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Anthropometric Human-Spacesuit Modeling Developments for Lunar Dynamic Loading Injury Scenarios

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ABSTRACT

Lunar surface exploration will inherently expose humans to dynamic loading conditions in spacecraft and vehicles, where risk of injury can occur. In Lunar Terrain Vehicle (LTV) driving scenarios, the crewmember operates the vehicle while wearing a spacesuit, which increases the risk of blunt and repetitive contact injuries as the body collides with the internal components of the spacesuit. To assess injury risk, NASA uses Finite element (FE) human body models (HBMs) to derive injury metrics from dynamic loading forces/accelerations. It is important that astronaut anthropometry can be accurately represented in these models as injury mechanisms will change for different crewmember body shapes and sizes. At NASA, the Global Human Body Models Consortium (GHBMC) 5th percentile female, 50th percentile male, and 95th percentile male HBMs are used to assess dynamic loading. An anthropometric evaluation of these models indicates that they do not fully represent spacesuit anthropometric requirements. There are tools to adjust the body shape of HBMs such as the Position and Personalize Advanced Human Body Models for Injury Prediction (PIPER) software, but the default morphing pipeline is limited at representing subtle body shape morphology. Therefore, custom control point selection from 3D body scans and morphing algorithms are being systematically investigated to improve scaling of the GHBMC models. Initial results from a proof-of-concept example were encouraging as the morphed torso segments closely approximated the original scan data. Anthropometrically accurate HBMs will enable effective occupant protection injury assessments and inform key hardware designs in the context of crewmember safety.

Keywords: Biomechanics simulation, Digital human modelling, Anthropometry, Occupant Injury

INTRODUCTION

Human lunar surface exploration is a key objective for the upcoming NASA Artemis lunar missions. At the beginning of these missions, astronauts may be restricted to traversing the lunar surface on foot. However, the added mass and mobility limitations of the pressurized spacesuit can make it difficult to travel far distances. During the NASA Apollo program, the Lunar Roving Vehicle (LRV) was deployed to expand the exploration range of lunar surface operations for the Apollo 15, 16, and 17 missions (Figure 1). The vehicle could accommodate two suited crewmembers for multiple lunar exploration sorties.

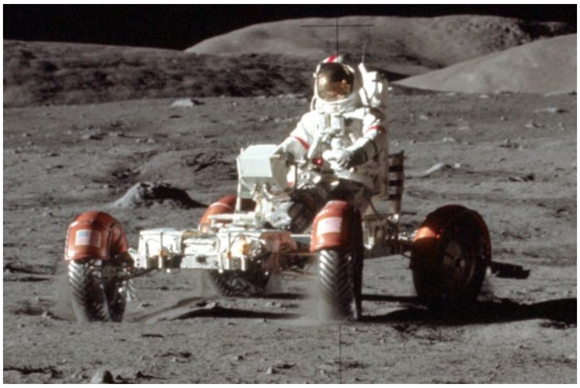

Figure 1: Lunar Roving Vehicle. (Photo credit: NASA).

To provide a similar capability to astronauts during later Artemis missions, new lunar terrain vehicles (LTV) are being developed to enable greater exploration and science capabilities. Compared to the LRV, the LTV will be able to travel farther away from the lunar lander, carry additional scientific equipment, and transport more lunar samples. However, operating the LTV carries inherent injury risks that need to be considered during the design process.

While operating the LTV, the astronauts will be exposed to dynamic loading conditions when crossing the lunar surface. The lunar surface is uneven, rocky, and contains numerous craters that can impart various accelerations and forces on the passengers. Thus, the LTV must be designed to mitigate unsafe levels of acceleration, vibration, and jerk that can lead to injury (Dolick et al. 2022). This injury risk is compounded by the astronauts wearing pressurized spacesuits during vehicle operation. While the suited crewmember is expected to be restrained in the LTV, their body may still shift around inside the spacesuit to some extent. This could expose them to body-to-spacesuit contact, such as collisions with the hardware inside the spacesuit, increasing the risk of blunt force and contact injuries. Impact forces will vary across different body shapes and depend on body-to-spacesuit fit, highlighting the need to understand how anthropometry influences these particular injury risks.

