Original Article
EPIDEMIOLOGY/GENETICS

Obesity

Impact Response Comparison Between Parametric Human Models and Postmortem Human Subjects with a Wide Range of Obesity Levels

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Objective: Field data analyses have shown that obesity significantly increases the occupant injury risks in motor vehicle crashes, but the injury assessment tools for people with obesity are largely lacking. The objectives of this study were to use a mesh morphing method to rapidly generate parametric finite element models with a wide range of obesity levels and to evaluate their biofidelity against impact tests using postmortem human subjects (PMHS).

Methods: Frontal crash tests using three PMHS seated in a vehicle rear seat compartment with body mass index (BMI) from 24 to 40 kg/m^2 were selected. To develop the human models matching the PMHS geometry, statistical models of external body shape, rib cage, pelvis, and femur were applied to predict the target geometry using age, sex, stature, and BMI. A mesh morphing method based on radial basis functions was used to rapidly morph a baseline human model into the target geometry. The model-predicted body excursions and injury measures were compared to the PMHS tests.

Results: Comparisons of occupant kinematics and injury measures between the tests and simulations showed reasonable correlations across the wide range of BMI levels.

Conclusions: The parametric human models have the capability to account for the obesity effects on the occupant impact responses and injury risks.

Obesity (2017) **25**, 1786-1794. doi:10.1002/oby.21947

Introduction

The proportion of the population with obesity has increased significantly worldwide since the 1980s, according to the World Health Organization. In the United States, the prevalence of overweight and obesity was 68.8%, and 35.7% for obesity alone, among adults in 2009-2010 (1). A study by Finkelstein et al. (2) predicted that the prevalence of obesity would be up to 42% in the United States in 2030.

Obesity may bring challenges for occupant protection in motor vehicle crashes. Field data analyses have shown that occupants with obesity have higher risks of fatality and injury in frontal crashes than individuals with normal weight (3-7). Specifically, the chest, lower extremities, and spine are more likely to be injured for occupants with obesity than other occupants. Cormier (3) reported that occupants with obesity had 26% and 33% higher risks of Abbreviated Injury Scale (AIS) 2+and AIS 3+thoracic injuries, respectively. Rupp et al. (8) estimated that AIS 3+lower-extremity injuries and spine injuries in frontal crashes would be reduced by 8% and 28%, respectively, if no vehicle occupants obesity. Desapriya et al. (9) and Simmons et al. (10) also found that obesity was associated with higher risks of fatality and lower-extremity fracture in frontal crashes.

While field crash-injury data have helped us understand the effects of obesity on occupant injury risks, laboratory tests are needed to understand the obesity effects on human impact responses, injury mechanism, and injury tolerance. The computational models of occupants with obesity, once validated, can further help us evaluate and improve vehicle safety designs for occupants with obesity. Forman et al. (11-14) compared the kinematics of five postmortem human subjects (PMHS) in frontal crash tests and found that high-BMI PMHS experienced greater body excursions due to the higher kinetic energy than low-BMI PMHS. Turkovich et al. (15) also reported that the increased body mass was the most significant factor affecting the injury risks for occupants with obesity. Cormier (3) found that the adipose tissues of an occupant with obesity may

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Funding agencies: This study was supported by National Science Foundation (award no.: 1300815). The authors would also like to thank China Scholarship Council for supporting student travel and living expenses at the University of Michigan.
Disclosure: The authors declared no conflict of interest.
Received: 9 May 2017; **Accepted:** 27 June 2017; **Published online 17 August 2017. doi:10.1002/oby.21947**

move the belt away from the bony structures, which may increase the injury risks for occupants with obesity. By analyzing volunteer seating and belt fit data, Reed et al. (16) concluded that a 10 kg/m^2 increase in BMI was associated with lap belt position 43 mm further forward and 21 mm higher relative to the anterior-superior iliac spines of the pelvis. Such belt fit has the potential to significantly degrade the restraint system performance in frontal crashes.

In the literature, injury assessment tools, such as crash test dummies and computational human body models, have mainly focused on occupants with normal weight, and injury assessment tools for populations with obesity are largely lacking. For example, only a few human models representing occupants with obesity are available in the literature. Kim et al. (17) and Turkovich et al. (15) developed occupant models with obesity using multibody simulation by adding a facet mesh representing more realistic body shapes of occupants with different BMI levels. However, it is difficult for multibody models to accurately simulate the complex interactions between the seat belt and the adipose tissues in the abdominal area.

Finite element (FE) models have been widely used in the injury biomechanics field as an important tool to study human impact response and assess injury risk. The basic principle of the FE method is to divide a continuous body into discrete small elements. By assigning proper material properties to different anatomical structures (e.g., bone, soft tissues) and defining contacts and other boundary conditions between adjacent components, FE human models offer the capability to investigate kinematic responses and stress and strain distributions throughout the human body in a crash event. Because the traditional method to build a whole-body FE human model is extremely time-consuming (18,19), Shi et al. (20) developed four FE human models with a constant midsize male stature but different BMI levels (25/30/35/40 kg/m^2) by morphing a baseline, midsize, male FE model. However, the body geometries of the morphed models only focused on the obesity effects on the torso but not the lower extremities, and they did not consider the effects of age, stature, and sex. Furthermore, in Shi's study, only the model-predicted obesity effects on the general trends of body excursions were compared to the PMHS tests; the subject-specific impact responses and injury measurements could not be evaluated because of the lack of subject-specific human models.

