Thoracolumbar vertebrae position transformation from supine to seated

T. Jeong[1], M. Lalwala[1], J. Aira[1], K. Devane[1], F. S. Gayzik[1], J. D. Stitzel[1], and A. A. Weaver[1]
[1] Wake Forest School of Medicine, Biomedical Engineering Department

ABSTRACT

Investigation of space-flight and landing conditions necessitates use of finite element human body models (FEHBMs) to simulate effects of loading. Current FEHBMs are developed with nominal geometry; there is significant interest in developing models with subject-specific geometry, especially for the spine where most of the loading under axial acceleration occurs. Methods exist for morphing FEHBMs from standardized to subject-specific geometry, but there is little investigation in reconstructing subject-specific spinal curvature. High contrast images of the spine are best obtained through CT scans and most capable machines are restricted to supine postures whereas subjects in crash and aerospace situations are seated. The objective of this study was to develop a transform function for occupants going from supine to seated postures for the purpose of these simulations. Visual observation of existing supine-seated scan pairs indicates a straightening of the spine in seated postures. Twelve human volunteers received supine and seated scans which were analyzed to determine change in vertebral position between postures and develop a transformation matrix that would predict vertebral displacement from supine-to-seated. The study also obtained supine MRIs of astronauts (n=9) and anthropometrically matched them to a corresponding human volunteer subject in order to derive an expected seated posture for the astronauts. Within the human volunteer data, the radius of curvature in the thoracic and lumbar regions was calculated and revealed that radius of curvature for seated subjects is significantly higher in the thoracic region (p=0.033), demonstrating that there is a straightening of the spine.

INTRODUCTION

In the year 2021, a total of 48 crewmembers have been launched into space (Smith, et al., 2021). Due to trends in development of commercial space travel, the number of spaceflight occupants is only expected to increase year by year. However, traveling into space is not yet a routine task; there are serious forces and loads that are implicated in launching and landing scenarios that are potentially injurious. The golden standard among vehicle cabin safety testing methods is the use of anthropomorphic test devices (ATDs) as occupants in vehicle crash scenarios. However, ATD-based injury prediction is not subject-specific and has limited spine prediction capability. A cost-effective method of determining aeronautical occupant safety is through use of finite element human body models (FEHBMs). Among existing FEHBMs, the models developed by the Global Human Body Models Consortium (GHBMC) are some of the most widely used but feature nominal geometry not specific to any subject.

The spine is one of the primary regions of interest in both automotive and spaceflight applications. A common metric for car safety and kinematic distress is T1 displacement. Spaceflight loadings can occur in a variety of configurations, with some of them featuring the occupant spine parallel to the direction of takeoff (Ye et al., 2019). Under axial loads, stress concentrations manifest along the occupant spine and it has been demonstrated that incorporation of subject specificity can influence vertebral loading predictions (Müller et al., 2021). This places immense significance on the spine and it is important to model this portion of the FEHBM as accurately as possible.

Thus, there is significant use for developing techniques to generate subject-specific models. Current methodology exists for obtaining subject-specific surface geometries by segmenting medical images. Subsequent research has resulted in the leveraging of computational methods to then morph GHBMC vertebrae into subject-specific ones (Rubenstein et al., 2021)**.** The highest contrast images of vertebrae are obtained from computed tomography (CT) scans and most capable machines are restricted to supine postures. However, in aerospace and crash situations subjects are seated when experiencing loading; simulations of these events require spine positioning in the seated posture as this can affect injury prediction. While supine CT scans can be leveraged for vertebral surface geometry, they do not give insight into the spinal curvature. Upright magnetic resonance image (MRI) scans allow for collection of upright positions, including standing and seated postures, leading to datasets with supine and seated scans for same subjects. This allows for a quantitative study of supine-to-seated transformation.

The objectives of this study were to: 1) analyze supine-seated scan pairs to develop a transformation matrix to obtain expected seated spinal curvature from the supine scans, and 2) find the closest match between astronaut subjects and a supine-seated reference subject pair and apply a transformation matrix to generate a seated posture for each astronaut scan.

METHODS

Supine and seated scan data was collected from an existing research dataset of reference subjects to quantify the change in vertebral positionings between postures. Supine scan data was also prospectively collected for astronauts. Through criteria of radius of curvature, spine length, weight, and age, astronaut subjects were matched to a closest fitting reference subject, from which a transformation matrix is obtained and applied.

Data acquisition for investigating supine and seated spine curvature

Supine and seated MRI scans from 12 participants (6 male, 6 female) were collected as a part of the Military Human Modeling (Mil-HuMod) project (Gayzik et al. 2018). Supine MRIs were obtained utilizing a 3.0 Tesla research MRI scanner at Atrium Health Wake Forest Baptist medical center capturing the entire thoracic and lumbar spine. A FONAR upright multi-position 0.6T MRI was utilized for seated scans. Though CT is the preferred choice for detailed study of bone, MRI scans are sufficient for characterizing the spinal curvature.

