# Human Body Model Cervical Spine Curvature Effect in Extracted Motion Segment Model in Tension, Extension, and Flexion

M. A. Corrales[1], D. S. Cronin[1]

[1]University of Waterloo

## ABSTRACT

*Cervical spine curvature varies between subjects, and can vary within a subject towards increased lordosis with increasing age. Understanding the effect of cervical spine curvature is important to assess injury risk in impact scenarios for the aging population. In the present study the GHBMC 50th percentile occupant male neck model was morphed into 3 different postures; 75 YO 50th percentile with average lordosis, 26 YO with superior and inferior Bézier angles reduced by 5 degrees, and 75 YO with superior and inferior Bézier angles increased by 5 degrees, representing a range of cervical spine curvatures. The C4-C5 motion segment in the modified postures was extracted and evaluated under flexion, extension and tension loading scenarios. No significant changes in kinetics and kinematics were identified for tension and flexion loading. However, significant changes were observed in the kinetic and kinematic response for extension loading at the larger and smaller spine curvatures, with similar response for the 26 YO 50th percentile and 75 YO 50th percentile models. The present study identified that average changes in curvature with age did not significantly change the motion segment response, while larger variations within the population values did affect the response of the motion segment, primarily in extension.*

## INTRODUCTION

Spine repositioning of finite element Human Body Models (HBMs) is important to integrate models into vehicle crash scenarios and to investigate the implications of different postures in impact scenarios. It has been shown that spine curvature undergoes a progressive change with age (Boyle et al. 2002), that is, the lordosis of the cervical spine increases (Klinich et al. 2004). HBM are usually developed in a unique position such as a seated posture, and morphing such models while retaining mesh quality can be challenging. The recent release of PIPER, an open source software, presents the opportunity to morph HBM to different postures (Bellias et al. 2015) while retaining mesh quality.

Although remarkable strides have been achieved in understanding posture-related effects in human spine response (Balzini et al. 2003; Grob, Frauenfelder et al. 2007; Katzman, Vittinghoff et al. 2011; McAviney et al. 2005), the isolated effect of change in posture in detailed models at the motion segment level has not been investigated. Frechede et al. 2006 investigated the effect of

cervical curvature using a simplified head-neck model (Fréchède, Bertholon, Le Coz, Lavaste, & Skalli, 2005) validated at full head-neck level and the target curvatures (lordotic, straight, and kyphotic) were defined using Cobb angles (Rinsky 2010; Tanure, M. C. et al. 2010). However, one previous study (Barker et al. 2017) suggested there may be a contribution of spinal curvature to the kinetic and kinematic response of the cervical spine at the motion segment level.

Finite element (FE) models are widely used to quantify mechanical phenomenon that are challenging to understand with experimental tests or traditional analysis. An example of a current HBM is the Global Human Body Models Consortium (GHBMC) 50th percentile detailed male 26-year-old (YO) seated vehicle occupant model, which includes a detailed head and neck (Figure 1, Left). The basic building block of the detailed neck model are the motion segments (Figure 1, Right) comprising two vertebrae, the intervertebral disc, articular facets, and the ligamentum flavum, capsular, interspinous, anterior longitudinal, and posterior longitudinal ligaments.

