loads (moment, axial force, and shear force) were linearly ramped to maximum magnitude and applied simultaneously over 50 ms on the inferior endplate of C5 vertebra. Fixed boundary condition was applied on the lower nodes of the C6 vertebra. FE solver LS-DYNA R8.1.0 (LSTC) was used to run 800 simulations in total (16 load cases x 50 parametric models).

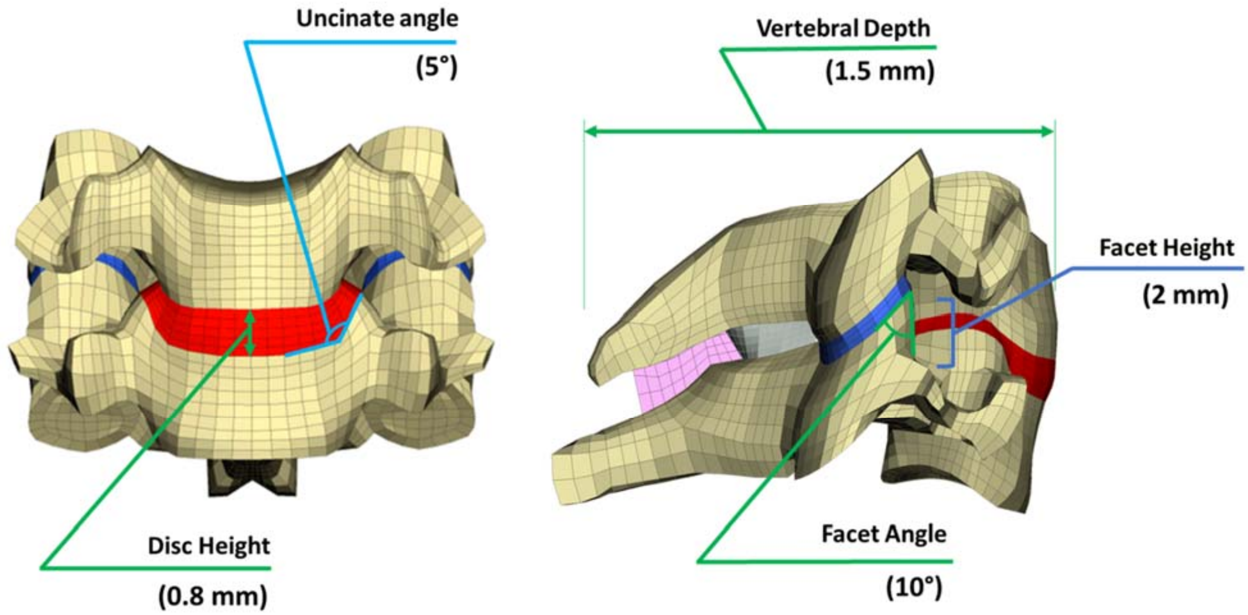

Fig 1: Finite element model of the cervical spine segment (C5-C6) used in this study is shown. The cervical spine geometries parameters are labelled, with their range of variation shown in parenthesis. In addition, the size of the segment was varied by ±5%.

III. RESULTS

The stiffnesses of the model compared to experiments were as follows (experimental range from Shea et al. [24] given in parentheses): Flexion 0.64 Nm/° (1.13±0.68 Nm/°), Extension 0.76 Nm/° (1.88±1.18 Nm/°), Compression 751 N/mm (718±48 N/mm), Distraction 477 N/mm (433±54 N/mm), Anterior Shear 223 N/mm (183±47 N/mm), Posterior Shear 181 N/mm (162±22 N/mm). The mean vertebral rotation for the various cases of combined loading and their range of variation due to geometrical variations is given in Figure 2. The contribution of each geometric variation to change in vertebral rotation is given in Figure 3, in terms of Sobol's sensitivity indices (expressed in percentage). Slope of the uncinate process had a negligible contribution in all cases, and hence not shown in the plots. The percentage variation in vertebral rotation due to the variation in geometric variation was on an average 30% (Figure 2(b)). The highest percentage variation was seen in extension compression with an anterior shear of 300N. In flexion, compressive force produced more vertebral rotation compared to distractive force. In extension, however, no similar trend was observed. Anterior shear increased vertebral rotation in flexion, while reducing the rotation in extension. The converse was observed for posterior shear.

