Development of Age and Sex-Specific Thorax Finite Element Models

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ABSTRACT

In motor vehicle crashes (MVCs), thoracic injury ranks second only to head injury in terms of the number of fatalities and serious injuries, the body region most often injured, and the overall economic cost. The shape, size, bone density, and cortical thickness of the thoracic skeleton vary significantly with age and sex. Computational modeling has emerged as a powerful and versatile tool to assess injury risk and improve the effectiveness of vehicle safety systems. However, current computational models only represent certain ages and sexes in the population. The purpose of this study was to morph an existing finite element (FE) model of the thorax using thin-plate spline interpolation to accurately depict thorax morphology for males and females of ages 0-100. The thin-plate spline is a smooth function that interpolates the connections between the nodes while minimizing the amount of change in landmark positions. In order to execute the thin-plate spline interpolation, homologous landmarks on the reference, target, and FE model are required. Homologous landmarks on the target geometries were previously collected using the Generalized Procrustes Analysis to create functions describing the size and shape changes and shape changes in the ribs and sternum for males and females of ages 0-100. The Global Human Body Models Consortium (GHBMC) thorax model was used as the reference mesh and the ribs, sternum, costal cartilage, intercostal muscles, spine, and simplified thoracic cavity were morphed accordingly based on the target homologous landmark data for the ribs and sternum. A total of 416 models were generated representing size and shape changes and shape changes of males and females for the following ages: 0 month, 3 month, 6 month, 9 month, and 1-100 years in one year increments. The biomechanical response of an average individual of a given age and sex was studied through simulations of various frontal and lateral impacts using hub loading and seatbelt loading. The development of these age and sex-specific FE models of the thorax will lead to an improved understanding of the complex relationship between thoracic geometry, age, sex, and injury risk.

INTRODUCTION

Motor vehicle crashes (MVCs) are a serious public health concern that resulted in more than 2,000,000 injured occupants and more than 33,000 fatalities in 2012 (National Center for Statistics and Analysis 2013). In MVCs, thoracic injury ranks second only to head injury in terms of the number of fatalities and serious injuries, the body region most often injured, and the overall economic cost (Cavanaugh 2002; Ruan, El-Jawahri et al. 2003).

Age and sex-related morphologic changes in the thorax may affect the injury tolerance especially in at risk populations such as pediatrics and the elderly. With a growing elderly population of adults aged 65+ years, which is projected to increase to 20% of the population by 2040, it is critical to understand the biomechanics of the human thorax with age since the elderly possess an increased risk of mortality and morbidity due to increased fragility and frailty (Finelli, Jonsson et al. 1989; Shorr, Rodriguez et al. 1989; Perdue, Watts et al. 1998; Stitzel, Kilgo et al. 2008; Hanna and Hershman 2009; Vincent and Velkoff 2010). In addition to age, there are structural and morphological differences in the thorax with sex (Weaver, Schoell et al. 2014). Studies have shown that females are more susceptible to severe injuries in comparison to males and analysis of real-world frontal MVCs determined that females and the elderly are the two most vulnerable groups of the entire population (Wang and Yang 1998; Welsh and Lenard 2001; Jingwen, Rupp et al. 2012). Variations in thoracic size, shape, bone density, and cortical thickness with age and sex will result in different injury tolerances to traumatic insults. In order to prevent and mitigate injuries, a better understanding of the biomechanics and injury mechanisms of the thorax is needed.

Computational modeling has emerged as a powerful and versatile tool to assess injury risk and improve the effectiveness of vehicle safety systems. Current finite element (FE) models are limited to certain ages and sexes in the population. The full-spectrum of ages was not investigated in any previous studies and females in particular are under-represented (Lizee, Robin et al. 1998; Plank 1998; Wang and Yang 1998; Deng, Kong et al. 1999; Ruan, El-Jawahri et al. 2003; Kent, Lee et al. 2005; Kimpara, Lee et al. 2005; Tamura, Watanabe et al. 2005; Gayzik, Loftis et al. 2006; Mattrey, Fournier et al. 2008; Ito, Dokko et al. 2009; Song, Trosseille et al. 2009; El-Jawahri, Laituri et al. 2010). While in theory, FE models can represent all ages and sexes, a limitation of FE modeling is the time-consuming process to develop subject-specific meshes. In order to accelerate the development of FE models, model morphing can be used to accurately and efficiently generate models of all ages and sexes. The purpose of this study is to develop and validate age and sex-specific FE models of the thorax to accurately model thorax morphology and mechanics for males and females of ages 0-100. The biomechanical response of an average individual of a given age and sex will be studied through simulations of various frontal and lateral impacts.