Cervical spine curvature can be described using a number of metrics including curvature index, chord length, or more specifically using inferior (InfBezAng) and superior (SupBezAng) Bézier angles (Figure 2) (Klinich et al. 2004, 2012). Extensive anthropometric investigations have characterized the relationship between sex, age, and height in cervical curvature. Reed and Jones 2017 developed a cervical spine posture software (C-Spine Predictor) based on a database of 144 adult subject cervical spine x-ray images (Snyder et al. 1975) from male and female subjects with a range of age and stature. The x-ray images were digitized and processed by Klinich et al. 2004, demonstrating the relationship between increasing age and increasing cervical lordosis.
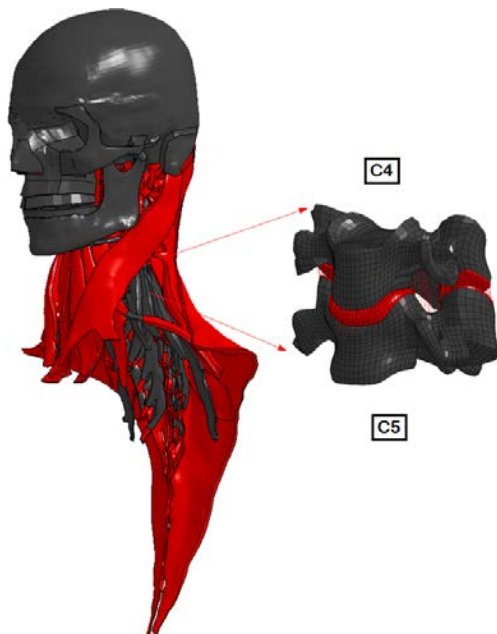


*Figure 1: GHBMC M50 Head and neck detailed model v4.5. Right: C4-C5 motion segment*
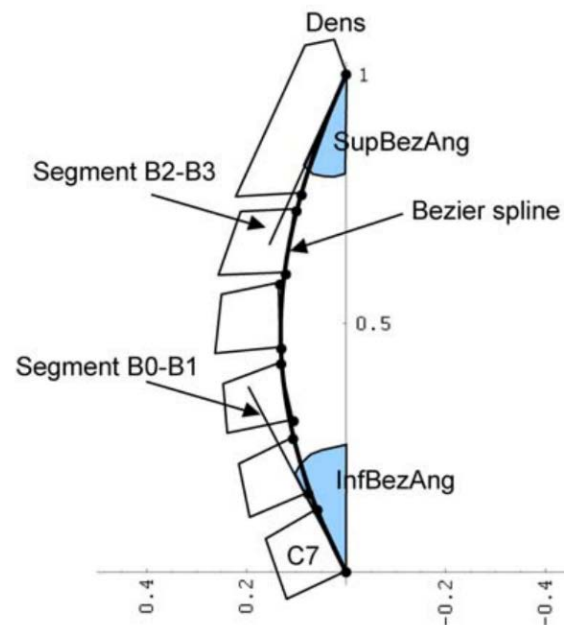
*Figure 1: Inferior and superior Bézier angle definition, adapted from Klinich et al. 2004*

## OBJECTIVE

This study presents a repositioned GHBMC 50th percentile male detailed HBM (M50-O, version 4.5) and assesses the effect of spinal curvature on response using the motion segment at the level of the fourth and fifth vertebra (C4-C5) (Figure 1, Right) under flexion, extension, and tension loading. The recent development and validation of a detailed human neck model (Barker et al. 2017) integrated with posture predictors (Reed & Jones, 2017) based on a large anthropometrics database (Klinich et al. 2004; 2012) presents the opportunity to perform detailed studies with the aim to better understand the effect of posture on neck response.

## METHODS

For this study, a detailed HBM that represents the 50th percentile male geometry (Gayzik et al., 2011) was used as the baseline (Figure 1). Details of the modeling techniques and material properties used can be found in Barker et al. 2017, Panzer et al. and 2009, and Fice et al. 2011. Mesh refinement studies (DeWit et al. 2012) demonstrated the mesh was sufficiently refined to predict motion segment kinetics and kinematics. The neck model has been extensively validated at motion segment level (Barker et al. 2017) against a wide range of experimental data including range of motion and traumatic loading (Camacho et al., 1997; Moroney, Schultz, Miller, & Andersson, 1988; Nightingale et al., 2007; Panjabi et al., 2001; Wheeldon, Pintar, Knowles, & Yoganandan, 2006).