Flexion-Compression

In the presence of compressive force, the vertebral flexion rotation varied between 6.1° and 8.9° in posterior shear, while it varied between 7.4° and 9.7° in anterior shear. The magnitude of shear force influenced the range of variation when it was in the posterior direction, while it did not have an influence when it was in the anterior direction. In this loading mode, disc height was the most sensitive geometric variation; followed by equal influence by vertebral size and depth variations.

Flexion-Distraction

In the presence of axial distraction force, the vertebral flexion rotation varied between 4.4° and 7.2° in posterior shear, with greater posterior shear resulting in lesser vertebral rotation. In anterior shear, the vertebral rotation varied between 8.4° and 6.2° and did not depend on the magnitude of shear force. In flexion-distraction, the sensitive geometric variation was size followed by disc height and vertebral depth.

Extension-Compression

In extension coupled with compressive force, the vertebral rotation varied between 6.8° and 8.8° in posterior shear. Anterior shear resulted in less vertebral rotation varying in between 3.0° and 6.9°. The magnitude of shear influenced the vertebral rotation in anterior shear more than posterior shear. In this loading mode, the contribution of geometric variations to vertebral rotation variation was highly dependent on the direction and magnitude of shear force. Variations in the vertebral rotation were highly dependent on facet angle in the presence of anterior shear, especially at higher magnitude of 300N.

Extension-Distraction

The extension vertebral rotation in the presence of distractive forces was similar to that with compressive forces. The rotation varied between 7.0° and 9.1° in posterior shear and 3.0° and 6.5°. Anterior shear resulted in less vertebral rotation compared to posterior shear. The magnitude of shear influenced the vertebral rotation in anterior shear more than posterior shear. Anterior shear force resulted in facet joint variations (angle and height) contributing significantly to variations in vertebral rotation.