METHODS

Morph GHBMC M50 Thorax to Age and Sex-Specific Models

Development of age and sex-specific FE meshes involves morphing an existing FE model of the thorax using radial basis function (RBF) interpolation, specifically with a thin-plate spline as the basis function. The thin-plate spline is a smooth function that interpolates the connections between the nodes while minimizing the amount of change in landmark positions. The thin-plate spline procedure as detailed by Bookstein involves the calculation of a bending energy matrix, L, and a partial warp score matrix, W, to determine the interpolation function and coefficients to map the reference landmark coordinates to the target landmark coordinates. Subsequently, the calculated interpolation function and coefficients can be applied to other coordinates associated with the reference, i.e. the nodal coordinates of the FE model (Bookstein, Schäfer et al. 1999). Thin-plate spline regularization was employed to relax interpolation requirements so that resulting surface does not have to go exactly through all the control points. Regularization is controlled by the regularization parameter, λ, which was adjusted to achieve the highest element quality (Donato and Belongie 2002).

In order to execute the thin-plate spline interpolation, homologous landmarks on the reference, target, and FE model are required. An image segmentation and registration algorithm was previously used to collect homologous rib and sternum landmark data from males and females aged 0-100 years (Weaver, Nguyen et al. 2013). The Generalized Procrustes Analysis (GPA) was applied to the homologous landmark data to quantify age and sex-specific size and shape changes, as well as isolated shape changes in the thorax. The results of the GPA defined the target homologous landmarks for specific ages and sexes for inputs into the FE morphing. A total of 416 models were developed representing the size and shape changes and shape changes of males and females for the following ages: 0 month, 3 month, 6 month, 9 month, and 1-100 years in one year increments. The Global Human Body Models Consortium (GHBMC) thorax model was chosen as the baseline or reference mesh. The GHBMC is representative of a 50th percentile male (M50) and was based on medical images of a 26 year old individual (height- 174.9 cm, weight- 78.6 ± 0.77 kg, and BMI- 25.7 ± 0.25) (Gayzik, Moreno et al. 2011; Vavalle, Moreno et al. 2013). The GHBMC M50 thorax mesh used includes the ribs, sternum, costal cartilage, intercostal muscles, spine, and a simplified thoracic cavity. Although homologous landmark data was only collected for the ribs and sternum, associated structures such as the costal cartilage, intercostal muscles, spine, and simplified thoracic cavity are morphed accordingly due to the connection of elements. The GHBMC atlas mesh consisted of 134,051 nodes and 115,291 elements. In order to reduce computational time of the morphing process, a uniform 5% subsample of the landmarks from the reference and target were selected resulting in a reduction to 9,524 landmarks. The element quality of the reference and morphed FE models was analyzed by comparing the Jacobian (>0.3), warpage angle (<50°), and aspect ratio (<8). The morphing process depicted in Figure 1 was used to create a model representative of a 10 year old male's thoracic size and shape.

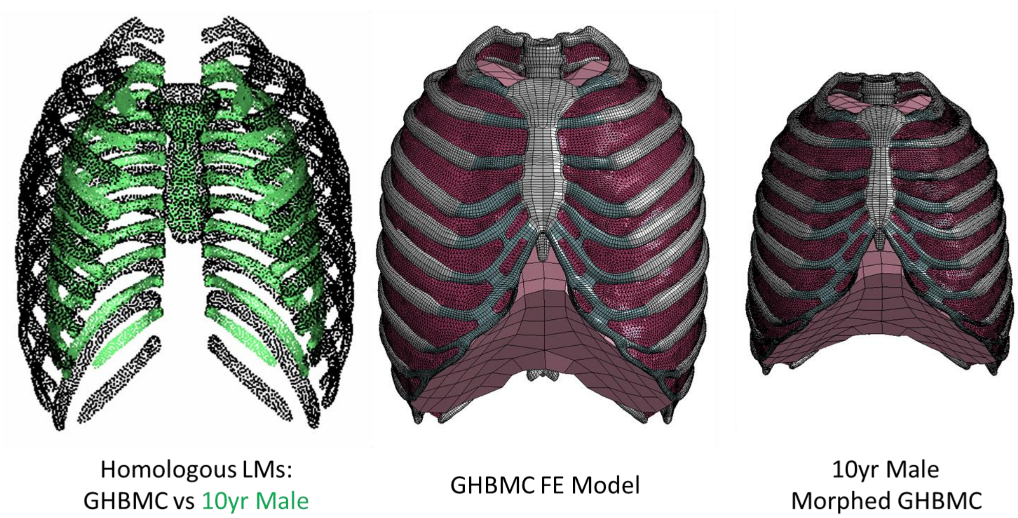

Figure 1: Depiction of the morphing process. On the left, the homologous landmarks for the reference and target configuration (10 year old male) are shown. In the middle, the GHBMC reference mesh and on the right, the resulting morphed 10 year old male.