As the technology for morphing FE human models has advanced, the question of how to evaluate these morphed parametric human models has become important. Historically, most human models for crash simulation have been created to match the reference anthropometry of crash test dummies, particularly the so-called "50th-percentile male" and "5th-percentile female." These models are then validated against the biomechanical response corridors (mean ± standard deviation of normalized impact responses from multiple PMHS tests) that have been developed for validating crash test dummies of the same sizes (19,21). However, this methodology is insufficient for validating generalized parametric human models that can represent a wide range of body sizes. Instead, validation of these highly flexible models requires a subject-specific modeling paradigm. Klein et al. (22) developed a set of subject-specific femur FE models by morphing a template FE model to match femur geometries in PMHS tests. They found that subject-specific femur models produced more accurate impact responses than a single midsize male model or scaled models using traditional scaling techniques. Hwang et al. (23) developed a method to rapidly morph a baseline whole-body human model to diverse human characteristics and evaluated the morphed models against two PMHS in side impacts (24). However, these two PMHS were both normal weight (BMI < 30 kg/m^2).

In the current study, we extended Hwang's approach to frontal impacts with a wider range of BMI levels. Unfortunately, very few whole-body crash tests with PMHS have been conducted with the level of subject characterization needed to perform accurate subject-specific modeling. Conceptually, values for all FE-model parameters that affect the simulation should be derived from measurements of the specimen. In practical terms, detailed geometric data, including the sizes and shapes of the whole body, skeletal components, and internal organs, can be obtained using modern imaging methods. However, relatively few whole-body PMHS tests have been conducted in which even supine computed tomography data are available, and we are not aware of any published tests in which the pretest seated skeletal posture and body shape are well characterized.

The current work was based on three PMHS tests in a rear seat, frontal crash scenario reported by Forman et al. (11-14). We have detailed experiment conditions and standard anthropometric dimensions for the three tested subjects. The objective of this study was to compare the simulation outcomes using the parametric human models generated by mesh morphing with the results of the PMHS tests.

Methods

Method overview

Figure 1 shows the method for developing and evaluating the morphed human models. Three frontal crash tests using PMHS with a wide range of BMI values were first selected. Skeleton and external body shape geometry targets were then generated for the three PMHS based on the statistical models developed previously (25-29). After the skeleton was positioned into the external body shape, mesh morphing was applied to morph a baseline FE human model into three models accounting for the subject-specific geometry. Simulations were conducted using these three morphed models based on the test conditions reported by Forman et al. (11-14). The outputs were compared with the PMHS test results.

Developing subject-specific whole-body human models by mesh morphing

The method for rapid generation of a subject-specific human model by mesh morphing has been reported in our previous studies (23). First, with a given target age, sex, stature, and BMI, the skeleton (including rib cage, femur, and pelvis) and external body shape geometries were predicted by the statistical geometry models developed previously (25-29). Second, a rigid registration algorithm was used to position the bones into the external body surface based on the bony landmarks (e.g., suprasternal notch, anterior-superior iliac spine, posterior-superior iliac spine) and joint centers (e.g., T1, T8, hip) available in the external body shape model. Third, the Total Human Model for Safety (THUMS) v4.01 midsize male model was used as the baseline model to be morphed into the target geometry using a radial basis function (RBF). The THUMS model has different versions with different mesh densities and anatomical features. Among them, THUMS v4 is the most widely used in the injury