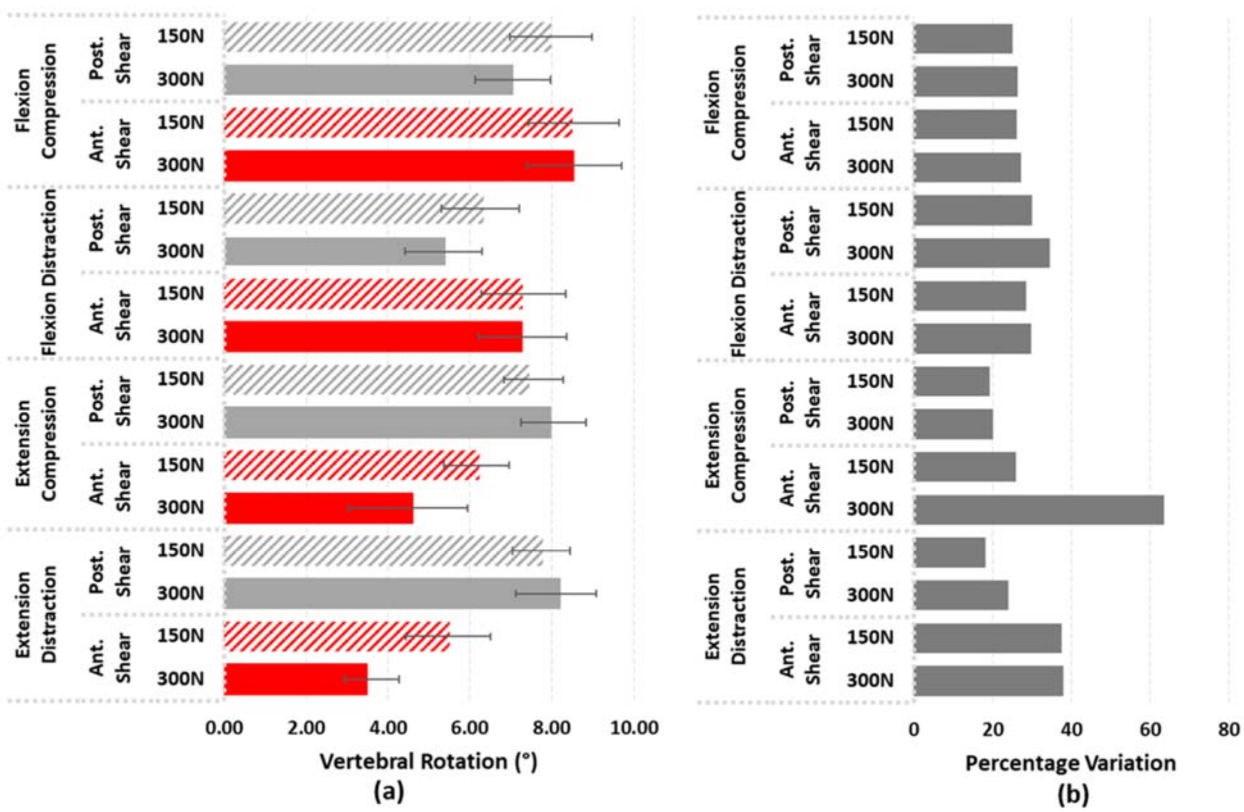

Figure 2: (a) The mean of vertebral rotation in each loading case is shown in degrees. The error bars indicate the range of variation in vertebral rotation in each case. (b) The percentage of variation in vertebral rotation due to geometric variations for the respective loading cases.

IV. Discussion

Vertebral rotation is a commonly measured output from volunteer and post-mortem human subject experiments [14,19,20]. These studies used visual markers to record position and orientation of vertebrae. In this study the relative rotation of straight lines on respective vertebral endplate about the sagittal plane was used as the vertebral rotation. The influence of geometric variations on vertebral rotation under various combinations of moment, axial force and shear force was investigated in this study. The magnitudes of the loads correspond to low change-in-velocity inertial loadings of the lower cervical spine reported from PMHS and volunteer studies [30–32]. The loads in these studies ramp up approximately in 50 ms. This time scale was used in this study to apply loads. Two magnitude levels of shear forces were selected in this study as shear forces was seen to influence vertebral rotation more than axial force in our preliminary studies [33].

In contrast to the traditional methods of using a model of single geometry, this study used several models with a range of variations in the geometrical features of the cervical spine. Latin Hypercube sampling was used to obtain a uniform and random distribution of parameter values across their range of variations [34]. This uniformly distributed experimental design also captures interaction between the parameters and aids in generation of accurate response surfaces for sensitivity analyses. The responses are not expected to be effected by the mesh shape changes due to morphing as the mesh quality deterioration was shown to be negligible on this model in our previous study [25]. As the focus of this study was geometric variations, the material and element definitions similar to widely used recent human body models was used in this study to ensure that the responses can be compared with these models [12-13].