### Posture definition:

Four curvatures were investigated: the current GHBMC M50-O v4.5, a repositioned spine representing 26 YO with Bézier angles reduced by 5 degrees (Figure 1), a curvature representing the 75 YO average population, and a curvature of a 75 YO with Bézier angles increased by 5 degrees. Although the variations of Bézier angle are much larger than 5 degrees in the young (15°) and aged (28°) populations, 5° was used for this study as a physical limit for repositioning the M50 model without generating interpenetration of the facet joint surfaces. The standard deviation for young subjects in the superior and inferior Bézier angles was 7° and 6°, respectively, while for aged subjects the standard deviation was 15° and 12°, respectively (Klinich et al. 2004). It has been found that the standard deviation of the angles increases with age. The four curvatures presented in this study where obtained using local translations and rotations for each vertebra based on the C-Spine Predictor software (Reed and Jones 2017). The curvature for each posture is presented in Figure 2 and the angles between vertebrae of the C4-C5 motion segment, the focus of this investigation, are presented in Table 1. The cervical spine was repositioned assuming that the modified tissue geometry was in a stress-free state, corresponding to the new posture.
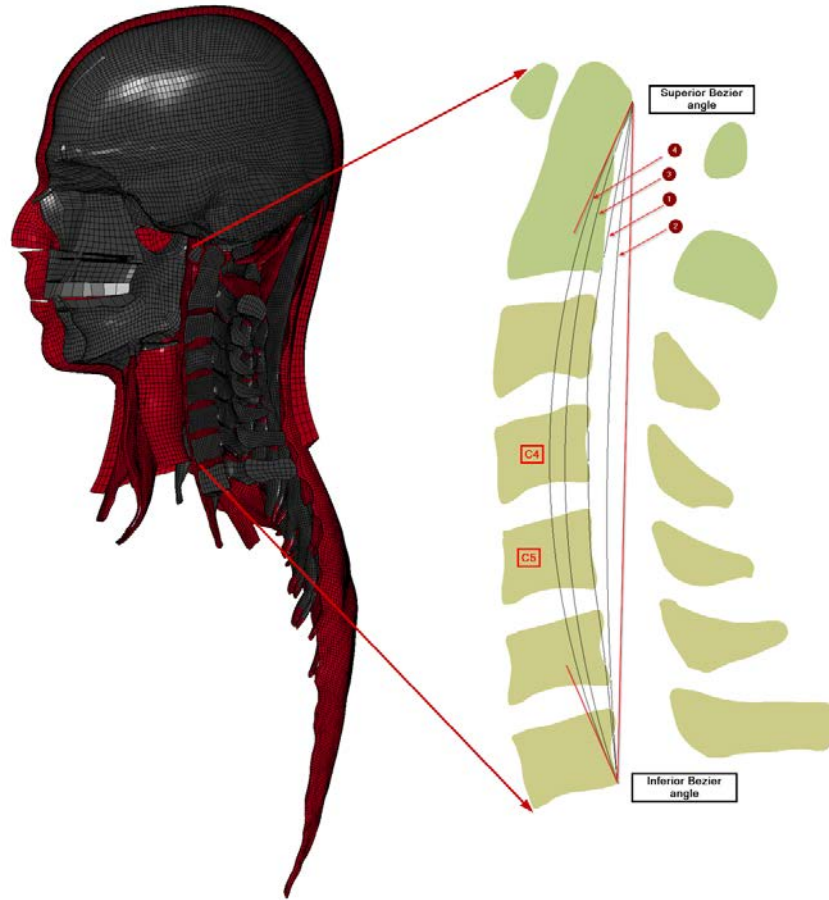
*Figure 3: Left: GHBMC M50-O v4.5 detailed head and neck model, sagittal view. Right: GHBMC M50-O v4.5 cervical vertebra sagittal view and curvature (1), 26 YO 50th percentile with 5 degrees decrease in the Bézier angles (2), 75 YO average lordosis (3), and 75 YO with 5 degrees increase in the Bézier angles (4).*