Validation and Simulation

For validation purposes, a simplified full body model using the GHBMC M50 v4.2 was developed by combining the detailed thorax, detailed abdomen, rigid head, rigid neck, and rigid lower extremity as depicted in Figure 2. The simplified full body model allowed for faster run time in order to perform a greater number of simulations than with the full detailed model. The simplified full body model was validated against the following experimental testing conditions to assess numerical stability and overall responses of the model: thorax hub impact (Lebarbé and Petit 2012) and thorax lateral impact (Kemper, McNally et al. 2008).

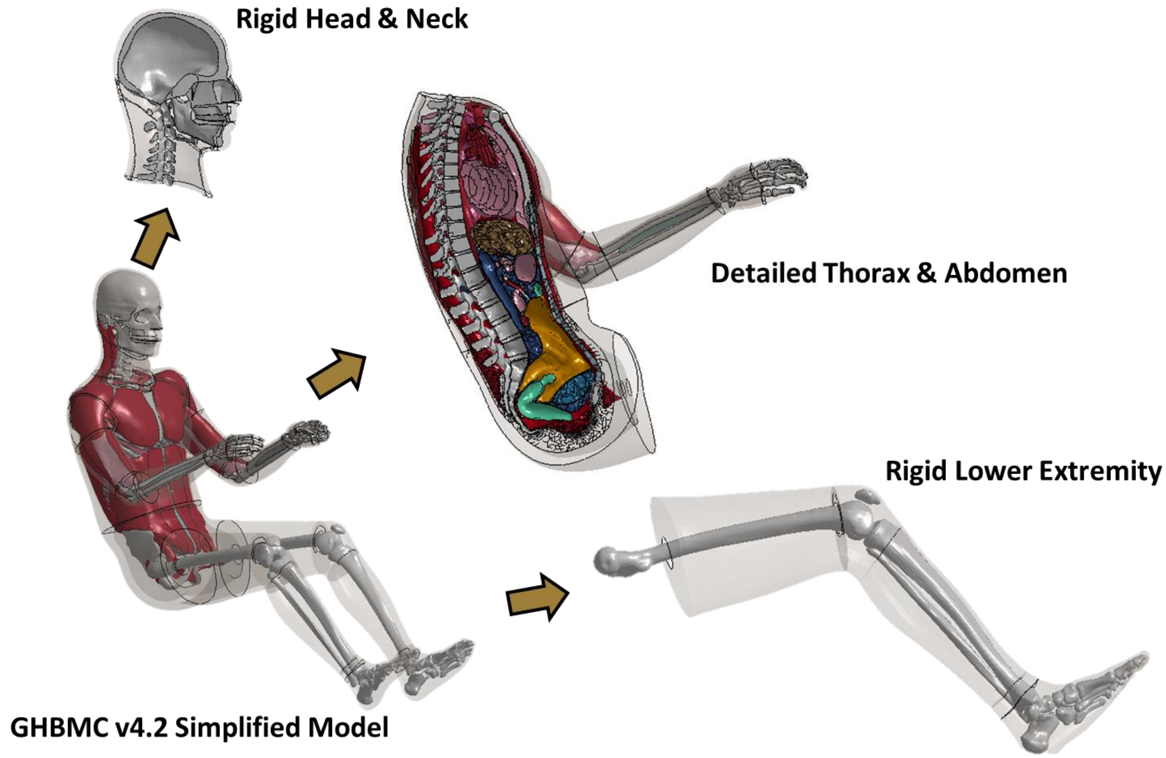

Figure 2: Full and cross-sectional views of the simplified full body model.

Since the M50 simplified full body model represents a 50th percentile male, only the age-specific thoracic shape change models (scaled to a 50th percentile male size) were included at this time. Once incorporated, the simplified full body FE model was used to characterize the response of the thorax based on shape changes alone for different loading conditions. For the purposes of this study, two loading cases of the thorax (frontal hub impact and lateral impact) were simulated for a 30 YO and 70 YO male for a total of 4 simulations (Table 1).The frontal hub impact was conducted at 6.7 m/s with a 23.4 kg cylindrical impactor striking the sternum at the 4th rib interspace. The raw data was mass-scaled to 75 kg using the method described by Eppinger and was filtered at 300 Hz with an SAE class filter (Eppinger, Augustyn et al. 1978). Deflection was normalized by chest depth and was calculated as a percentage to compare models. The lateral impact was conducted at 12.0 m/s with a 23.4 kg flat plate impactor striking the shoulder, arm, and ribs. The raw data was filtered at 600 Hz with an SAE class filter and mass-scaled to 76 kg.