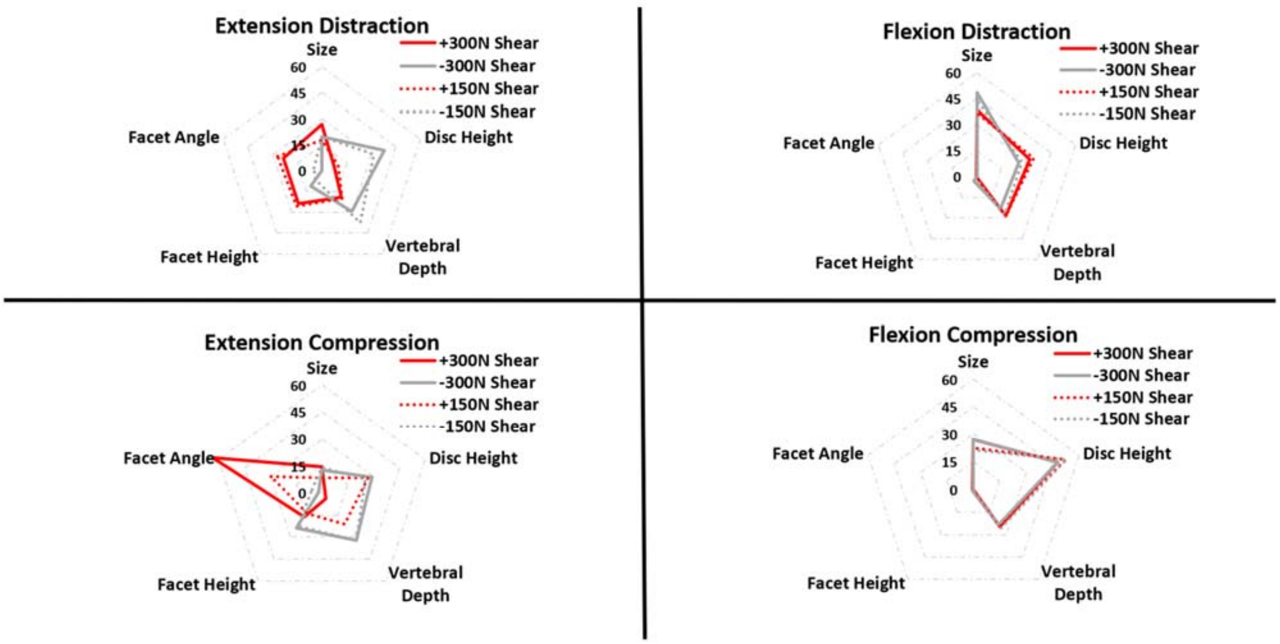

Figure 3: Influence of each geometric variation in the sensitivity analysis towards the change in vertebral rotation, given in terms of percentage influence with respect to total variation of vertebral rotation in each loading case.

PMHS experiments by Deng et al. reported vertebral rotation of 9°±4° under low velocity whiplash loading, while Stemper et al. reported vertebral rotation of 6°±3° for low velocity whiplash experiments with head-neck complexes [14,19]. The vertebral rotations in simulations were similar to these experiments. These magnitudes of vertebral rotations for low velocity loading do not usually cause injuries, though minor soft tissue injuries can be expected at higher magnitudes of vertebral rotation as reported by Deng et al. The change in vertebral rotation due to geometrical variations depended on the type of loading (Figure 3). Variation in vertebral depth, disc height and segment size influenced the vertebral rotation in most loading cases. Variation in facet geometries influenced the vertebral rotation more in the extension cases, as the facet joints have a limited load bearing role in flexion. Antero-posterior depth being a gender dependent metric [8,10], this study shows that the vertebral rotation of the female cervical spine can be expected to be different from the male cervical spine in most combined loading cases.

Although this study looked at combined loading cases, this model was validated separately for the different loading modes for lack of experimental data in segmental combined loading cases. The next step would be to parameterise a whole cervical spine column with the influential geometric variations identified in this study. As whole cervical spine models take substantially more time to run compared to segmental models, implementing only the influential variations identified in this study will reduce the number of simulations required for whole neck sensitivity analysis. Such studies would be imperative in the development of personalized FE models [35]. Studies such as these would also be useful to characterise FE models for gender and age variations, increasing the utility of virtual human body models in crash and injury assessment programmes. Sensitivity studies will be instrumental to identify which variations observed in the human population are influential and to reduce the uncertainty in simulation outputs that arise from these variations.

V. CONCLUSIONS

This study showed the influence of geometric variations in the cervical spine towards vertebral rotations under combined loading. The geometric variations considered in this study resulted in an average of 30% variation in vertebral rotation. Among the geometric variations considered in this study, disc height, antero-posterior vertebral body depth and segment size influence vertebral rotations in combined loading.