*Table 1: Angle between vertebrae (C4-C5)*

|  | 26 YO Bezier angles decreased by 5° | GHBMC M50-O v4.5 Curvature | 75 YO Average Lordosis | 75 YO Bezier angles increased by 5° |
|---|---|---|---|---|
| Angle (Deg) | 1.1° | 4.1° | 6.2° | 8.4° |

**Posture implementation:**

To translate the model to the target posture obtained from the C-Spine Predictor software, a kinematic chain was developed in a commercial CAD software (CATIA V5). The translations and rotations of each vertebra were then imported to an open source repositioning software (PIPER)

to reposition the GHBMC full body model for later extraction of the C4-C5 motion segment. Distorted elements and surface penetrations were addressed in order to maintain mesh quality after repositioning and the final mesh was assessed using a variety of metrics including element warpage (<50 deg), aspect ratio (<8), skew (<70 deg), and Jacobian (>0.4) for all elements.

Following extraction of the C4-C5 motion segment, the boundary conditions were applied. The inferior vertebra (C5) was constrained at the inferior endplate and moment was applied to the unconstrained superior vertebra (C4) in the superior endplate following existing methodologies (Barker et al. 2017). The motion segment models were then analyzed using a commercial explicit finite element solver (LS-DYNA, version R71.2). The model was loaded at a rate of 90 Nm/s up to tissue failure (Figure 5) as in published dynamic experiments (Barker et al. 2017). The corresponding moment and rotation angle were monitored and compared.
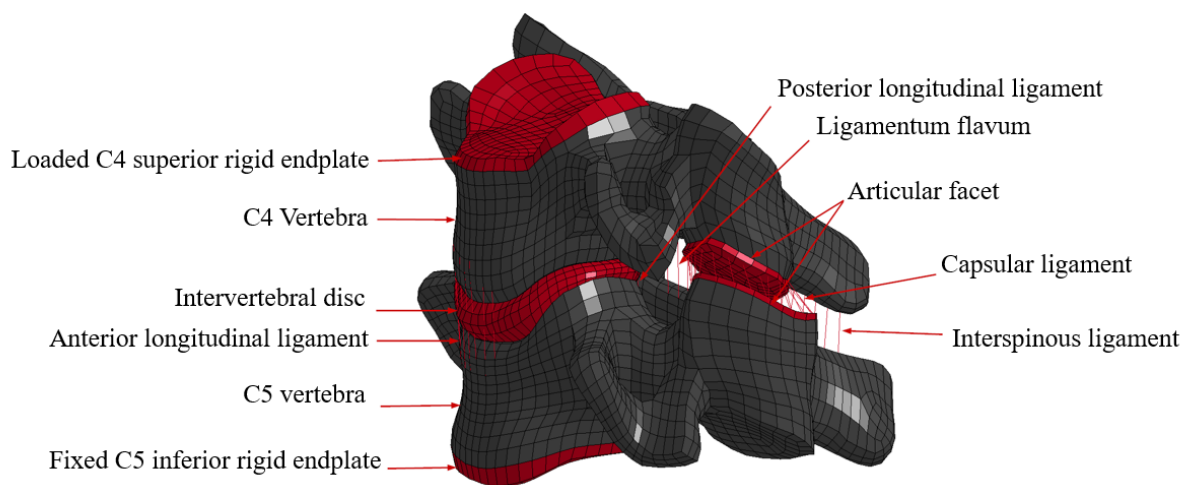