Nine astronaut subjects of long-duration (greater than 6 months) spaceflight were the interest of this study. Supine MRI scans and anthropometric data for all nine subjects were obtained. Supine MRI scans were taken using a Siemens Magnetom Verio 3T Scanner.

Quantitative representation of Mil-HuMod subject spine geometry

For each scan, spinal position was quantitatively represented by marking coordinates of the vertebral body centroids. This was accomplished in MIMICS (v20, Materialise, Leuven, Belgium) by marking the diagonals of the vertebral body and marking the intersection. Due to the quality of the scans, only centroids for the T3 vertebrae down to the sacrum were included in all scans. These points were exported as coordinates into MATLAB (r2021, MathWorks, Natick, USA) and were fitted to a spline using cubic interpolation. Due to differences in calibration for seated and supine MRI, the splines need to be aligned both translationally, and rotationally. Figure 1 shows the result of the alignment process.

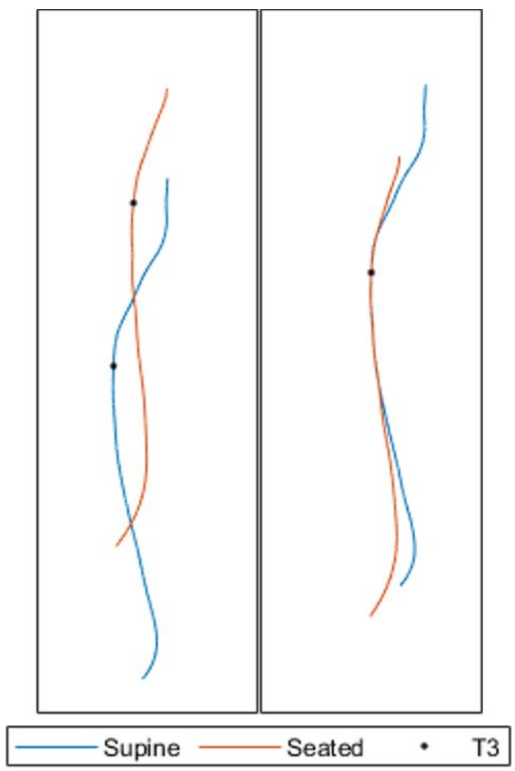

Figure 1: Left: raw input coordinates for Mil-HuMod subject scan data. Right: splines after translational and rotational alignment process.

The seated spline was shifted so that the T3 coordinates would overlap. This assumption was made based on the visual observation that the T3 vertebrae appears static between seated and supine postures. The process of rotation was accomplished by determining the angle for which the distance between adjacent vertebrae is minimized. The seated spline was rotated in increments of 0.001 radians and the angle with the lowest total vertebral deviation was chosen.

For ease of display and cross-subject examination, all T3 centroids were translated and fixed to the origin.

Matching astronaut and Mil-HuMod splines

The absence of astronaut seated scans necessitates that the transform for a Mil-HuMod subject be used instead. Determining the appropriate transform for each astronaut subject is achieved by a quantitative comparison made between astronaut and Mil-HuMod supine splines and additional metadata to computationally determine the closest match. To quantitatively characterize the curvature of splines, the radius of curvature (RoC) was determined for the thoracic (T3-12) and lumbar (L1-L5) regions. The length of the curve was determined to compute the spine length from T3-L5.

Thoracic RoC, lumbar RoC, spine length, weight, and age for Mil-HuMod subjects were normalized. Astronaut subject matches were determined by identifying the Mil-HuMod subject with the smallest total distance in these factors. The matching was performed using both preflight and postflight astronaut scans.

Transformation function generation from supine to seated posture

Transformation matrices were generated for each Mil-HuMod subject by determining the change in respective vertebral positions in supine and seated splines. Some scans did not include cervical and upper thoracic vertebrae, but at a minimum captured the spine from T3 to the sacrum. Distances were normalized based on distance from T3 vertebrae and length of the spine to account for the inherent correlation between spine length and degree of vertebral change, i.e. a 95^{th} percentile male's L5 vertebrae is expected to have more displacement than a 5^{th} percentile female. These transformations were then applied to corresponding astronaut subjects for T4-L5 vertebrae to obtain expected seated postures.

Statistical testing

Paired t-testing was conducted for the Mil-HuMod RoC values between seated and supine postures in both the thoracic and lumbar regions at a significance level of 0.05. Additionally, post-hoc F-testing was conducted for variance in vertebrae angle. This required the measurement of vertebrae angle, which was accomplished by calculating the slope of the spline at each vertebral point.