VI. ACKNOWLEDGEMENT

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VII. REFERENCES

[1] Yoganandan N., Yoganandan N., Nahum AM. (2015) Accidental Injury. Springer New York

[2] Schmitt K-U., Niederer PF., Cronin DS., Muser MH., Walz F. (2014) Trauma Biomechanics. Springer Berlin Heidelberg;

[3] Gilad I., Nissan M. (1986) A Study of Vertebra and Disc Geometric Relations of the Human Cervical and Lumbar Spine. *Spine,* 11(2), 154–157.

[4] Nowitzke A., Westaway M., Bogduk N. (1994) Cervical zygapophyseal joints: Geometrical parameters and relationship to cervical kinematics. *Clinical Biomechanics,* 9(6), 342–348.

[5] Milne N. (1991) The role of zygapophysial joint orientation and uncinate processes in controlling motion in the cervical spine. *Journal of anatomy,* 178, 189–201.

[6] Panjabi MM., Oxland T., Takata K., Goel V., Duranceau J., Krag M. (1993) Articular facets of the human spine. Quantitative three-dimensional anatomy. *Spine,* 18(10), 1298–1310.

[7] Parenteau CS., Zuby D., Brolin KB., Svensson MY., Palmertz C., Wang SC. (2013) Restrained male and female occupants in frontal crashes: Are we different? In: 2013 IRCOBI Conference Proceedings - International Research Council on the Biomechanics of Injury. 2013. p. 803–817.

[8] Parenteau CS., Wang NC., Zhang P., Caird MS., Wang SC. (2014) Quantification of pediatric and adult cervical vertebra-anatomical characteristics by age and gender for automotive application. *Traffic injury prevention,* 15(6), 572–582.

[9] Stemper BD., Yoganandan N., et al. (2008) Anatomical gender differences in cervical vertebrae of size-matched volunteers. *Spine,* 33(2), 44–49.

[10] Vasavada AN., Danaraj J., Siegmund GP. (2008) Head and neck anthropometry, vertebral geometry and neck strength in height-matched men and women. *Journal of Biomechanics,* 41(1), 114–121.

[11] Laville A., Laporte S., Skalli W. (2009) Parametric and subject-specific finite element modelling of the lower cervical spine. Influence of geometrical parameters on the motion patterns. *Journal of biomechanics,* 42(10), 1409–1415.

[12] Maurel N., Lavaste F., Skalli W. (1997) A three-dimensional parameterized finite element model of the lower cervical spine, study of the influence of the posterior articular facets. *Journal of Biomechanics,* 30(9), 921–931.

[13] Przybyla AS., Skrzypiec D., Pollintine P., Dolan P., Adams MA. (2007) Strength of the cervical spine in compression and bending. *Spine,* 32(15), 1612–1620.

[14] Stemper BD., Yoganandan N., Pintar FA. (2003) Gender dependent cervical spine segmental kinematics during whiplash. *Journal of biomechanics,* 36(9), 1281–1289.

[15] Yang KH., Hu J., White NA., King AI., Chou CC., Prasad P. (2006) Development of numerical models for injury biomechanics research: a review of 50 years of publications in the Stapp Car Crash Conference. *Stapp Car Crash Journal,* 50(November), 429–490.

[16] Panzer MB., Fice JB., Cronin DS. (2011) Cervical spine response in frontal crash. *Medical Engineering and Physics,* 33(9), 1147–1159.

[17] Östh J., Mendoza-Vazquez M., Sato F., Svensson MY., Linder A., Brolin K. (2017) A female head–neck model for rear impact simulations. *Journal of Biomechanics,* 51, 49–56.

[18] White NA., Moreno DP., Gayzik FS., Stitzel JD. (2015) Cross-sectional neck response of a total human body FE model during simulated frontal and side automobile impacts. *Computer Methods in Biomechanics and Biomedical Engineering,* 18(3), 293–315.