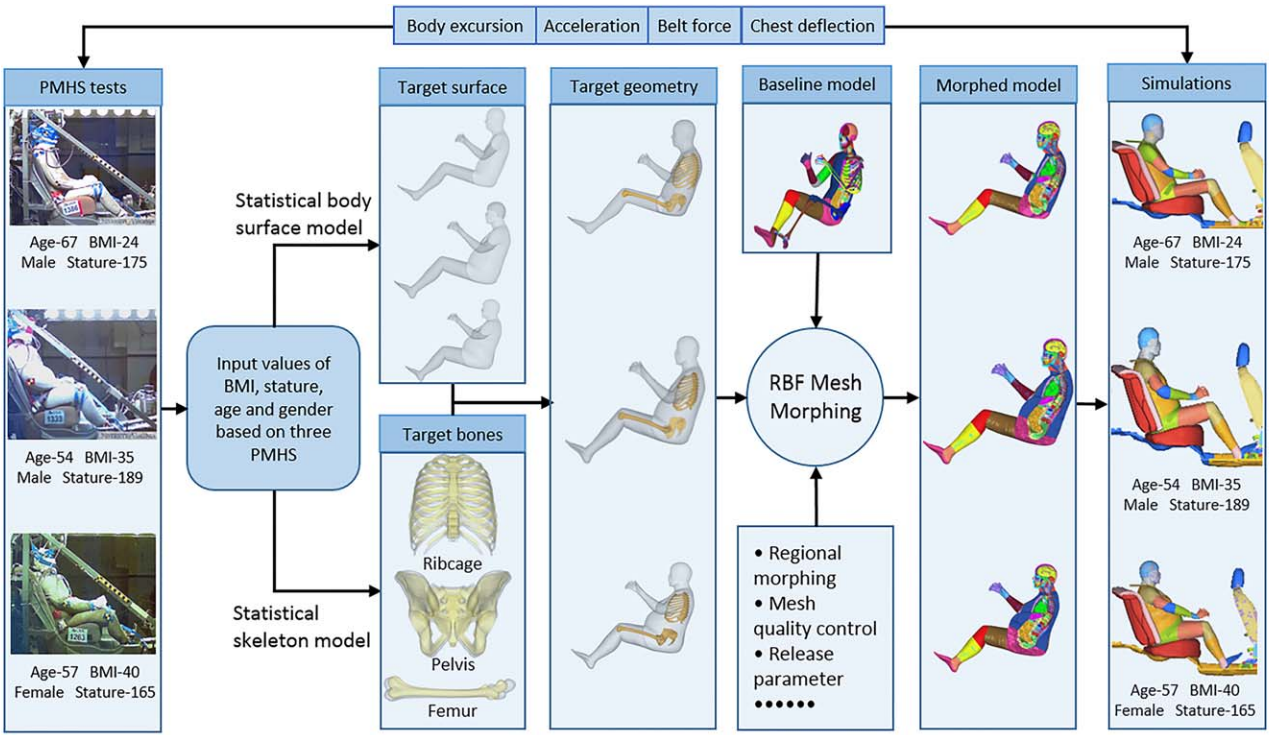

Figure 1 Method overview for developing and evaluating morphed human body models. [Color figure can be viewed at wileyonlinelibrary.com]

biomechanics field, which has detailed anatomical structures with about 2 million elements but no active muscle functions, while the most recent released version, THUMS v5, consists of only about 600,000 elements but has 262 one-dimensional Hill-type muscle models over the entire body for muscle activation. Because the main objective of this study was to validate the morphed human models against PMHS tests, THUMS v4 was chosen as the baseline model to better simulate the detailed anatomical structures without considering the active muscle forces. To conduct the whole-body mesh morphing, a large set of corresponding nodes was selected on the skeleton and external body surface between the THUMS and the target geometry to morph the internal organs and other soft tissues. More details of the RBF mesh morphing methods can be found in our previous studies (24,30).

PMHS test setup

Generally speaking, it is extremely difficult to conduct cadaver tests with a large sample size due to cadaver availability and the associated high cost. The outcomes of three PMHS frontal crash tests at 48 km/h conducted previously by Forman et al. (13) were used to evaluate the simulated outcomes with the morphed human models. The three PMHS included a male subject with a stature of 175 cm and BMI of 24 kg/m^2, a male subject with a stature of 189 cm and BMI of 35 kg/m^2, and a female subject with a stature of 165 cm and BMI of 40 kg/m^2, which covered a wide range of stature and BMI for both males and females. The impact velocity was based on Federal Motor Vehicle Safety Standard 208 (31) with a crash pulse from a popular midsize sedan. Because the goal of PMHS tests was to understand the impact kinematic difference between the occupants with different BMI levels, rear seat sled tests with simplified boundary conditions were used. In the tests, the subjects were positioned on the right side of a rear seat in a test buck designed to represent the rear occupant compartment of a 2004 Ford Taurus. The front seats were removed to better monitor the interaction between the PMHS and the seat belt without the potential confounding effects from the knee-to-front-seat interaction. The feet of the PMHS were blocked using a rigid plate at the front seat position. The sled test buck and the crash pulses are shown in Figure 2A and 2B. The front seat was installed on the buck (shown in Figure 2A) to record initial subject position measurements and was removed prior to each test. The sled test with the BMI-40 PMHS was performed using a standard three-point belt without pretensioner and load limiter, while the sled tests with BMI-24 and BMI-35 PMHS were performed using an advanced belt system with a retractor pretensioner and a progressive load limiter with 3 kilonewtons and 6 kilonewtons force levels (Figure 2D).

