TITLE:

Impact Response Comparison between Parametric Human Models and Post-Mortem Human Subjects with a Wide Range of Obesity Levels

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RUNNING TITLE:

Crash Modeling for People with Obesity

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KEYWORDS:

Obesity, Mesh morphing, Parametric human body model, Injury risk

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WORD COUNT: 3694

FUNDING:

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 expense at the University of Michigan.

Disclosure: The authors declare no conflict of interest.

What is already known about this subject?

- People with obesity sustain increased risk of injuries in motor-vehicle crashes.
- The injury assessment tools for people with obesity are largely lacking in the literature.
- The existing computational human models for people with obesity are lack of validations against impact tests using post-mortem human subjects (PMHS).

What does this study add?

- This study developed a method to rapidly develop human models of people with obesity for impact simulations.
- This study compared the human model responses against PMHS impact tests with a wide range of obesity levels.
- This study showed that the parametric human models have the capability to account for the obesity effects on the occupant impact responses and injury risks.

Abstract

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 mesh morphing method to rapidly generate parametric finite element human models with a wide range of obesity levels and to evaluate their biofidelity against impact tests using post-mortem human subjects (PMHS).

Methods

Frontal crash tests using three PMHS seating 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, ribcage, 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 measurements between the tests and simulations showed reasonable correlations across the wide range of BMI levels.

Conclusion

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

Introduction

The proportion of population with obesity has increased significantly worldwide since 1980s, according to World Health Organization. In the United States, the prevalence of overweight and obesity were 68.8% and 35.7% in 2009-2010 (1). A study by Eric *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, 4, 5, 6, 7). Specifically, the chest, lower extremities and spine are more likely to be injured for occupants with obesity than other occupants. Cormier *et al*. (3) reported that occupants with obesity had 26% and 33% higher risks of 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 drivers were associated with obesity. Ediriweera *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, 12, 13, 14) compared the kinematics of five post-mortem 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 *et al*. (3) found that the adipose tissues of an occupant with obesity may 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 body mass index (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, mainly focused on occupants with normal weight, and thus injury assessment tools for population 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 multi-body simulation by adding a facet mesh representing more realistic body shapes of occupants with different BMI levels. However, it is difficult for multi-body models to accurately simulate the complex interactions between the seatbelt 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 FE method is to divide a continuous body into discrete small elements. By assigning proper material properties to different anatomical structures (*e.g.* bone and 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, 21) developed four FE human models with a constant mid-size male stature but different BMI levels (25/30/35/40 kg/m^2) by morphing a baseline mid-size male FE human 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 due to 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 (22, 23). 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*. (24) 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*. (25) 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 (26). However, these two PMHS are both with 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 CT data are available, and we are not aware of any published tests in which the pre-test 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, 12, 13, 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 (27, 28, 29, 30, 31). 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, 12, 13, 14). The outputs were compared with the PMHS test results.

[Figure 1]

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 (25). First, with a given target age, sex, stature and BMI, the skeleton (including ribcage, femur and pelvis) and external body shape geometries were predicted by the statistical geometry models developed previously (27, 28, 29, 30, 31). 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, and posterior-superior iliac spine) and joint centers (e.g. T1, T8, and hip) available in the external body shape model. Third, the Total Human Model for Safety (THUMS) v4.01 mid-size male model was used as the baseline model to be morphed into the target geometry using a radial basis function (RBF). THUMS model has different versions with different mesh densities and anatomical features. Among them, THUMS v4 is the most widely used in the injury 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, is consist of only about 600k elements but has 262 one-dimensional (1D) 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 were 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 (26, 32).

PMHS test setup

Generally speaking, it is extremely difficult to conduct cadaver tests with a large sample size due to the 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 male and female. The impact velocity was based on Federal Motor Vehicle Safety Standard 208 (33) with a crash pulse from a popular mid-size 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 condition 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 seatbelt 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 3-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 kN and 6 kN force levels (Figure 2d).

[Figure 2]

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. Pre-simulations were performed to adjust the upper and lower extremities to the testing locations. Seat belt was fitted based on the routes identified from PMHS pre-test 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 measured for all three simulations. Different filters (SAE CFC1000, CFC180, and CFC60) were used for different measurements following the SAE standard (34), 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.

[Table 1]

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 (380mm vs 230mm) 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%.

[Figure 3]

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 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.

[Table 2]

[Figure 4]

Figure 5 shows the ribcage 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 ribcage along the shoulder belt orientation, which is consistent to the ribcage fracture locations in the tests. The models with obesity sustained higher peak principal strains than the lower BMI model.