RESULTS

Radius of curvature and vertebral angle

Summary statistics for the radius of curvature are shown in Table 1, as well as the resultant p-value from two-sample paired t-testing. Post-hoc F-testing revealed that the variance in vertebral angle for the thoracic region of seated subjects is significantly smaller than the variance of supine subjects (p=0.0431).

Table 1: Radius of curvature for supine and seated postures

RoC Measurements			
Region	**Supine**	**Seated**	***p*-value**
Thoracic (mm)	817±317	1250±701	0.033*
Lumbar (mm)	448±117	910±768	0.059

*Indicates statistical significance.

Astronaut and Mil-HuMod matching

Matched supine splines are shown in Figure 2. Only a few examples are shown and are unlabeled to protect anonymity of the subjects. In all these plots the magenta line represents the astronaut subject and the blue line indicates the matching Mil-HuMod participant.

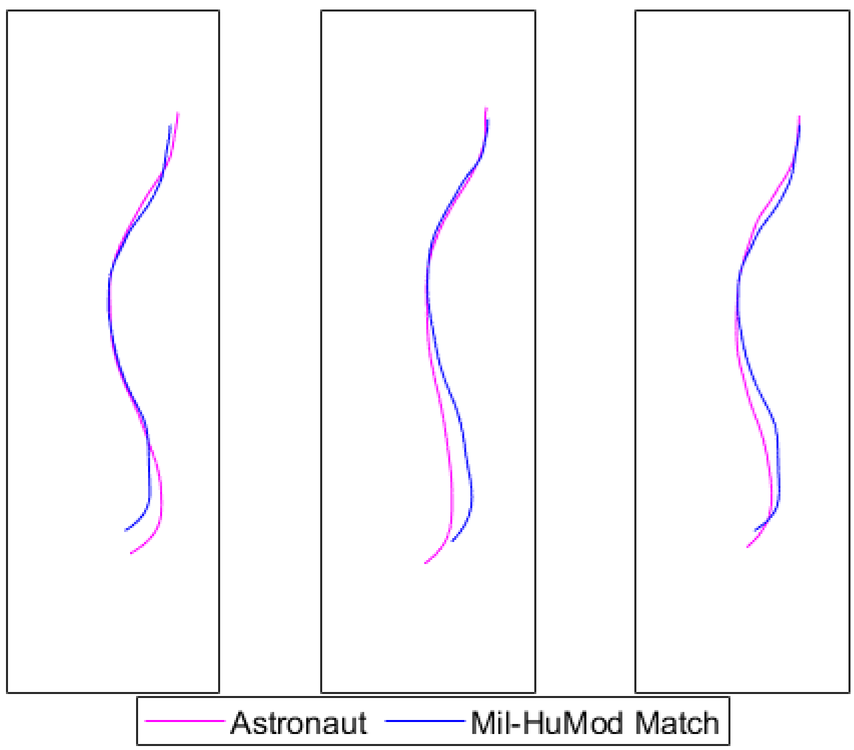

Figure 2: Astronaut supine splines and respective Mil-HuMod matches based on radius of curvature and subject metadata.

Transformation matrix and application

The transformation pipeline for a sample astronaut subject is shown in Figure 3. A corridor of all possible transformations obtained from Mil-HuMod data and applied to a 40th percentile male is shown in Figure 4.