Finite element (FE) human body models (HBMs) can be used to calculate injury metrics from dynamic loading forces/accelerations. HBMs are commonly used as a complement to anthropomorphic test devices (ATDs) in safety evaluations during automotive crash simulation (Jost and Nurick 1999; Ruan et al. 2003). These models are also useful for various biomechanical applications, ranging from assessing soft tissue discomfort in seated positions (Grujicic et al. 2009) to understanding spaceflight launch and re-entry injury risk (Lawrence et al. 2009; Putnam et al. 2015). Recent lunar dynamic loading simulations have been performed with the Global Human Body Model Consortium (GHBMC) model. The GHBMC model contains high fidelity computerized anatomy and was created in 2006 by consolidating the findings from HBM research activities across the world (Gayzik et al. 2012).

An initial study by Yates, Drake, and Davis (2024) assessed LTV injury risks at vehicle linear acceleration requirements with the GHBMC model. The model was first positioned within the spacesuit Hard Upper Torso (HUT) FE model, then spacesuit sizing components were modified to index the HBM inside the suit. The model was posed into a seated position based on the LTV government reference vehicle seat. Simulations were performed across three GHBMC models with discrete body sizes that represent the 95^{th} and 50^{th} percentile male, and 5^{th} percentile female (Figure 2). However, NASA has requirements (e.g., EVAS System Requirements Document) that future spacesuits and vehicles must be able to accommodate an anthropometric population that contains 1^{t} percentile female to 99^{th} percentile male measurements. To properly assess the injury risk of all potential crew, simulations conducted with the GHBMC models must span the full anthropometric range.

Figure 2: 5^{th} female, 50^{th} male, and 95^{th} male percentile GHBMC models posed into a seated configuration.

In this paper, an anthropometric evaluation of the standard GHBMC models will be performed and measurements will be compared against requirements. As there is a gap between the GHBMC models and requirements, there is a need to morph or scale the body shape of the GHMBC models to accurately represent the NASA population. Existing tools to modify the GHBMC model body shape will be described, but these are limited when representing subtle changes to body morphology. On-going efforts to improve individualized body morphing will be described and demonstrated in a proof-of-concept example. Accurate dynamic injury assessments are critical to understanding mission risk profiles and informing safe vehicle design across the population.

ANTHROPOMETRIC EVALUATION OF GHBMC MODELS FOR LTV APPLICATIONS

Anthropometric measurements were taken on all three GHBMC models and compared to spacesuit hardware requirement standards found in NASA xEVAs system requirements document. In order to take measurements that are comparable to the standards, the pedestrian version of the GHBMC model was reposed into a standing posture (Figure 3). Digital measurements of the 5th percentile female and 95th percentile male GHBMC models were taken in the Anthroscan software (Humanetics, Kaiserslautern, Germany) utilizing standard NASA anthropometry measurement protocols (Gupta et al. 2024).

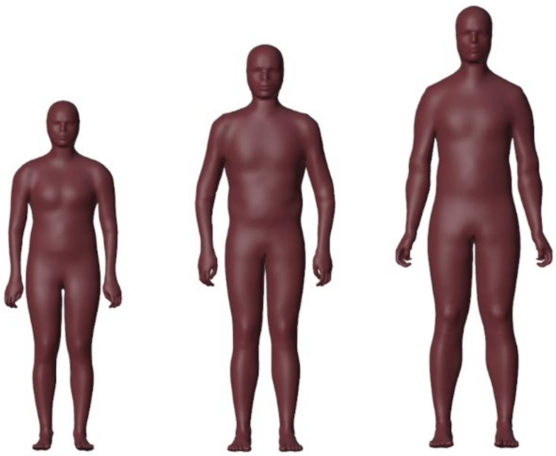

Figure 3: 5th female, 50th male, and 95th male percentile GHBMC models posed into standing posture.