Table 1: Simulation test matrix for 30 YO and 70 YO male

Model		Simulation	Velocity (m/s)	Evaluation Criteria
Age (yrs)	**Sex**			
30	Male	Frontal Hub Impact	6.7	F vs. D
		Lateral Impact	12.0	F vs. t
70	Male	Frontal Hub Impact	6.7	F vs. D
		Lateral Impact	12.0	F vs. t

RESULTS

Select ages of the rib cage FE models illustrating the size and shape changes in both males and females are depicted in Figure 3 and Figure 4. For ages 0-20, there is an increase in size, a decrease in upper thoracic kyphosis, and an inferior rotation of the ribs. For ages 20-60, there is an increase in thoracic kyphosis and superior rotation of the ribs. For ages 60 and older, there is an increase in thoracic kyphosis, an inferior rotation of the ribs, and a superior rotation of the lower ribs.

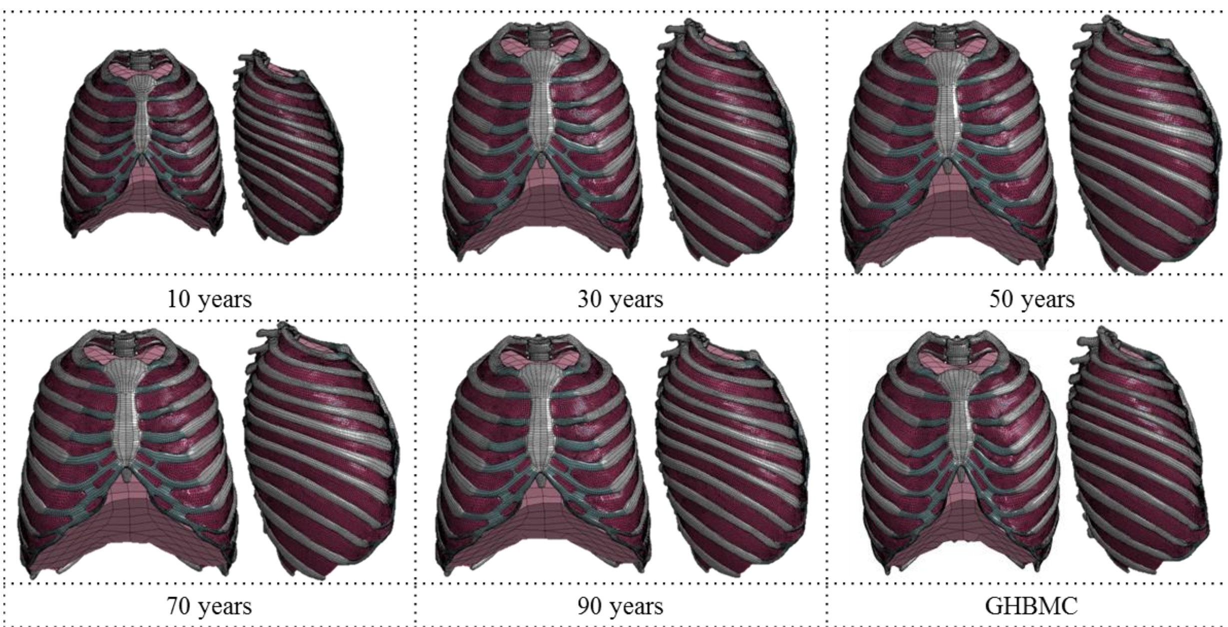

Figure 3: Rib cage finite element models illustrating the size and shape changes in males.