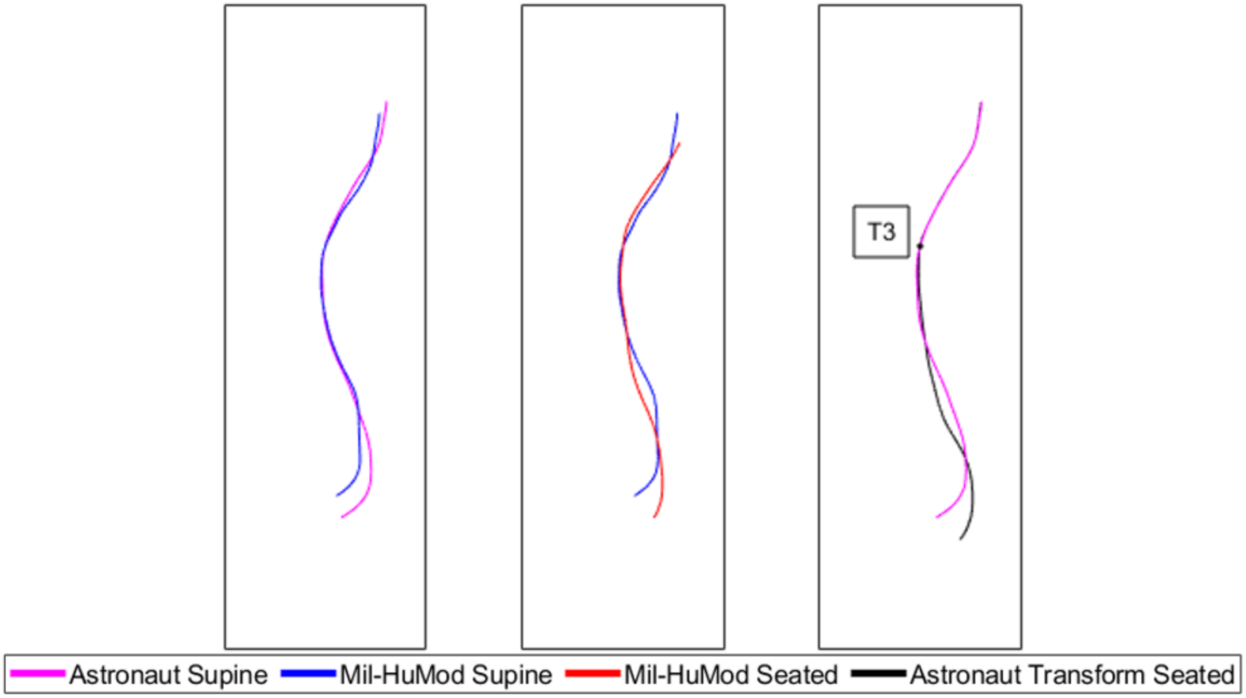

Figure 3: (A) Astronaut supine spline matched with Mil-HuMod supine spline, (B) Corresponding Mil-HuMod supine and seated spline, (C) Astronaut supine spline and result of transformation to seated.

Figure 4: Supine-to-seated transform corridor for 40th percentile male.

DISCUSSION

Matching was conducted using existing MRI data of human volunteer subjects and astronauts. While being able to incorporate additional factors such as subject height and percentile has potential to increase match fidelity, principal component analysis determined that thoracic RoC, lumbar RoC, and spine length already accounted for 93% of the variability in the dataset. Notably, there was no change in matched pairs when using preflight and postflight scans, suggesting that long-duration spaceflight does not change spinal characteristics enough to affect supine-to-seated behavior.

In the thoracic region, the radius of curvature of the seated scans were significantly higher than the supine scans. Similar near significant results were determined in the lumbar region. A higher radius of curvature is indicative of a straighter spine. This corroborates the visual observation that the spinal curvature is straighter when seated. Significance of post-hoc F-testing indicates that there is less angular deviation is seated spines. This is another metric for signifying the reduced amount of spinal curvature when seated. It is important to incorporate subject-specific spinal curvature changes as straightening of the spine can impact vertebral loading predictions. The transform corridor visualizes how the lumbar region of the spine might move either anteriorly or posteriorly and as a result reduce the amount of spinal curvature.

Future steps in this work are to apply both subject-specific vertebral geometry and spinal curvature into the GHBMC model for space-flight launch and landing simulations. This study predicts that this will more accurately predict injury risk for specific astronauts and contribute to a better understanding of how spinal curvature relates to load bearing and injury risk. The study suffers mostly from having a small selection of supine-seated scan pairs and would be improved by having access to a more extensive database of scan pairs.

CONCLUSIONS

Supine-seated scan pairs were used to develop a transformation matrix to obtain expected seated spinal curvature from the supine scans. Methodology to find closest match between test subjects and reference subjects was developed and transformation was applied to generate seated postures. Within the development process, metrics were measured to determine quantitative differences between supine and seated postures and found that seated spines are significantly straighter.

ACKNOWLEDGEMENTS

This project was funded by the U.S. Army Research Lab (W911NF-13-2-0039) and a NASA Human Research Program grant (NNX16AP89G).

REFERENCES

MULLER, A., ROCKENFELLER, R., DAMM, N., KOSTERHON, M., KANTELHARDT, S.R., AIYANGAR, A.K., GRUBER, K. (2021). Load Distribution in the Lumbar Spine During Modeled Compression Depends on Lordosis. Frontiers in Bioengineering and Biotechnology 9.

RUBENSTEIN, R., LALWALA, M., DEVANE, K., KOYA, B., WEAVER, A.A. (2021). Comparison of Morphing Techniques to Develop Subject-specific Finite Element Models of Vertebrae. Biomedical Engineering Society Annual Meeting 2021.

SMITH, T.G., BUCKEY, J.R. (2022). Anaesthetists and aerospace medicine in a new era of human spaceflight. Anaesthesia 77(4), 384-388.

YE, X., JONES, D.A., GAEWSKY, J.P., KOYA, B., MCNAMARA, K.P., SAFFARZADEH, M., PUTNAM, J.B., SOMERS, J.T., GAYZIK, F.S., STITZEL, J.D., WEAVER, A.A. (2020). Lumbar Spine Response of Computational Finite Element Models in Multidirectional Spaceflight Landing Conditions. Journal of Biomechanical Engineering 142(5).