*Figure 4: Motion Segment C4-C5 FE Model*

## RESULTS

The most significant effect on response due to posture was observed in extension loading (Figures 6 and 7). This was attributed to the articular facet and spinous process interaction between vertebras. In contrast, during flexion and tension (Figures 8 and 9 in Appendix A) the effect of posture on response was modest.
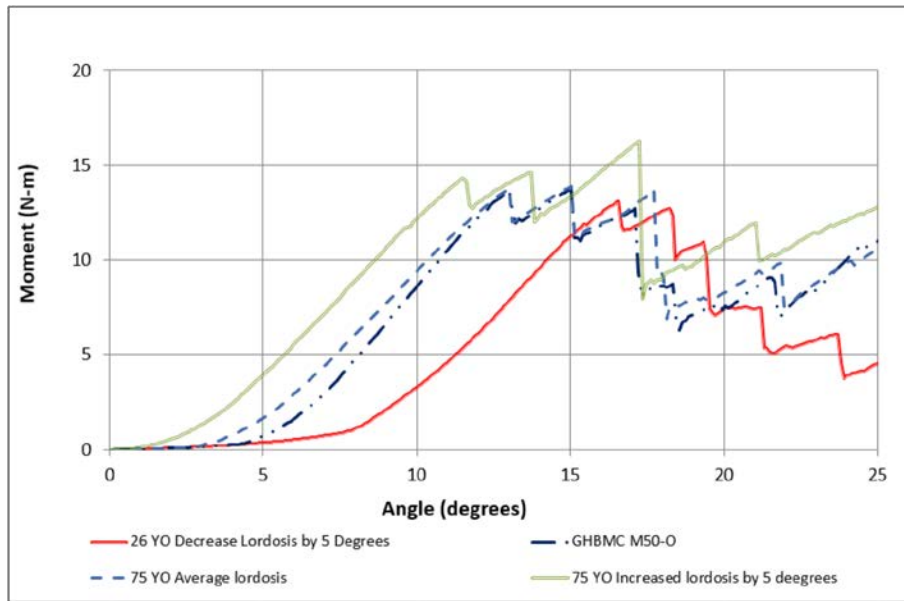
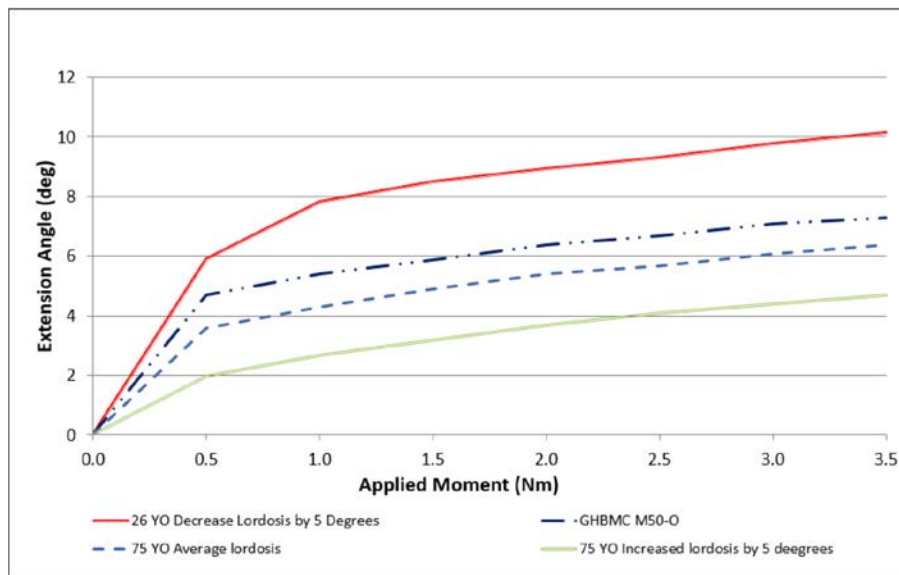*Figure 5: C4-C5 moment rotation for extension loading*



*Figure 6: C4-C5 –Range of motion loading in extension*

## CONCLUSION AND DISCUSSION

While the response in extension up to traumatic failure was similar between the 26 YO GHBMC average lordosis (13.68 Nm at failure) and 75 YO average lordosis (13.77 Nm at failure), the 26 YO posture with decreased lordosis (13.1 Nm at failure) was lower in strength compared to

the 75 YO posture with increased lordosis (14.2 Nm at failure). This demonstrates that small changes in average posture, corresponding to aging did not have a significant effect on the mechanical response and failure of the motion segment, while wider variations within the population variability did have a significant effect.