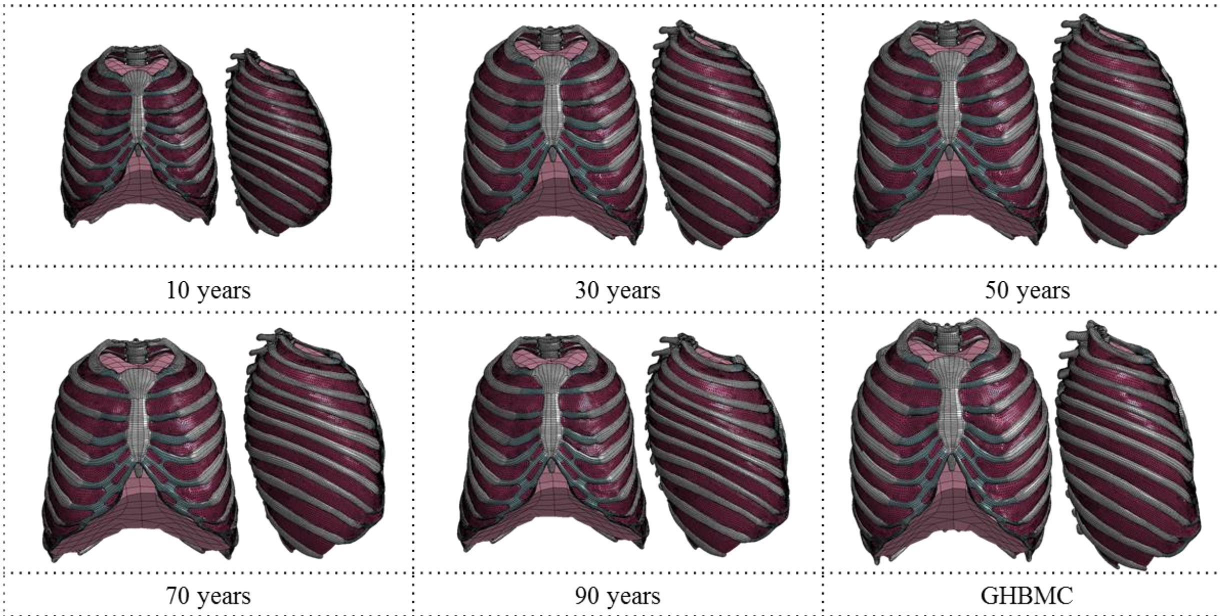

Figure 4: Rib cage finite element models illustrating the size and shape changes in females.

The results of the element quality assessment are shown in Table 2 for the models illustrated in Figure 3 and Figure 4. For the 3D elements of the GHBMC model, the target element quality standards that are sought include a Jacobian above 0.3, an aspect ratio below 8, and a warpage below 50 degrees (Global Human Body Models Consortium 2014). Overall, the element quality of the morphed FE model was comparable to the GHBMC reference model. The values shown in Table 2 are prior to mesh refinement and cleanup. Therefore, mesh adjustments will be performed on models with elements not meeting the thresholds to improve overall element quality.

The simplified full body model was validated against a set of experimental testing conditions that were also used in the GHBMC M50 v4.2 validation. Overall responses of the simplified model were comparable to the experimental data as well as the GHBMC M50 v4.2. The simplified full body model responses resulted in slight deviations from the GHBMC M50 v4.2 due to the simplifications of the head and neck.

The resulting morphed simplified full body models of the 30 YO and 70 YO are shown in Figure 5. The shape changes are evident in comparison to the GHBMC v4.2 as the rib angle increases with age as well as an outward expansion of the lower ribs. The preliminary results of the simulations for the 30 YO and 70 YO male for the frontal hub impact and lateral impact are shown in Figure 6 and Figure 7. Due to the geometrical changes with age, there were observed differences in the response of the thorax in both the frontal and lateral impacts. The 30 YO and 70 YO both resulted in greater deflection in comparison to the simplified GHBMC v4.2 model with the 30 YO experiencing the greatest deflection. The 30 YO predicted 2 rib fractures and the 70 YO predicted 3 rib fractures. The experimental data for this test configuration resulted in 9.4 ± 7.2 rib fractures.

For the lateral impacts, the 30 YO and 70 YO also experienced higher peak forces for the lateral impact in comparison to the simplified GHBMC v4.2. The 30 YO predicted a total of 9 rib fractures (3 Posterior, 6 Anterior/Lateral) on the impacted side and 1 rib fracture on the non-impacted side. The 70 YO predicted a total of 8 rib fractures (3 Posterior, 5 Anterior/Lateral) on the impacted side and 1 rib fracture on the non-impacted side. In the experimental data, the two subjects experienced 21 rib fractures on the impacted side and 1 to 2 rib fractures on the non-impacted side.