Model setup and result evaluation

A 2001 Ford Taurus FE model previously developed by the National Crash Analysis Center was used to represent the sled buck (Figure 2C). Before the simulation, the three morphed human models were positioned according to PMHS hip location and torso angle measured before the tests. Presimulations were performed to adjust the upper and lower extremities to the testing locations. The seat belt was fitted based on the routes identified from PMHS pretest photos. The initial stress in the seat cushion due to the PMHS weight was simulated by compressing the seat cushion using a body-surface pusher at the beginning (first 8 ms) of the simulation. The body excursions (head, shoulder, pelvis, and knee), chest deflection, belt forces, and body accelerations (head, pelvis, and T8 vertebrae) were

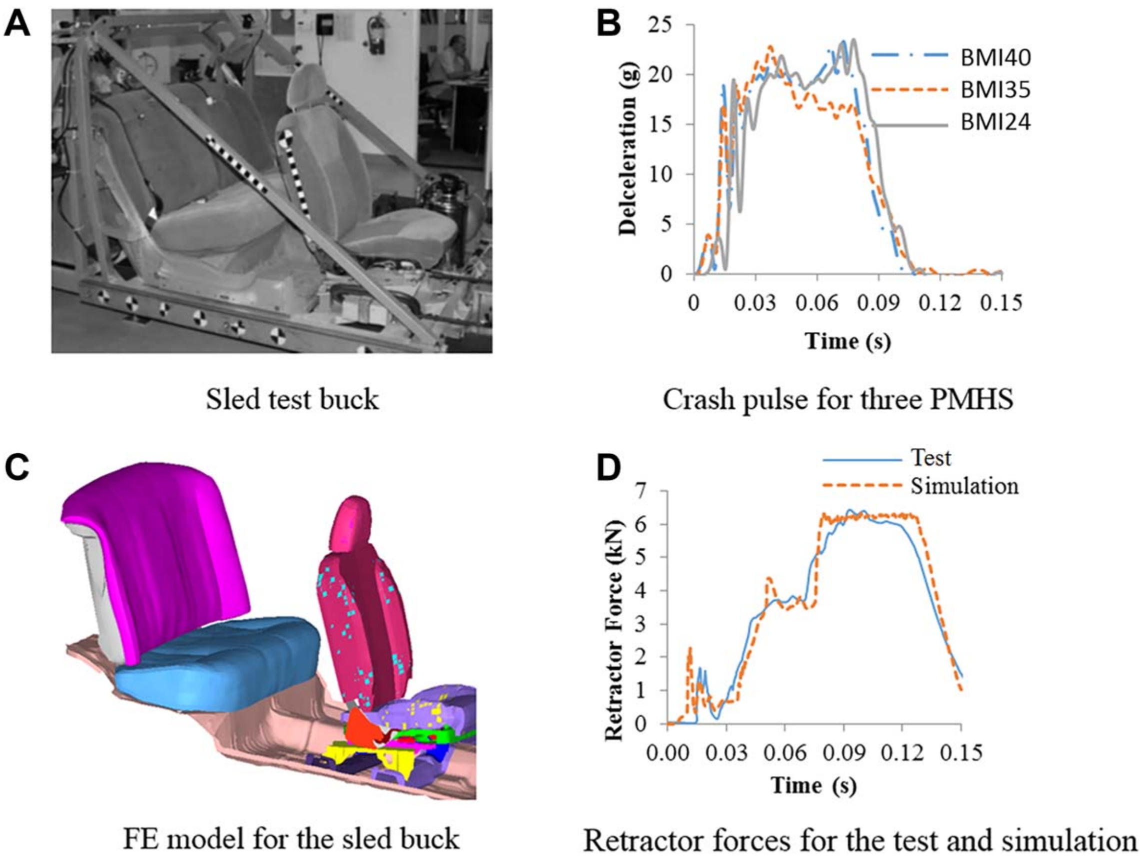

Figure 2 Sled test conditions and model setup. [Color figure can be viewed at wileyonlinelibrary.com]

measured for all three simulations. Different filters (SAE CFC1000, CFC180, and CFC60) were used for different measurements following the Society of Automotive Engineers standard (32), which is consistent between the tests and simulations. To quantitatively compare the impact responses between the morphed human models and PMHS, errors in the peak values and correlation and analysis (CORA) ratings were calculated. The CORA score was calculated using the cross-correlation metric, which measures the extent of linear relationship between the time histories of test and simulation signals based on ratings of phase, size, and shape.

Results

Overall, the morphed models had similar mesh quality as the baseline model. Comparisons of occupant kinematics and injury measurements between the tests and simulations showed reasonable correlations across the wide range of BMI levels.

Morphed subject-specific human models

The target and model-predicted subject characteristics of the three morphed models are shown in Table 1. The differences in weights between the morphed models and their weight targets were all below 3%. The mesh qualities evaluated by Jacobian for both 2D and 3D elements are shown in Table 1 as well. The threshold value of Jacobian was 0.7 for 2D elements and 0.5 for 3D elements. Although the mesh qualities for the morphed model were slightly lower than the baseline model, the simulations ran smoothly without any numerical errors.

Kinematics comparison between the simulations and tests

Figure 3 shows the occupant kinematics comparison between the simulations and PMHS tests. The two PMHS with BMI $> 30\,kg/m^2$ produced substantially greater body excursions than the BMI-24 PMHS, especially in the pelvis, and produced more submarining-type of kinematics. As an example, even with a standard seat belt system without load limiter, the pelvis excursion of the BMI-40 PMHS was 65% greater (380 mm vs. 230 mm) than that of the BMI-24 PMHS (13). The simulation results with the morphed high-BMI human models showed consistent trends with the PMHS test results. In general, the body excursion errors were small ($<$ 10%), except the knee excursion for the BMI-24 subject and the shoulder excursion for the BMI-40 subject, which deviated by less than 15%.