The anthropometric dimensions for the GHBMC models are reported in Table 1. As anticipated, the 5th percentile female model is larger than the requirement minimum (Req min) in all anthropometric dimensions by an average difference of 4.8 cm. The largest difference was found in the right thigh circumference (7.3 cm, followed by a 6.2 cm difference in crotch height. Similarly, the 95th male GHBMC model was smaller than the requirement maximum (Req max) by an average of 2.4 cm. The largest difference for the 95th percentile male model was found in the chest breadth measurement (4.5 cm). However, the GHBMC lower body is close to the requirement maximum for hip breadth, right thigh circumference, and knee height (< 1.5 cm).

Table 1. GHBMC Anthropometric Measurement Comparison to Requirements (Unit: cm)

Measurement Name	5th percentile model [A]	Req Min [B]	Diff [A – B]	95th percentile model [C]	Req Max [D]	Diff [C – D]
Stature	**153.0**	**148.6**	**4.4**	**192.6**	**194.6**	**-2.0**
Crotch Height	**72.7**	**66.5**	**6.2**	**91.5**	**95.8**	**-4.3**
Inter-Acromion Distance	**37.0**	**32.3**	**4.7**	**40.2**	**44.5**	**-4.3**
Chest Breadth	**27.9**	**23.6**	**4.3**	**34.9**	**39.4**	**-4.5**
Chest Depth	**22.5**	**19.1**	**3.4**	**28.2**	**30.2**	**-2.0**
Hip Breadth	**32.7**	**29.7**	**3.0**	**40.5**	**40.6**	**-0.1**
Right Thigh Circumference	**55.1**	**47.8**	**7.3**	**71.4**	**71.9**	**-0.5**
Knee Height (Mid-patella)	**44.7**	**39.6**	**5.1**	**56.6**	**57.9**	**-1.3**

Since the GHBMC models do not exactly match the requirement minimums/maximums, there may be challenges when assessing LTV dynamic loading injury risk across the astronaut anthropometric range. Based on simulations results from Yates, Drake, and Davis (2024), possible injury modes include the chin or neck impacting the suit neck ring and fore/aft torso impacts with the HUT. For this injury scenario, it is important that individuals with minimum stature are assessed. Given the differences in suit sizing, the neck ring interference is often exacerbated for shorter individuals in a seated posture. Therefore, crewmembers with close to 1st percentile stature measurements may be at greater risk for head/neck injuries, when compared to the 5th percentile GHBMC model. With the chest breadth and chest depth being smaller than requirement values for both the 5th and 95th percentile models, injury risk may differ in fore-aft HUT injury scenarios. The amount of suit padding used for body indexing will differ for more extreme torso shapes. In addition to encompassing the overall maximum and minimums of the anthropometric range, it is necessary to evaluate worst-case anthropometry combinations most affected by the hardware to accurately capture injury risk for the given operation or design. For example, individuals with a larger head and a long neck could have greater injury risk when compared to the GHBMC models. Thus, there is a strong need to morph the body shape and size of the GHBMC to accurately represent critical anthropometric dimensions.

BODY SHAPE MORPHING EFFORTS FOR GHBMC MODEL AT NASA

To evaluate injury risk at anthropometry requirement extremes or worst-case combinations, the anatomical structure of the 5th and 95th GHBMC models can be virtually altered via morphing or scaling methods. The conventional approach is to use a spline interpolation function such as a radial basis function (RBF) to morph and change the body size of the HBM (Hwang et al. 2016; Zhang et al. 2017). At NASA, the open-source Position and Personalize Advanced Human Body Models for Injury Prediction (PIPER) software framework (Hwang et al. 2016) has been commonly used to morph the GHBMC model. In PIPER, a dynamic regression model is applied to generate manipulatable scaling targets (Figure 4), using user-selected anthropometric measurements as predictors for a given population such as the Anthropometric Survey of U.S Army Soldiers (ANSUR). The resulting scaling targets can then be used for kriging interpolation in PIPER (Jolivet et al. 2015) to scale the HBM (Figure 4). Kriging is a spatial interpolation technique that is similar to RBF, but calculates the localized, weighted averages of known values for prediction.