[Figure 5]

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 mid-size 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 show an increase 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 are associated with their increased body mass and the poor belt fit caused by their external body shape (35). The results of this study are in agreement with several previous field data analyses (7, 36), cadaver tests (12) and computational studies (17, 21), all of which 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 skeleton in overweight people is not higher, they are more likely to be injured. Furthermore, the increased adipose tissues in the abdominal area may affect the seatbelt fit by effectively introducing slack in the seatbelt 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 (20).

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 have 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 lack measurements of bone position within the PMHS in the test position, we were not able to verify the accuracy of these estimates.

We have 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 pre-test 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 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 ribcage. 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.

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Table 1. Subject characteristics and mesh quality

		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 (year)	67	67	54	54	57	57
Mesh quality	Minimum Jacobian* (% < 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)	
	Ribcage (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)	

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

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 acc (g)	47.3	49.4	4.4%	38.7	44.8	13.6%	60.6	65.0	7.3%
T8 acc (g)	41.0	40.9	-0.2%	31.2	35.9	15.1%	-**	35.4	-
Pelvis acc (g)	59.9	68.6	14.5%	47.0	43.8	-6.8%	-**	60.8	-
Shoulder belt F (kN)	4.29	4.38	2.1%	6.43	6.59	2.5%	6.43	7.43	15.6%
Lap belt F (kN)	4.63	5.12	10.6%	8.29	7.45	-10.1%	5.97	6.5	8.9%
Chest deflection*	25%	24.7%	-1.2%	45.7%	32.6%	-28.6%	24.8%	26.2%	5.6%

*Peak deflection measured at the upper chest.

**Accelerometer mounts were found loose post-test.

Figure 1. Method overview for developing and evaluating morphed human body models

Figure 2. Sled test conditions and model setup

Figure 3. Maximum body excursions and amination comparisons

Figure 4. Injury measurements for different BMI human body models
*Accelerometer mounts were found loose post-test.

Figure 5. Peak ribcage deformations for the human body models

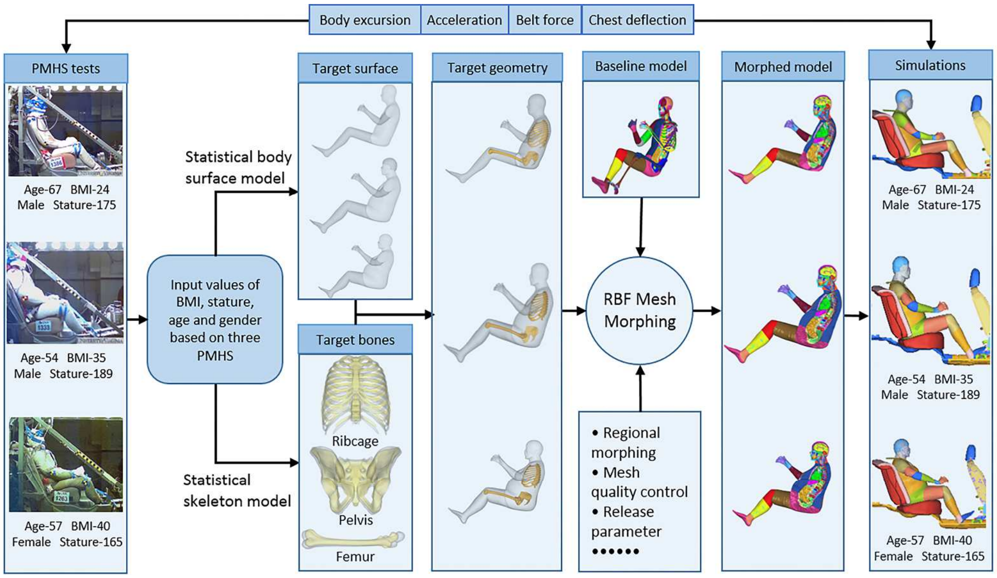
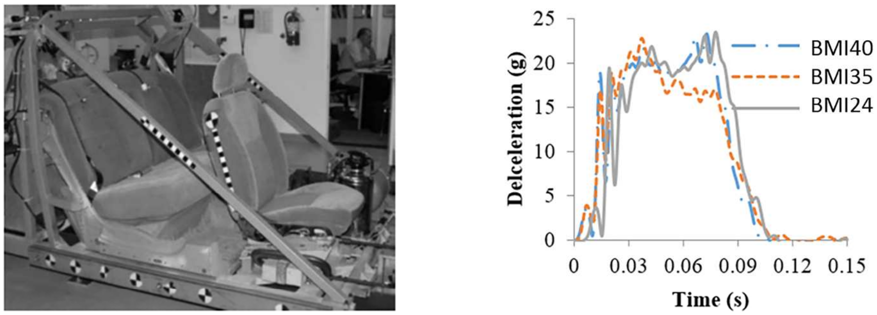