Injury measure comparison between the simulations and tests

Table 2 and Figure 4 show the injury measurement comparison between the simulations and PMHS tests. The resultant head, chest, and pelvis accelerations, chest deflection, and belt force were used to

TABLE 1 Subject characteristics and mesh quality. [Color table can be viewed at wileyonlinelibrary.com]

		BMI 24		BMI 35		BMI 40	
							
		PMHS	Model	PMHS	Model	PMHS	Model
Subject characteristics	Stature (cm)	175	175	189	189	165	165
	Weight (kg)	73	71	125	122	108	110
	BMI (kg/m^2)	24	23.2	35	34.2	40	40.4
	Age (y)	67	67	54	54	57	57
Mesh quality	Minimum Jacobian[a] (% < 0.5 for solid elements or 0.7 for shell elements)						
	Body surface (2D)	0.37 (1% < 0.7)		0.36 (1% < 0.7)		0.30 (1% < 0.7)	
	Rib cage (2D)	0.46 (3% < 0.7)		0.45 (4% < 0.7)		0.38 (3% < 0.7)	
	Pelvis (2D)	0.52 (6% < 0.7)		0.50 (6% < 0.7)		0.38 (7% < 0.7)	
	Femur (3D)	0.38 (0% < 0.5)		0.32 (1% < 0.5)		0.30 (1% < 0.5)	
	Whole body (2D)	0.28 (2% < 0.7)		0.20 (2% < 0.7)		0.10 (2% < 0.7)	
	Whole body (3D)	0.25 (0% < 0.5)		0.25 (0% < 0.5)		0.04 (0% < 0.5)	

[a]Jacobian measures deviation of an element from its ideal or "perfect" shape and is a good indicator of mesh quality. Jacobian value ranges from 0.0 to 1.0, with 1.0 representing the best quality.

evaluate the morphed human models. In general, the simulated results were in good agreement with the test data. The errors of peak value of injury measurements were under 20%, except the chest deflection for the BMI-35 subject. Based on CORA scores, responses of the morphed models showed reasonable correlations (0.52-0.94) to the tests except the chest upper deflection for the BMI-35 subject.

Figure 5 shows the rib cage deformations and strain distributions for the morphed human models. The maximum principal strain values of all three models occurred on the lower left side and upper right side of the rib cage along the shoulder belt orientation, which is consistent to the rib cage fracture locations in the tests. The models with obesity sustained higher peak principal strains than the lower-BMI model.

Discussion

Subject-specific model evaluation

To our knowledge, this is the first study to compare PMHS frontal impact test data with outcomes of simulations using FE human models tailored to body dimensions from the PMHS with a wide range of obesity levels. Specifically, the stature, BMI, age, and sex were used as inputs of statistical models to predict the external body shape and internal skeletal geometry. The rapid mesh morphing method is a critical enabler of this methodology, because at least a few months would be needed to build a subject-specific FE model using conventional methods. The current approach relied on the parametric models of the external body surface and skeleton to yield a morphed model much closer to the subjects than a midsize male model. Results showed that the human models with obesity tended to predict greater body excursions, especially for the pelvis, than those from the model with normal weight, which is consistent with the PMHS test results. The greater pelvis excursion would be associated with an increased risk of the lower extremities contacting the vehicle interiors for occupants with obesity. This is consistent with field data analyses that have shown an increased risk of lower-extremity injuries for occupants with obesity (4,8). At the same time, both the human models and PMHS tests showed that the occupants with obesity experienced greater chest deflections than the occupant with normal weight.

In general, the model-predicted injury measurements (accelerations and chest deflections) matched the test results reasonably well. However, large differences were observed in the chest deflections of the BMI-35 subject. In this study, the material property variation was not considered for developing subject-specific models, and the original THUMS material was used for all three models.

Crash protection for occupants with obesity

The higher risk of injury for occupants with obesity is associated with their increased body mass and the poor belt fit caused by their