Table 2: Morphing and element quality results

	Jacobian Range	**% of Elements Not Meeting Threshold (> 0.3)**	**Aspect Ratio**	**% of Elements Not Meeting Threshold (<8)**	**Warpage (deg)**	**% of Elements Not Meeting Threshold (<50°)**
GHBMC Ref. 3D Elements	0.30-0.99	0.00%	1.02- 13.65	0.14%	0.28-94.60	0.82%
Male- Age 10 3D Elements	0.29- 0.99	0.01%	1.04-15.47	0.16%	0.26-99.24	0.84%
Male- Age 30 3D Elements	0.29-0.99	0.01%	1.05-15.48	0.14%	0.29-101.62	0.87%
Male- Age 50 3D Elements	0.28-0.99	0.01%	1.05-15.47	0.13%	0.21-104.25	0.91%
Male- Age 70 3D Elements	0.28-0.99	0.01%	1.06-15.11	0.13%	0.26-104.35	0.94%
Male- Age 90 3D Elements	0.30-0.99	0.01%	1.03-14.42	0.12%	0.23-103.38	0.96%
Female- Age 10 3D Elements	0.29-0.99	0.01%	1.03-14.95	0.14%	0.20-101.85	0.86%
Female- Age 30 3D Elements	0.29-0.99	0.01%	1.02-14.82	0.14%	0.23-98.98	0.90%
Female- Age 50 3D Elements	0.28-0.99	0.01%	1.03-14.44	0.13%	0.28-100.62	0.96%
Female- Age 70 3D Elements	0.28-0.99	0.01%	1.06-13.08	0.13%	0.30-103.21	0.97%
Female- Age 90 3D Elements	0.29-0.99	0.02%	1.02-14.03	0.13%	0.32- 107.40	1.05%

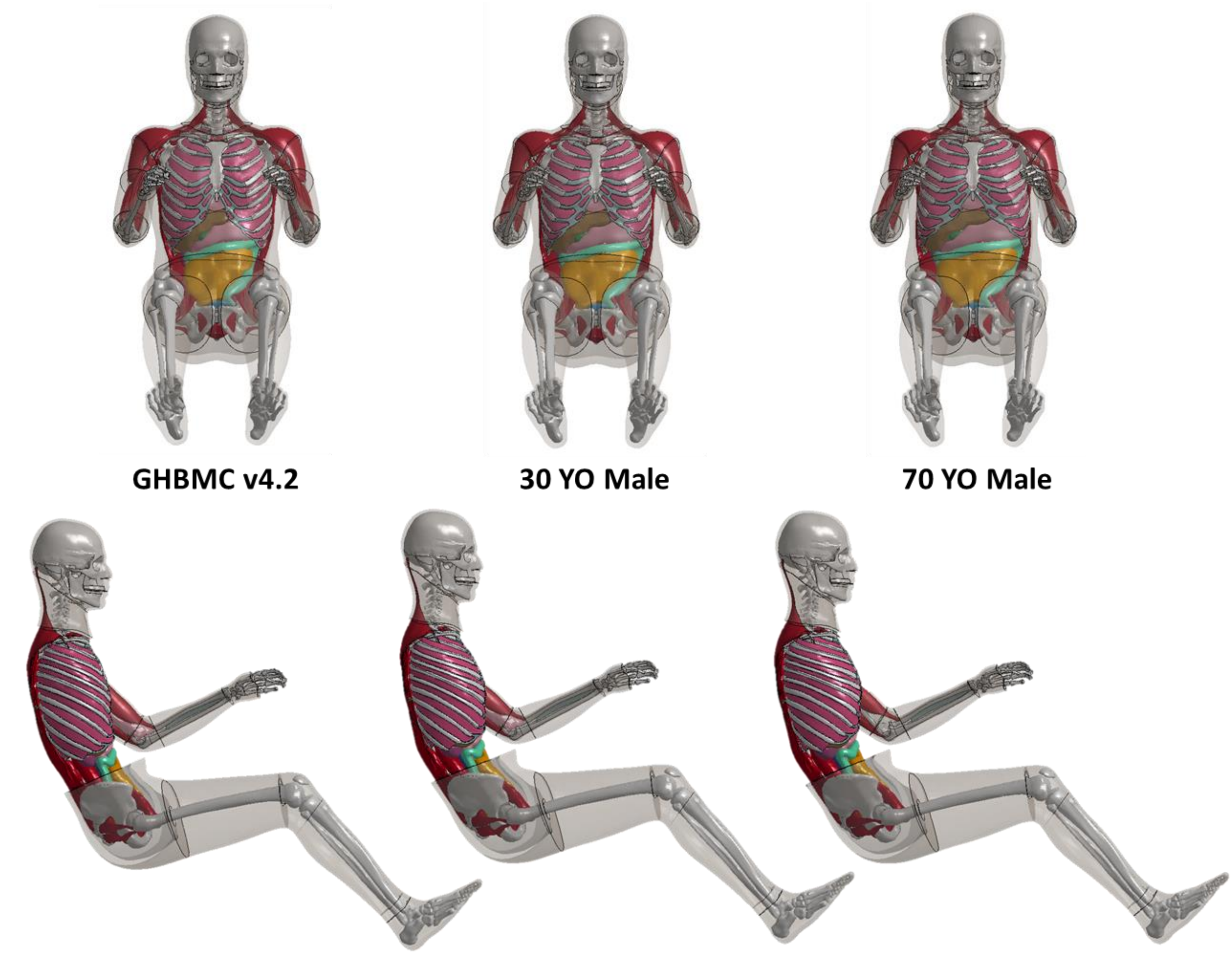

Figure 5: Comparison of the simplified GHBMC v4.2, 30 YO male, and 70 YO male models.