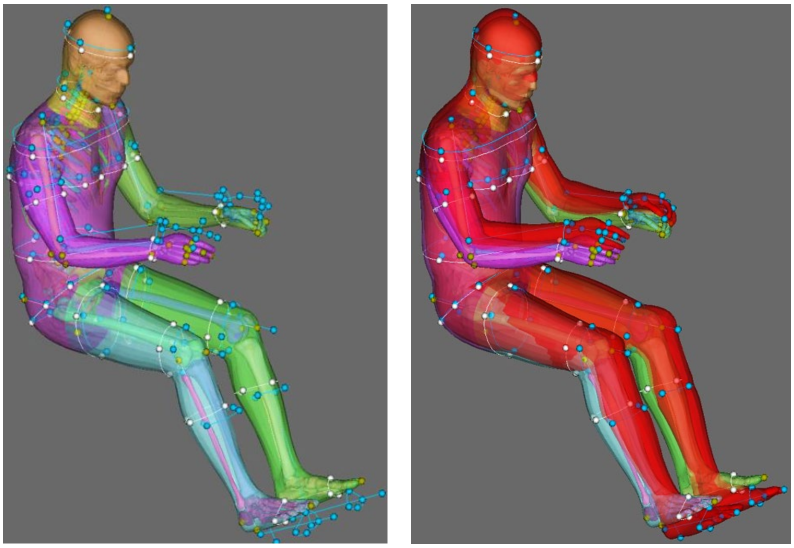

Figure 4: PIPER scaling module with desired scaling targets (blue) shown in the left image. Final morphed mesh (red) pictured in right image.

The default PIPER scaling pipeline may be constrained when representing subtle body shape morphology. Due to a fixed set of scaling targets, there can be challenges when representing important neck and shoulder region morphology. Specifically, there are minimal capabilities to adjust neck length, which can affect injury prediction for key LTV injury mechanisms (e.g., head colliding with internal spacesuit helmet surface). Furthermore, the scaling pipeline lacks the ability to reconstruct differing torso proportions with detailed, localized soft tissue bulging. Given the limitations of this scaling framework, alternative methods are being systematically investigated to better refine the scaling of the GHBMC models. One possible solution is to provide the scaling targets directly from a 3D scan of the body into the kriging morphing process instead of measurement-inferred scaling targets. NASA collects and maintains a large database of 3D body scans and poses, which would facilitate this approach.

The effectiveness of using scaling targets extracted from the 3D body scans was explored. Specifically, body scans that were close to the stature requirement mins and maxes, but with different torso proportions were evaluated. In this proof-of-concept example, only the torso region of the pedestrian GHBMC model was morphed to match 3D scans with different torso sizes and shapes (Figure 5). The torso region provided body shape morphology differences that were easily observable and was useful in determining initial feasibility of this approach. To facilitate consistent scaling target selection, the scans and GHBMC body model were parameterized with a homologous body shape template, which would allow for point-to-point mesh correspondence.