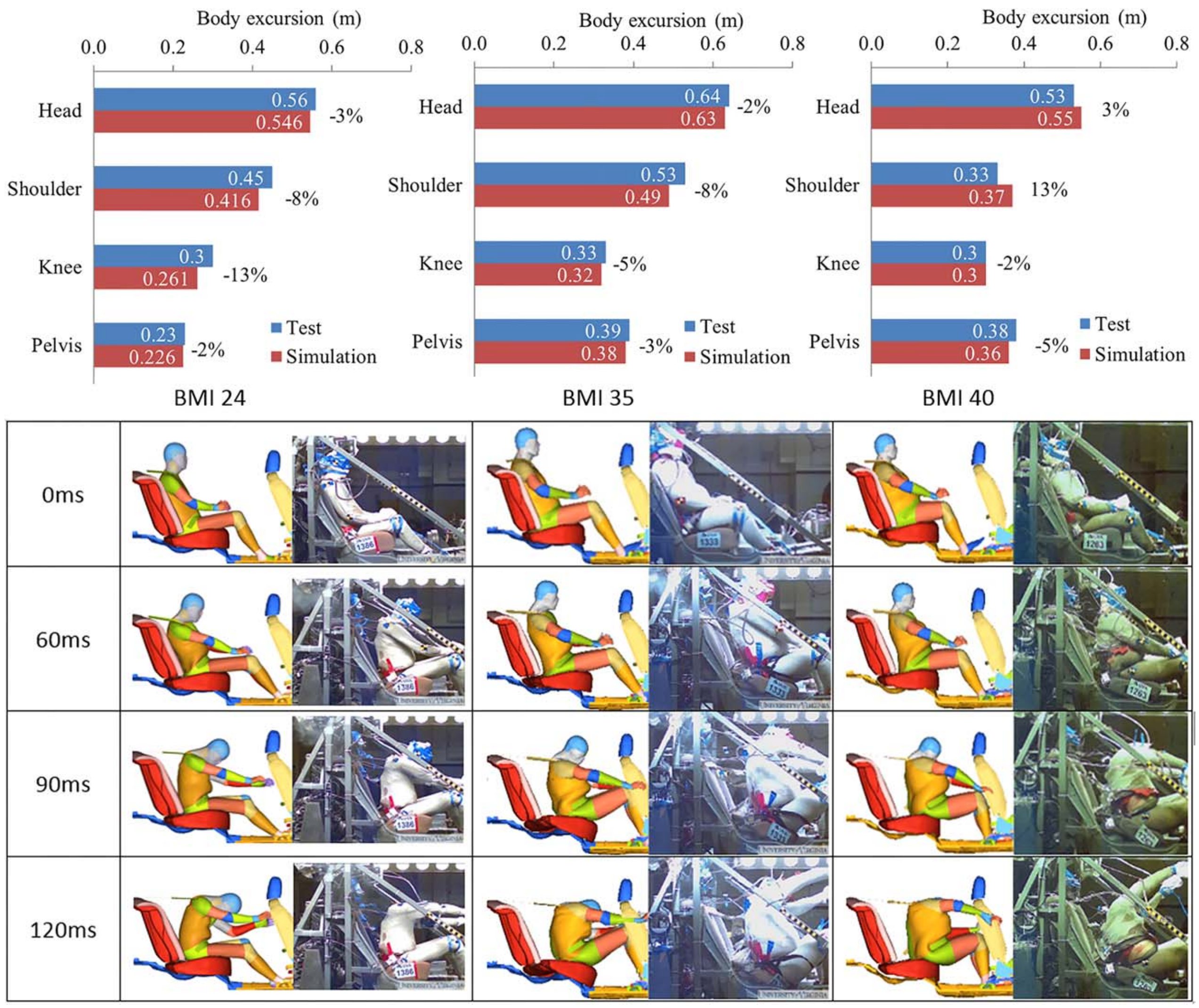

Figure 3 Maximum body excursions and animation comparisons. [Color figure can be viewed at wileyonlinelibrary.com]

TABLE 2 Peak value of injury measurements for different human body models

	BMI 24			BMI 35			BMI 40		
	Test	Simulation	Error	Test	Simulation	Error	Test	Simulation	Error
Head acceleration (g)	47.3	49.4	4.4%	38.7	44.8	13.6%	60.6	65.0	7.3%
T8 acceleration (g)	41.0	40.9	−0.2%	31.2	35.9	15.1%	–[a]	35.4	–
Pelvis acceleration (g)	59.9	68.6	14.5%	47.0	43.8	−6.8%	–[a]	60.8	–
Shoulder belt force (kN)	4.29	4.38	2.1%	6.43	6.59	2.5%	6.43	7.43	15.6%
Lap belt force (kN)	4.63	5.12	10.6%	8.29	7.45	−10.1%	5.97	6.5	8.9%
Chest deflection[b]	25%	24.7%	−1.2%	45.7%	32.6%	−28.6%	24.8%	26.2%	5.6%

[a]Accelerometer mounts were found loose post test.
[b]Peak deflection measured at the upper chest.
kN, kilonewtons.