[19] Deng B., Begeman PC., Yang KH., Tashman S., King AI. (2000) Kinematics of human cadaver cervical spine

during low speed rear-end impacts. *Stapp car crash journal,* 44, 171–188.

[20] Kaneoka K., Ono K., Inami S., Hayashi K. (1999) Motion analysis of cervical vertebrae during whiplash loading. *Spine*24(8), 763–9; discussion 770.

[21] John JD., Arun MWJ., Saravanakumar G., Yoganandan N. (2017) Cervical spine finite element model with anatomically accurate asymmetric intervertebral discs. In: Summer Biomechanics, Bioengineering, and Biotransport Conference. 2017.

[22] John JD., Arun MWJ., Yoganandan N., Saravana Kumar G., Kurpad SN. (2017) Mapping block-based morphing for subject-specific spine finite element models. In: 54th Annual Rocky Mountain Bioengineering Symposium. Denver, Colorado: 2017.

[23] Mattucci SFE., Cronin DS. (2015) A method to characterize average cervical spine ligament response based on raw data sets for implementation into injury biomechanics models. *Journal of the Mechanical Behavior of Biomedical Materials,* 41, 251–260.

[24] Shea M., Edwards WTT., White AAA., Hayes WCC. (1991) Variations of stiffness and strength along the human cervical spine. *Journal of Biomechanics,* 24(2), 95–107.

[25] John JD., Yoganandan N., Arun MWJ., Saravana Kumar G. (2018) Influence of morphological variations on cervical spine segmental responses from inertial loading. *Traffic Injury Prevention,* 19(sup1), S29–S36.

[26] Baldwin MA., Langenderfer JE., Rullkoetter PJ., Laz PJ. (2010) Development of subject-specific and statistical shape models of the knee using an efficient segmentation and mesh-morphing approach. *Computer Methods and Programs in Biomedicine,* 97(3), 232–240.

[27] Penning L. (1988) Differences in anatomy, motion, development and aging of the upper and lower cervical disk segments. *Clinical Biomechanics,* 3(1), 37–47.

[28] Panjabi MM., Duranceau J., Goel V., Oxland T., Takata K. (1991) Cervical human vertebrae. Quantitative three-dimensional anatomy of the middle and lower regions. *Spine,* 16(8), 861–869.

[29] Sobol IM., Kucherenko SS. (2005) Global sensitivity indices for nonlinear mathematical models. Review. *Wilmott,* 2005(1), 56–61.

[30] Pintar FA., Yoganandan N., Maiman DJ. (2010) Lower cervical spine loading in frontal sled tests using inverse dynamics: potential applications for lower neck injury criteria. *Stapp Car Crash Journal,* 54(10), 133.

[31] Ono K., Kaneoka K., Wittek A., Kajzer J. (1997) Cervical Injury Mechanism Based on the Analysis of Human Cervical Vertebral Motion and Head-Neck-Torso Kinematics During Low Speed Rear Impacts. In: Stapp car crash journal. SAE; Lake Buena Vista, FL, USA: 1997. p. 339–356.

[32] Beeman SM., Kemper AR., Duma SM. (2016) Neck forces and moments of human volunteers and post mortem human surrogates in low-speed frontal sled tests. *Traffic Injury Prevention,* 17(S1), 141–149.

[33] John JD., Yoganandan N., Arun MWJ., Saravana Kumar G. (2018) Contributioni of Forces and Morphology to Segmental Rotation during Combined loading of cervical spine: Investigation using parametric Finite Element Models. In: IRCOBI Asia 2018. Lonavala: 2018. p. 72–75.

[34] Kleijnen JPC. (2005) An overview of the design and analysis of simulation experiments for sensitivity analysis. *European Journal of Operational Research,* 164(2), 287–300.

[35] Chen H., Poulard D., Forman J., Crandall J., Panzer MB. (2018) Evaluation of Geometrically Personalized THUMS Pedestrian Model Response against Sedan-Pedestrian PMHS Impact Test Data. *Traffic Injury Prevention,* , 1–27.