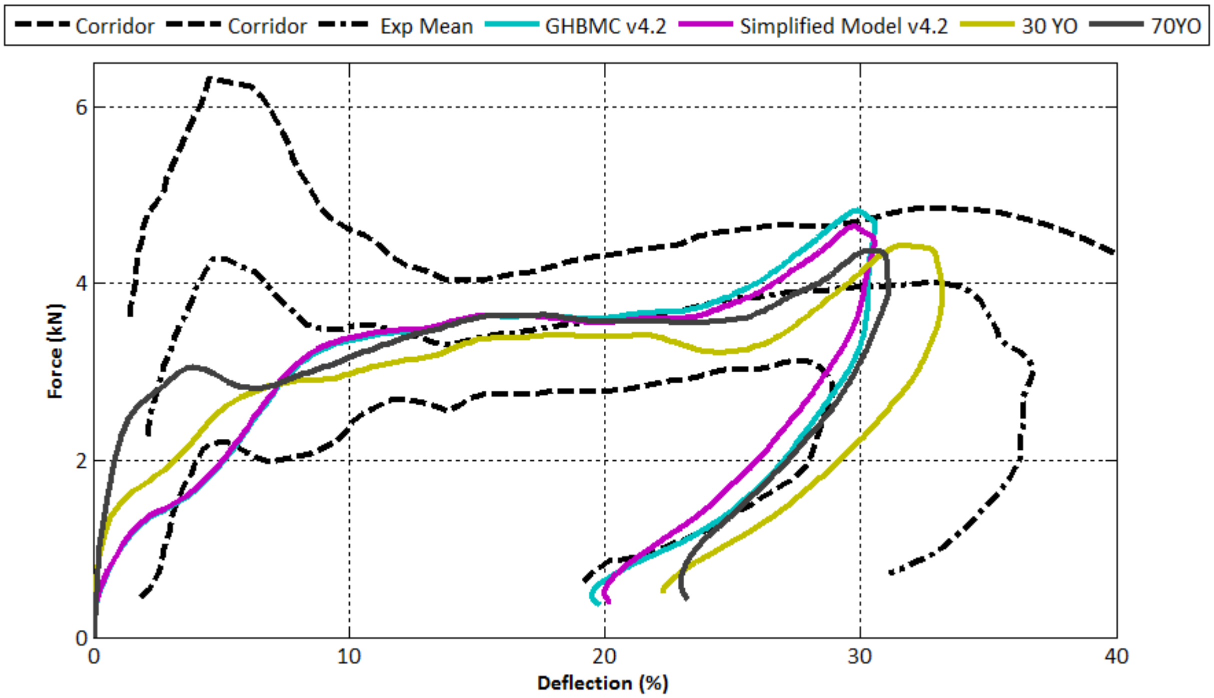

Figure 6: Force vs. deflection for thoracic frontal hub impact.