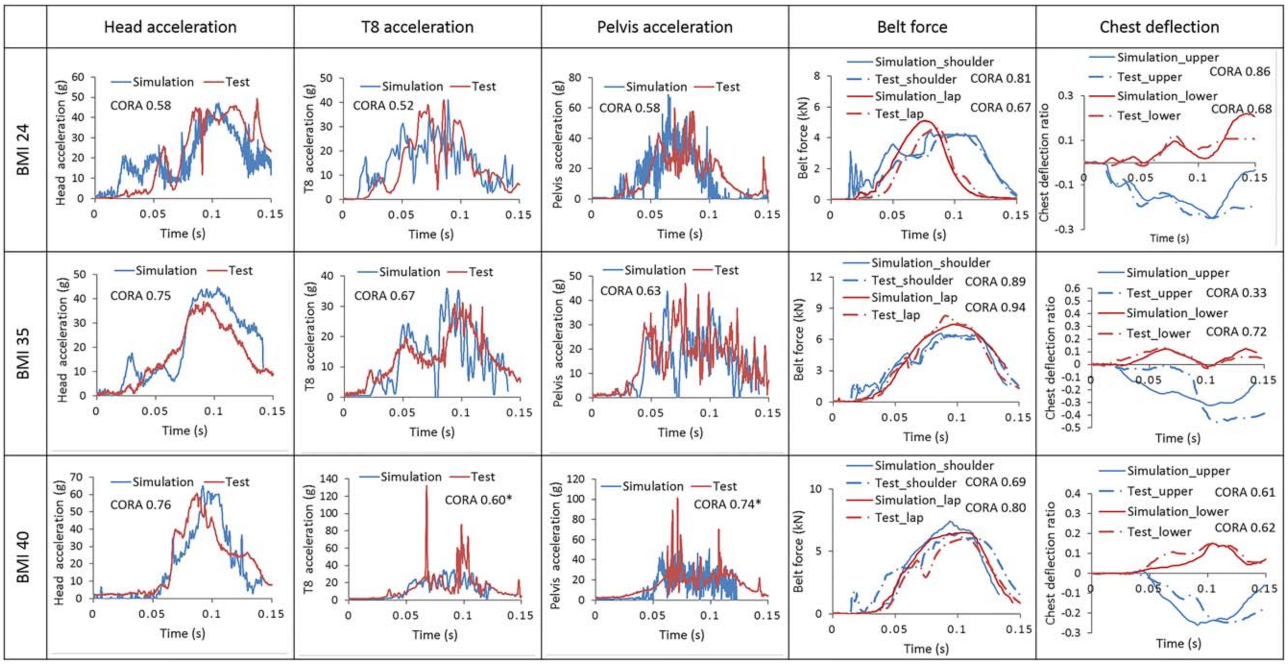

Figure 4 Injury measurements for different BMI human body models. *Accelerometer mounts were found loose post test. [Color figure can be viewed at wileyonlinelibrary.com]

external body shape (33). The results of this study are in agreement with several previous field data analyses (7,34), cadaver tests (12), and computational studies (17,20), all of which have demonstrated the challenges of managing the additional body mass of high-BMI occupants. In a frontal crash, having greater soft tissue mass will generate higher energy and force that have to be held by the skeleton. Therefore, if the strength of the skeleton in people with overweight is not greater, they are more likely to be injured. Furthermore, the increased adipose tissues in the abdominal area may affect the seat belt fit by effectively introducing slack in the seat belt system through changing the routing of the belt relative to the underlying skeletal structures. The simulation results showed that high-BMI occupants produced significantly higher body excursions, especially for the lower extremities, and higher chest deflections than those in low-BMI occupants. An advanced seat belt system with shoulder or lap pretensioner can effectively reduce the body excursions, and a seat belt load limiter can reduce the chest deflection at the cost of increasing the head excursion in severe frontal crashes. Therefore, load limits that can adapt to occupants with different obesity levels are needed to protect the head and chest at the same time (35).

Limitations and future work

The model morphing process has several limitations and challenges. Accurately positioning the skeleton geometry models into the external body shape model using the landmarks associated with the external body shape requires care, because the skeleton and body surface models were generated based on different samples of subjects and can have small geometric incompatibilities. We addressed this issue through careful prioritization. For example, the skeleton was given priority over the external surface in situations in which the bones protrude slightly from the separately predicted body shape. We also must be careful to ensure that the bones interface realistically at the joints, such as the knee and hip. Because we lacked measurements of bone position within the PMHS in the test position, we were not able to verify the accuracy of these estimates.

We found that the overall mesh quality of the morphed model depends on the geometry similarity between the baseline model and the target geometry. Therefore, lower-quality elements may occur when there is a large difference between the target geometry and the baseline model. A new baseline model representing occupants with obesity may be needed to completely resolve this problem. However, the low-quality elements did not prevent a smooth simulation in the current study. Moreover, the material properties of the human models were not changed according to the human characteristics (age, sex, etc.), which needs to be considered in the future.

The model evaluation process is also substantially limited by the availability of suitable data. In the current study, detailed data from three PMHS were used. However, important information on the test setup was not available, which limited the potential accuracy of the assessment. For future testing, the locations of skeletal landmarks thoroughly defining the pretest posture are needed, along with careful quantification of belt routing. Future PMHS tests should also include measurement of 3D surface shape to enable more accurate representation of seated body shape.

