# *Parametric Modeling of Cervical Spine Geometry Across Diverse Populations*

Kyle Wakerley[1,2], Xinyue Mao[1,3], Michelle Baek[1,4], Sumukha Shrouthy[1,5], Monica L.H. Jones[1], Jingwen Hu[1,6,*]

[1]University of Michigan Research Transportation Institute, Ann Arbor, MI, United States

[2]Department of Biology, University of Michigan, Ann Arbor, MI, United States

[3]Department of Statistics, University of Michigan, Ann Arbor, MI, United States

[4]University Hospital, University of Michigan, Ann Arbor, MI, United States

[5]Integrative Systems + Design, University of Michigan, Ann Arbor, MI, United States

[6]Department of Mechanical Engineering, University of Michigan, Ann Arbor, MI, United States

**Introduction**:

Cervical spine injuries caused by motor vehicle accidents (MVA) remain a significant public health concern in the United States, with approximately 869,000 new cases reported annually, including 1,500 cases involving vertebral dislocations [1]. Current computational human models represent only three standardized body sizes: small female, midsize male, and large male, failing to represent the morphological variation associated with the human population [2]. Parametric human modeling addresses this limitation by capturing geometric variations across diverse populations, contributing to more inclusive and equitable safety assessments.

**Objective**:

This study aims to develop a comprehensive parametric model of the cervical spine and quantify the effects of subject covariates and cervical spine structural dimensions on its geometry. By accounting for population variability, this approach seeks to improve simulation accuracy, ultimately enabling adaptive designs for human safety.

**Methodology**:

The neck CT images used in this study were originally gathered from 170 participants (73 males and 97 females) from the University of Michigan Hospital system. These participants had ages ranging from 18 to 79 years (mean ± standard deviation: 47.62 ± 17.28 years for males, 49.21 ± 18.08 years for females), stature ranging from 1.50 to 1.98 m (1.78 ± 0.08 m for males, 1.65 ± 0.07 m for females), and BMI ranging from 15.81 to 48.45 (28.85 ± 6.12 for males, 27.20 ± 6.41 for females). Cervical vertebrae were segmented using TotalSegmentator, refined in Materialise Mimics with scripting, and manually post-processed to produce final geometric outputs. A refined cervical spine mesh from the THUMS model was then morphed to match the geometry of each segmented subject. To address incomplete C7 data, Principal Component Analysis (PCA)-based imputation was applied, ensuring data consistency across subjects. Cervical spine geometry was modeled using Generalized Procrustes Analysis (GPA), PCA, and linear regression, analyzing its relationship with anthropometric and cervical spine structural dimensions.

**Results**:

Figure 1 shows the size and shape variations of the cervical spine explained by the top three PCs, which account for 71.29% of the total variation. The regression model achieved an overall $R^2$ value of 0.64, indicating that age, stature, BMI, sex, cervical spine height, curvature angle, and associated interactions

collectively account for approximately 64% of the cervical spine geometry variations. The overall Root Mean Squared Error (RMSE) of the model is 1.50 mm, with an average RMSE of 1.44 mm across subjects. The heatmap (Figure 1, rightmost panel) illustrates the average prediction error of our parametric model. Errors are primarily concentrated in the spinous process regions of each vertebra, with a maximum of approximately 4.65 mm.

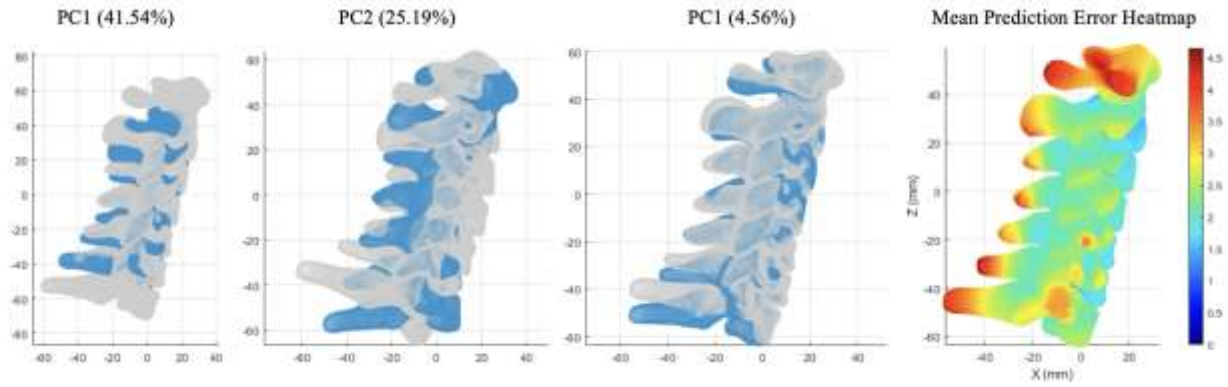


**Figure 1:** Top 3 PCs variations and prediction error visualization.

**Conclusions**:

This study presented a parametric cervical spine model based on CT scans of 170 participants, demonstrating good predictive accuracy for cervical spine geometry and its potential to serve as a foundation for personalized injury assessment and adaptive safety design.

**References**:

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[2] Hu, J. (2018). Parametric Human Modeling. In *Basic Finite Element Method as Applied to Injury Biomechanics* (pp. 417-445). https://doi.org/10.1016/b978-0-12-809831-8.00010-6