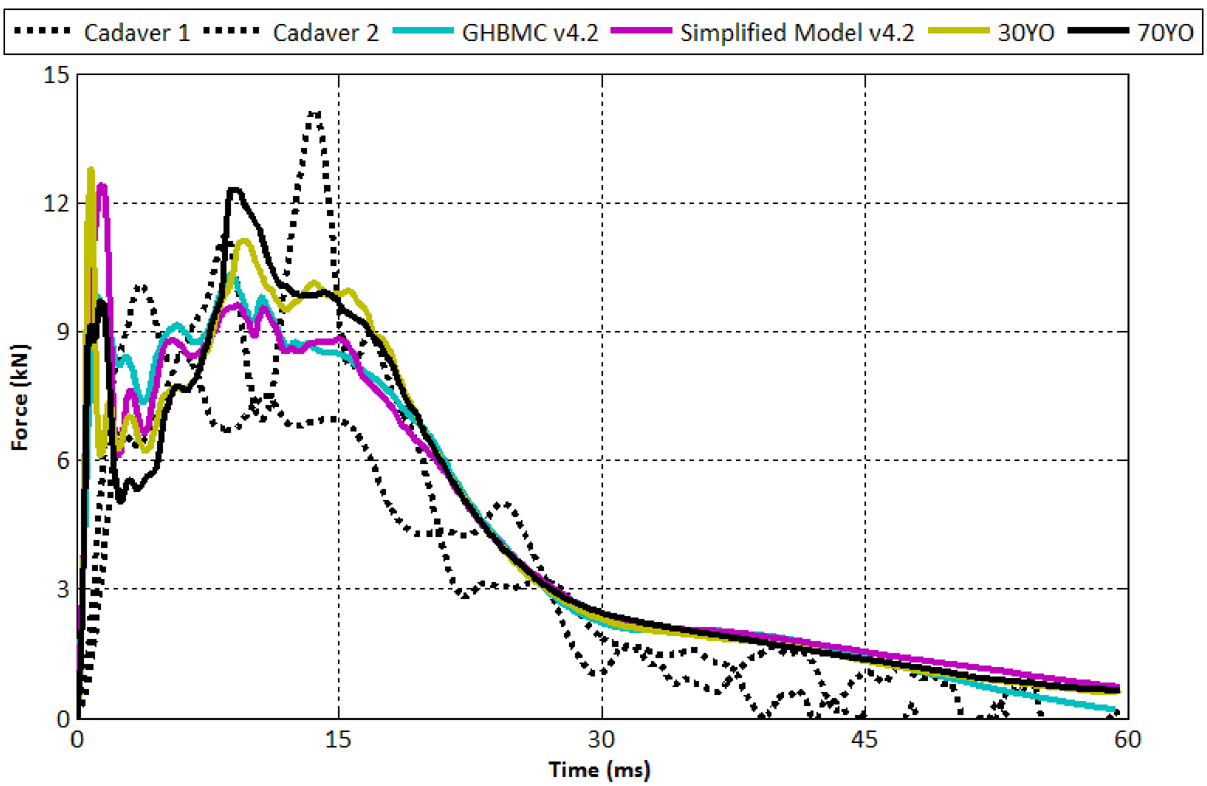

Figure 7: Force vs. time for thoracic lateral impact.

DISCUSSION

Shape changes due to age resulted in different responses of the thorax. For the frontal impact, the 30 YO experienced the greatest deflection as well as peak force. However, due to the horizontally angling of the ribs relative to the spine with age, it would be expected that the 70 YO would experience the most deformation. For the lateral impact, the 30 YO experienced the greatest peak force which is expected since maximum force generated decreases with age (Gayzik, Loftis et al. 2006). Incorporation of variable cortical thickness as well as material property changes with age could yield differing responses.

The results presented focused on only the geometrical differences with age. Further characterization of the thoracic response with age and sex will be completed. Studies have shown that material properties are related to age (Stitzel, Cormier et al. 2003; Kemper, McNally et al. 2005; Kemper, McNally et al. 2007). Future work includes implementing material property changes with age and sex based on the literature. One limitation of the morphing technique is that it does not account for variability in cortical bone thickness. Cortical bone thickness is modelled by shell elements overlaid on top of the solid elements. Future work includes incorporation of cortical thickness differences with age and sex based on medical imaging data.

Additional future work includes validation and simulation of the size and shape FE models. Techniques will be developed to incorporate mass scaling and body segment masses to account for the size differences across different ages. Simplified simulations will be performed with reduced anatomy in order to characterize the biomechanical response and injury tolerance due to the combined size and shape effects.

Understanding the age and sex-specific biomechanics of the thorax will lead to advancements in vehicle safety design such as restraint systems which could be tailored to an occupant's age and sex. Assessment of injury risk and effectiveness of the performance of vehicle safety systems can be performed using computational models. Current FE models are limited to certain ages and sexes in the population. Development of age and sex-specific FE models of the thorax will provide valuable tools for evaluating vehicle crashworthiness and understanding variations in thoracic injury patterns due to MVCs across populations. The goal of this proposed research was to develop the age and sex-specific FE models to predict, prevent, and mitigate thoracic injuries for the whole population with specific interest in at risk populations including pediatrics and the elderly.

CONCLUSIONS

Morphed age and sex-specific FE models of the thorax were developed using thin-plate spline interpolation. The advantages of this approach include smooth interpolation between the reference and target geometry and a time efficient method of developing a large number of FE models in comparison to the development of patient-specific models. The GHBMC thorax model was used as the reference mesh and the ribs, sternum, costal cartilage, intercostal muscles, spine, and simplified thoracic cavity were morphed accordingly based on the homologous landmark data for the ribs and sternum. Validation and simulation was completed to analyze the effects of thoracic shape changes for age and sex. The development of these age and sex-specific FE models of the thorax will lead to an improved understanding of the complex relationship between thoracic geometry, age, sex, and injury risk. The improved understanding gained from these models will aid in changes in restraint design and use to not only reduce injuries but also save lives.

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