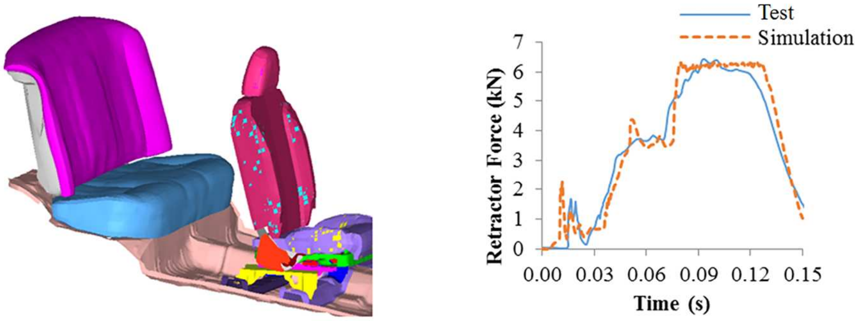
Figure 1. Method overview for developing and evaluating morphed human body models

334x191mm (300 x 300 DPI)



(a) Sled test buck

(b) Crash pulse for three PMHS



(c) FE model for the sled buck

(d) Retractor forces for the test and simulation

Figure 2. Sled test conditions and model setup

237x181mm (300 x 300 DPI)

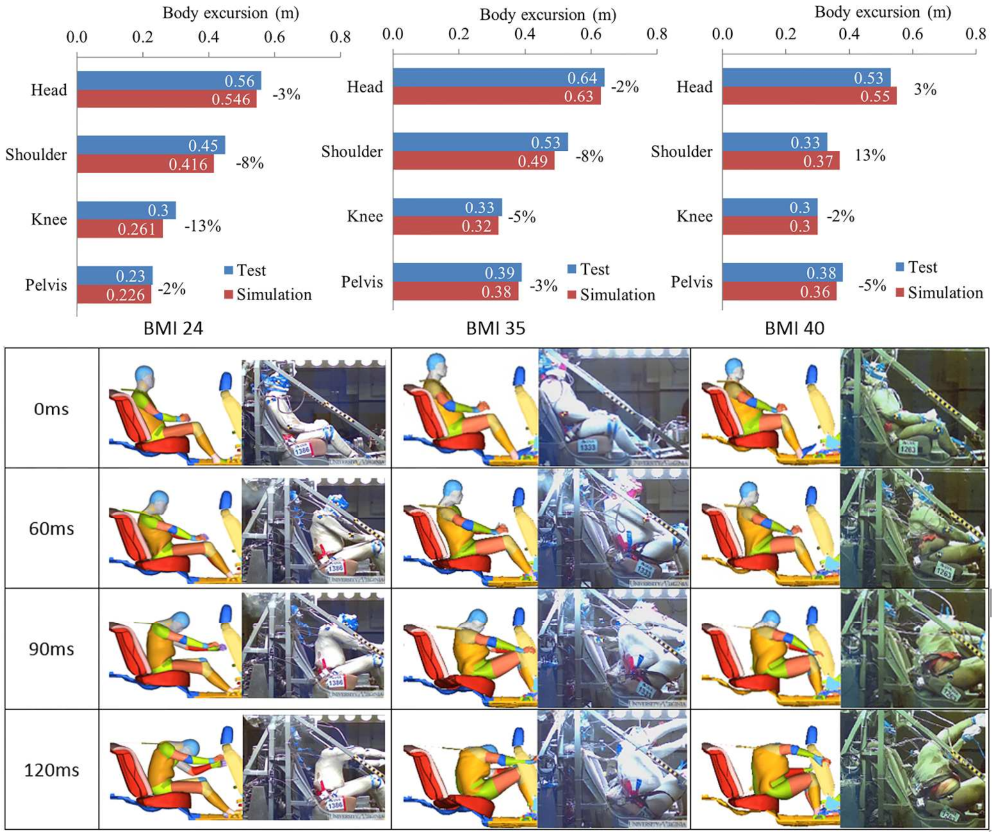


Figure 3. Maximum body excursions and amination comparisons

448x374mm (300 x 300 DPI)