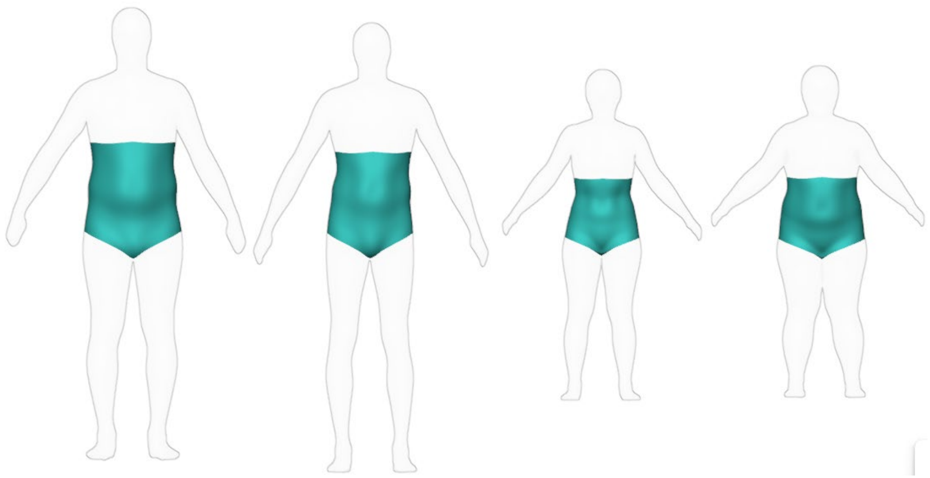

Figure 5: Selected torso shapes and sizes (blue) that vary in circumference, length, and shape.

A sparse set of scaling targets across the torso (Figure 6) were extracted from each homologous scan. These targets were imported into PIPER, in addition to matching landmarks on the GHBMC torso model. Direct kriging algorithms were then used to morph the GHBMC body shape. The skeletal structure was also scaled using similar kriging algorithms, but included additional constraints to mitigate bone protrusion through the skin (Jolivet et al. 2015). The vertex differences were then compared between the morphed model and original scan. The root mean squared error (RMSE) was calculated for each morphed model.

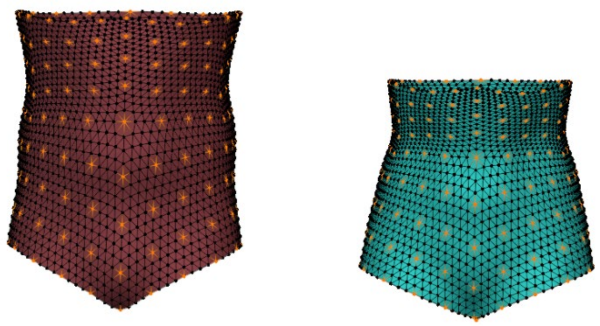

Figure 6: Control point distribution for GHBMC torso model (red) and scan torso model (blue).

Initial results from this proof-of-concept example were promising. Prediction errors across each morphed torso model are illustrated in Figure 7, as well as the underlying skeletal structures. The average RMSE across all torso shapes was 0.9 cm and all RMSE values were under 1.0 cm across all body shapes. The highest prediction errors generally resided near the crotch region across all body shapes. The basic skeletal structure seemed to be visually comparable with scaling results from similar PIPER morphing efforts (Zhang et al. 2017).