Considering range-of-motion for loading up to 2.0 Nm in extension, the 26 YO GHBMC model (6.4º) demonstrated higher compliance compared to the 75 YO model with average lordosis (5.4º). A wider variation was observed between the 26 YO with decreased lordosis (8.9º) and the 75 YO with increased lordosis (3.7º). The 26 YO GHBMC and 75 YO average lordosis models were within the range of published data (6.55º +/- 1.9º) (Nightingale et al. 2007).

One limitation of the current study was that the same material properties were used for all models. The response difference could be amplified considering changes in the material properties corresponding to aging.

The current study indicates that increased spinal curvature resulted in increased motion segment stiffness, with the largest effect in extension loading and the greatest differences for wide variations of posture. Future studies will consider aged material properties and full neck simulations to further investigate the effect of posture on kinematic and kinetic neck response in impact scenarios.

## ACKNOWLEDGMENTS

## REFERENCES

BELLIAS, P., P. PETIT, S. KLEIVEN, S. KIRSCHT, A. CHAWLA, E. JOLIVET, F. FAURE, N. PRAXL, A. BHASKAR 2015. "Specifications of a Software Framework to Position and Personalize Human Body Models" *IRCOBI short communication 2015*.

BALZINI, L., VANNUCCHI, L., BENVENUTI, F., BENUCCI, M., MONNI, M., CAPPOZZO, A., & STANHOPE, S. J. (2003). Clinical characteristics of flexed posture in elderly women. *Journal of the American Geriatrics Society*, *51*(10), 1419–1426. https://doi.org/10.1046/j.1532-5415.2003.51460.x

BARKER, J. B., CRONIN, D. S., & NIGHTINGALE, R. W. (2017). Lower Cervical Spine Motion Segment Computational Model Validation: Kinematic and Kinetic Response for Quasi-Static and Dynamic Loading. *Journal of Biomechanical Engineering*, *139*(6), 61009. https://doi.org/10.1115/1.4036464

BOYLE, J. J. W., MILNE, N., & SINGER, K. P. (2002). Influence of age on cervicothoracic spinal curvature: An ex vivo radiographic survey. *Clinical Biomechanics*, *17*(5), 361–367.

https://doi.org/10.1016/S0268-0033(02)00030-X

CAMACHO, D. L., NIGHTINGALE, R. W., ROBINETTE, J. J., VANGURI, S. K., COATES, D. J., & MYERS, B. S. (1997). Experimental flexibility measurements for the development of a computational head-neck model validated for near-vertex head impact. *Most*, *paper97334*, 473–486. https://doi.org/10.4271/973345

DEWIT, J. A., & CRONIN, D. S. (2012). Cervical spine segment finite element model for traumatic injury prediction. *Journal of the Mechanical Behavior of Biomedical Materials*, *10*, 138–150. https://doi.org/10.1016/j.jmbbm.2012.02.015

FICE, J. B., CRONIN, D. S., & PANZER, M. B. (2011). Cervical spine model to predict capsular ligament response in rear impact. *Annals of Biomedical Engineering*, *39*(8), 2152–2162. https://doi.org/10.1007/s10439-011-0315-4

FRÉCHÈDE, B., BERTHOLON, N., LE COZ, J.-Y., LAVASTE, F., & SKALLI, W. (2005). Finite element model of the human neck during omni-directional impacts. *Revue Européenne Des Éléments Finis*, *14*(4–5), 463–485. https://doi.org/10.3166/reef.14.463-485