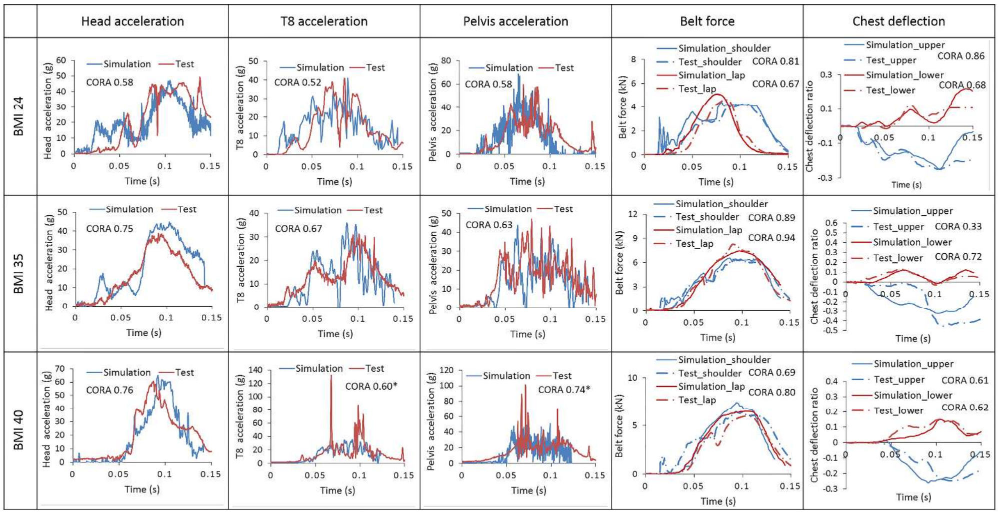


Figure 4. Injury measurements for different BMI human body models

704x357mm (300 x 300 DPI)

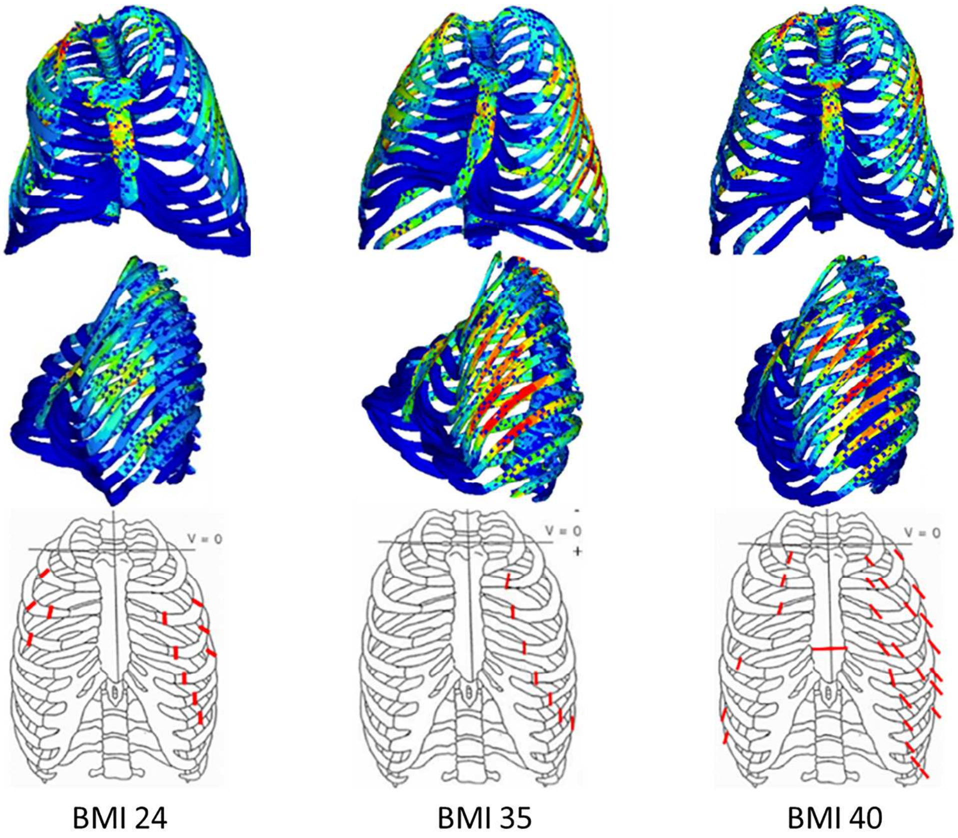


Figure 5. Peak ribcage deformations for the human body models

296x255mm (300 x 300 DPI)