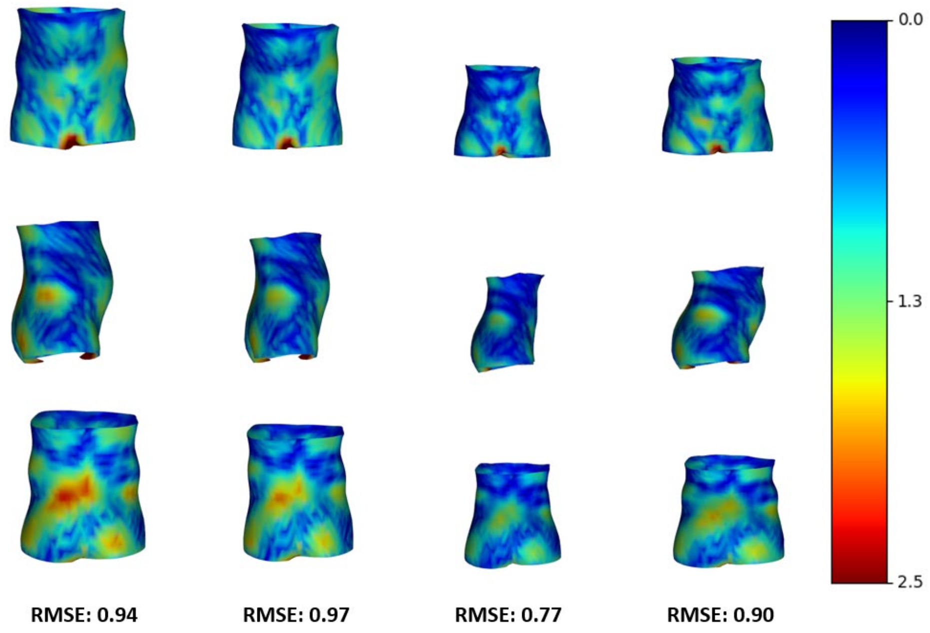

Figure 7: Color-coded prediction root mean square errors (RMSEs) across morphed torso shapes shown from the anterior (top row), sagittal (second row), and posterior (third row) view. [Unit: cm]

Figure 8: Hypothetical illustrations of underlaying skeletal structure for representative morphed model.

There are several areas for future work to improve the morphing approach using scans. To minimize morphing errors, it is important that the scan and HBM model are placed in very similar postures to reduce extrapolation variation. Therefore, additional work is planned to better align the default GHBMC seated model to the current NASA scan postures (Figure 8). The morphed models should be compared to anatomical imagery such as Computed tomography (CT), Magnetic Resonance Imaging (MRI), or dual energy X-ray absorptiometry (DEXA) scans to verify the accuracy of the internal anatomical structures. Sensitivity studies should also be conducted for LTV injury scenarios to better quantify the injury risk associated with small changes in anthropometry and body shape.

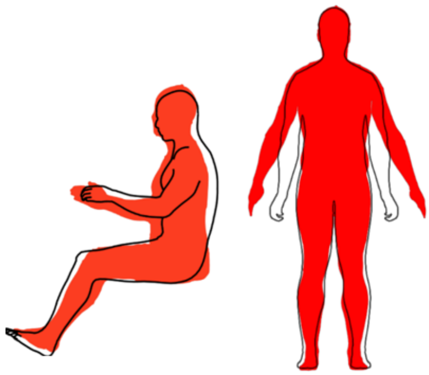

Figure 8: GHBMC model (black) overlaid with default scan posture (red).

An effective and efficient method to morphing HBMs would have several implications for spaceflight occupant protection. Dynamic loads assessments can be performed across the population and with more worst-case anthropometry represented. Thus, a deeper understanding of dynamic loading associated injury risks for LTV scenarios would be gained. This method could also be extrapolated to launch and re-entry scenarios of various spacecrafts. Personalized risk assessments could be performed for individual crewmembers and customized countermeasures (e.g., personalized padding configurations) could be provided.

CONCLUSION

For expected LTV dynamic loading scenarios, there are complex injury mechanisms that result from spacesuit-to-body contact. Body shape and size plays a large role in the severity and type of injury that can occur. The GHBMC model is used at NASA for dynamic loading injury assessments, but the current three GHBMC models are not representative of the worst-case anthropometry within the spacesuit requirements values. PIPER is a tool that can be used to perform body shape morphing and there is on-going work to investigate if scan data can be used to morph the models directly. Across different torso shapes and sizes, an average RMSE of 0.9 cm was observed, using the scan data for custom control point selection. While this is a promising first step, additional work is needed to morph the rest of the body to accurately represent worst-case anthropometry. With continued development and improvement of these scaling frameworks, HBMs can better assess the risk of dynamic loading injuries across the astronaut population. Ultimately, this knowledge will lead to greater occupant protection of crewmembers during spaceflight.

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