FRECHEDE, B., BERTHOLON, N., SAILLANT, G., LAVASTE, F., & SKALLI, W. (2006). Finite element model of the human neck during omni-directional impacts. Part II: relation between cervical curvature and risk of injury. *Computer Methods in Biomechanics and Biomedical Engineering*, *9*(6), 379–386. https://doi.org/10.1080/10255840600980940

GAYZIK, F. S., MORENO, D. P., GEER, C. P., WUERTZER, S. D., MARTIN, R. S., & STITZEL, J. D. (2011). Development of a full body CAD dataset for computational modeling: A multi-modality approach. *Annals of Biomedical Engineering*, *39*(10), 2568–2583. https://doi.org/10.1007/s10439-011-0359-5

GROB, D., FRAUENFELDER, H., & MANNION, A. F. (2007). The association between cervical spine curvature and neck pain. *European Spine Journal*, *16*(5), 669–678. https://doi.org/10.1007/s00586-006-0254-1

KATZMAN, W. B., VITTINGHOFF, E., & KADO, D. M. (2011). Age-related hyperkyphosis, independent of spinal osteoporosis, is associated with impaired mobility in older community-dwelling women. *Osteoporosis International*, *22*(1), 85–90. https://doi.org/10.1007/s00198-010-1265-7

KLINICH, K. D., EBERT, S. M., & REED, M. P. (2012). Quantifying Cervical-Spine Curvature Using Bézier Splines. *Journal of Biomechanical Engineering*, *134*(11), 114503. https://doi.org/10.1115/1.4007749

KLINICH, K. D., EBERT, S. M., VAN EE, C. A., FLANNAGAN, C. A. C., PRASAD, M., REED, M. P., & SCHNEIDER, L. W. (2004). Cervical Spine Geometry in the Automotive Seated Posture: Variations with Age, Stature, and Gender. *Stapp Car Crash Journal*, *48*, 301–330. https://doi.org/2004-22-00014 [pii]

MCAVINEY, J., SCHULZ, D., BOCK, R., HARRISON, D. E., & HOLLAND, B. (2005). Determining the relationship between cervical lordosis and neck complaints. *Journal of Manipulative and Physiological Therapeutics*, *28*(3), 187–193. https://doi.org/10.1016/j.jmpt.2005.02.015

MORONEY, S. P., SCHULTZ, A. B., MILLER, J. A. A., & ANDERSSON, G. B. J. (1988). Load-displacement properties of lower cervical spine motion segments. *Journal of Biomechanics*, *21*(9), 769–779. https://doi.org/10.1016/0021-9290(88)90285-0

NIGHTINGALE, R. W., CAROL CHANCEY, V., OTTAVIANO, D., LUCK, J. F., TRAN, L., PRANGE, M., & MYERS, B. S. (2007). Flexion and extension structural properties and strengths for male cervical spine segments. *Journal of Biomechanics*, *40*(3), 535–542. https://doi.org/10.1016/j.jbiomech.2006.02.015

PANJABI, M. M., CRISCO, J. J., VASAVADA, A., ODA, T., CHOLEWICKI, J., NIBU, K., & SHIN, E. (2001). Mechanical properties of the human cervical spine as shown by three-dimensional load-displacement curves. *Spine*, *26*(24), 2692–2700. https://doi.org/10.1097/00007632-200112150-00012

PANZER, M. B., & CRONIN, D. S. (2009). C4-C5 segment finite element model development, validation, and load-sharing investigation. *Journal of Biomechanics*, *42*(4), 480–490. https://doi.org/10.1016/j.jbiomech.2008.11.036

REED, M. P., & JONES, M. L. H. (2017). A Parametric Model of Cervical Spine Geometry and Posture A Parametric Model of Cervical Spine Geometry and Posture, (February).