Finally, work is needed to better implement the proposed subject-specific model validation paradigm. Under the historical paradigm, FE human models were evaluated against corridors generated by scaling

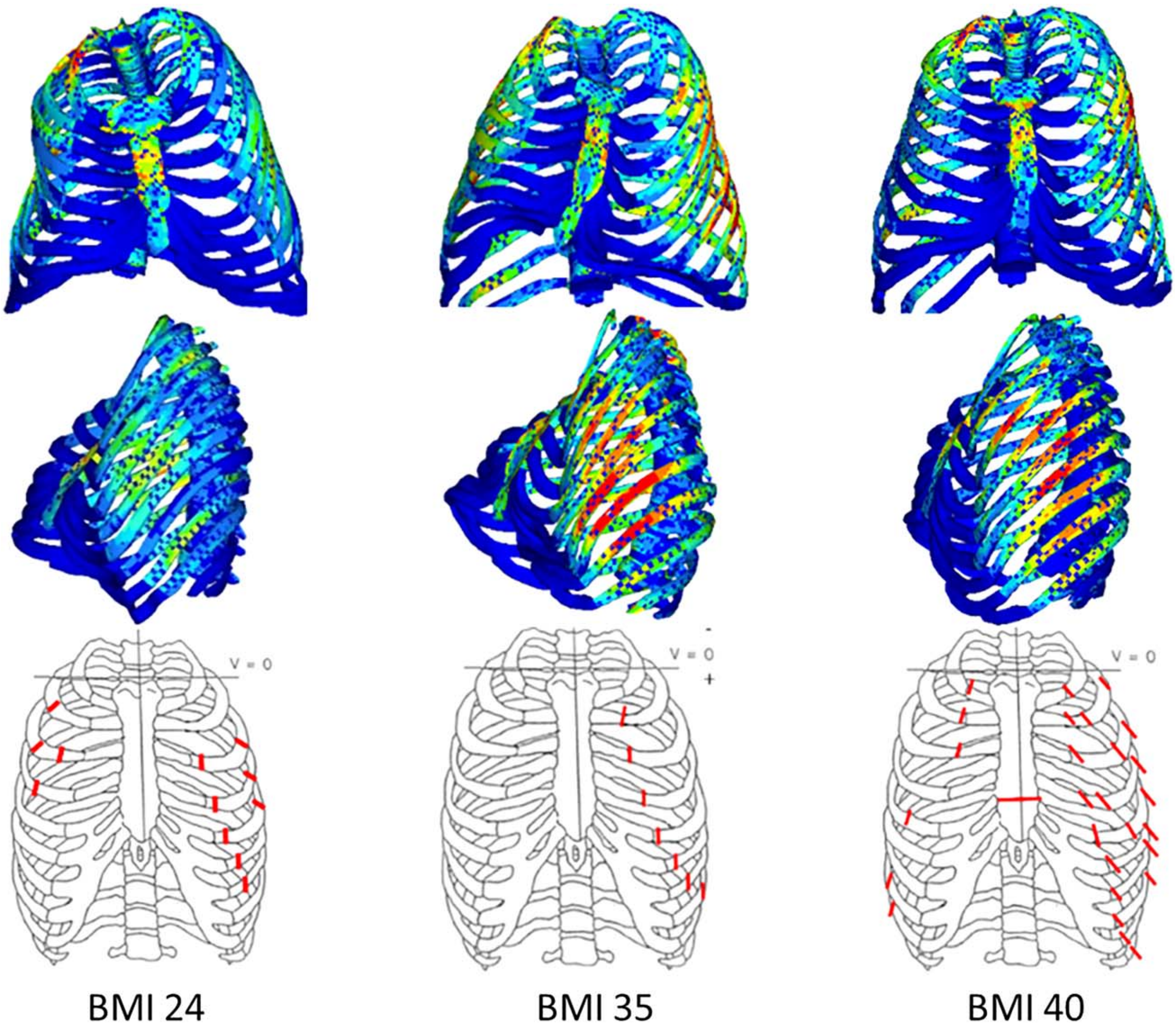

Figure 5 Peak rib cage deformations for the human body models. [Color figure can be viewed at wileyonlinelibrary.com]

individual PMHS responses using simple assumed relationships between response and subject variables such as body mass. These corridors are often quite wide, and, hence, "valid" model responses can vary considerably. Importantly, the tuning of FE models to conform to the corridors has often been performed through adjustments of material properties and/or boundary conditions. However, this process may result in inaccurate model parameters that compensate for a lack of representativeness in model geometry. Hence, there is a strong need to understand the relationships between geometry and material properties, particularly for critical structures such as the rib cage. New methods are also needed to evaluate and grade model performance against data from individual tests. Because whole-body PMHS test data will always be scarce, methods are needed to provide estimates of model accuracy and precision for particular aspects of the outcome from a relatively small number of samples. Importantly, the evaluation of model performance against tests with individual PMHS needs to provide confidence bounds for subsequent simulations with other body sizes, shapes, and exposures.

Conclusion

This study developed three subject-specific FE human models presenting three PMHS with a wide range of stature and obesity levels using the RBF mesh morphing method. Comparisons of the occupant kinematics and injury measures between the PMHS and the models showed that the morphed human models had the capability to account for the obesity effects on the occupant impact responses. The mesh morphing method and the human models developed in this study can enable applications that are not possible with existing human models, such as safety design optimization for people with a wide range of body characteristics. O

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