RINSKY, L. A. (2010). Quantifying scoliosis: We are still not there. *Spine Journal*. https://doi.org/10.1016/j.spinee.2010.06.021

SNYDER, R. G., CHAFFIN, D. B., & FOUST, D. R. (1975). Bioengineering study of basic physical measurements related to susceptibility to cervical hyperextension-hyperflexion injury. http://hdl.handle.net/2027.42/1424

TANURE, M. C., PINHEIRO, A. P., & OLIVEIRA, A. S. (2010). Reliability assessment of Cobb angle measurements using manual and digital methods. *The Spine Journal*, *10*(9), 769–774. https://doi.org/10.1016/j.spinee.2010.02.020

WHEELDON, J. A., PINTAR, F. A., KNOWLES, S., & YOGANANDAN, N. (2006). Experimental flexion/extension data corridors for validation of finite element models of the young, normal cervical spine. *Journal of Biomechanics*, *39*(2), 375–380. https://doi.org/10.1016/j.jbiomech.2004.11.014

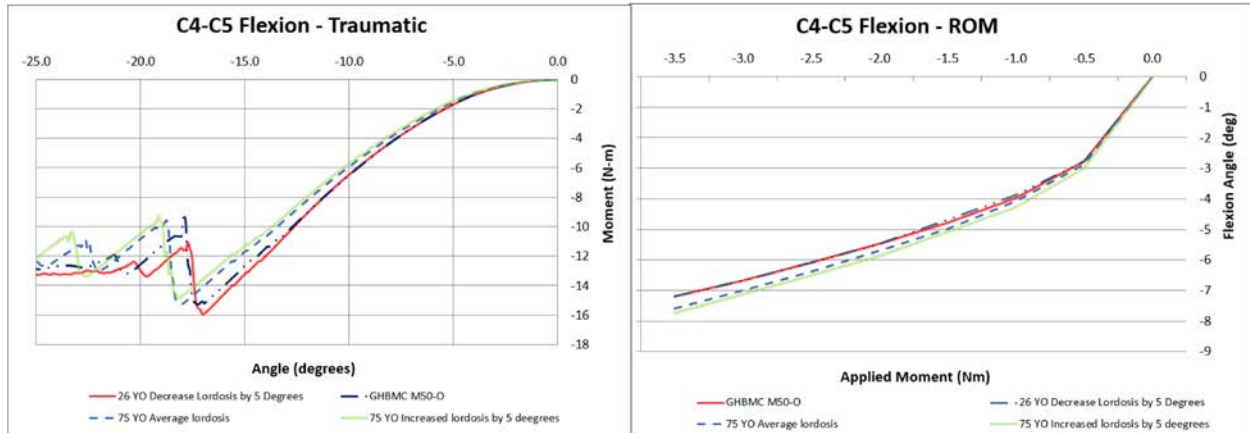# Appendix A: C4-C5 Motion Segment in Flexion and Tension
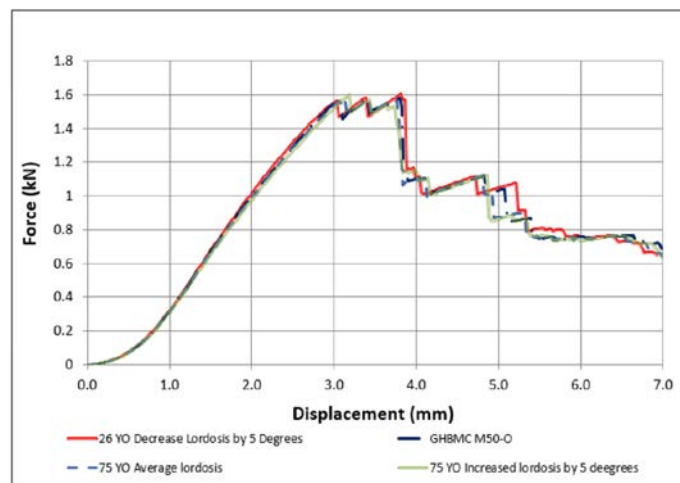


*Figure 7: C4-C5 Motion segment, flexion loading*



*Figure 8: C4-C5 Motion segment, tension loading*