Stature and Body Shape Effects on Driver Injury Risks in Frontal Crashes: A Parametric Human Modelling Study

Jingwen Hu, Kai Zhang, Abeselom Fanta, Monica L.H. Jones, Matthew P. Reed, Mark Neal, Jenne-Tai Wang, Chin-Hsu Lin and Libo Cao

Abstract Current procedures for evaluating vehicle safety designs for drivers use human surrogates with only a small number of body sizes, while field data analyses have shown significant stature and obesity effects on occupant injury risks in frontal crashes. In this study, six finite element human models, including three models corresponding to the three sizes of adult crash test dummies (small female, mid-size male, and large male) and three obese models with the same reference statures but a BMI of 40 kg/m^2, were developed by morphing the GHBMC M50-OS model using a landmark-based radial basis function and a regional mesh morphing approach. US NCAP frontal crashes were simulated with the human models on the driver side. For both non-obese and obese drivers, the short female and tall male had higher injury risks than the mid-stature male. At each stature, higher injury risks were observed for obese drivers than for non-obese drivers. These results suggest that driver body size and shape affect occupant interactions with the restraints, occupant kinematics, and injury risks in severe frontal crashes. Simulations with parametric human body models capable of representing the diversity of occupant populations may provide a means of improving protection for individuals who differ in size, shape and position from the surrogates typically used for restraint optimisation.

Keywords body shape, frontal crash, obesity, injury risk, parametric human model, stature

I. INTRODUCTION

The current design process for vehicle safety systems relies extensively on crash tests with one or more anthropomorphic test devices (ATDs) to assess crashworthiness and occupant protection. In the United States, crash test programmes include those defined in Federal Motor Vehicle Safety Standards (FMVSS), US New Car Assessment Program (US NCAP), and the safety rating system conducted by Insurance Institute for Highway Safety (IIHS). Similar programmes are also conducted in Europe, China, Japan, and many other countries. Globally, only a few adult occupant sizes are represented by ATDs. In the US, regulatory testing is conducted using midsize-male and small-female ATDs. These are commonly referred to as *50th percentile male* and *5th percentile female* ATDs, but in fact their reference body dimensions do not correspond to those percentiles for any particular population of interest. For example, the body weight of the midsize-male ATDs used for the majority of frontal- and side-impact tests (approximately 78 kg) is now the 33rd percentile of U.S. adult body weight [1].

Field data analyses have shown significant stature and body shape effects on occupant injury risks in frontal crashes. Based on an analysis of the NASS-CDS crash injury database, airbags were reported to be less effective in preventing injuries for smaller occupants than for midsize men [2]. Many studies have also shown that the obese occupants have higher risks of fatalities and injuries in frontal crashes than normal-weight individuals [3-9]. More specifically, the chest [3,10-13] and lower extremities [10,14-17] are more likely to be injured for obese than non-obese occupants.

The proportion of population that is obese, defined as a body mass index (BMI) greater than 30 kg/m^2, has increased significantly worldwide since the 1980s according to the World Health Organization (WHO). In 2014, 39% of adults aged 18 years and over were overweight and 13% were obese around the world. In the United

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States, the prevalence of overweight and obesity were 68.8% and 35.7% in 2009-2010, compared with 55.9% and 22.9% in 1988-1994 [18]. A study [19] predicted that the prevalence of obesity would be up to 42% in the United States in 2030. These demographic trends further necessitated the research on improving driver protection beyond the few sizes represented by current ATDs.

The higher risks of injuries for the obese occupants are believed to be caused primarily by the increased body mass, exacerbated by poor belt fit resulting from corpulence [20,21]. Experimental studies [22-25] compared the kinematics of five post-mortem human subjects (PMHSs) in frontal crash tests and found that the obese PMHSs experienced greater body excursions attributed to higher kinetic energy. A modelling study by Turkovich et al. [26] also reported that the increased body mass was the most significant factor affecting the injury risks for obese occupants, followed by body shape. Cormier [3] found that the adipose tissues of an obese occupant may move the belt away from the bony structures, which will increase the injury risks for obese occupants. By analysing driver belt fit data, Reed et al. [21] concluded that a 10 kg/m^2 increase in BMI was associated with a lap belt position 43 mm further forward and 21 mm higher relative to the anterior–superior iliac spines of the pelvis. Such belt fit is expected to adversely affect occupant kinematics in frontal crashes. Compared with the obesity effects, the stature effects on occupant injury risk seem more subtle. However, driving postures and positions are known to vary with stature [27], and hence restraint interactions and the resulted injury risks in a frontal crash may also be expected to differ.

Finite element (FE) human models are among the most widely used injury assessment tools. A number of FE whole-body human models have been reported in the literature, including HUMOS [28], H-model [29], Ford Human Body Model [30,31], WSU Human Model [32,33], THUMS model [34,35], and GHBMC model [36-38]. However, they have typically been constructed to simulate the same small number of body sizes and shapes currently represented by ATDs, in particular the midsize male, small female, and large male. Over the past few years, mesh morphing method has been applied to morph a mid-size male human model into other body sizes or ages [39-41], and our research group has developed an approach to parametric human FE modelling that allows the size and shape of an FE human model to be rapidly varied based on age, sex, stature, and body mass index (BMI). The parametric approach eliminates the costly and time-consuming process of building entirely new models for each desired occupant size. Using this approach, Shi et al. [42] developed four FE HBMs with different BMI levels (25/30/35/40 kg/m^2) by morphing the THUMS v4 midsize male model into geometries representing obese subjects. The obesity effects predicted by the models are consistent with those reported in PMHS tests (increased body excursions and submarining tendency) and field data (increased injury risks for the chest and lower extremities). Using the same models, Wang et al. [43] investigated the efficacy of advanced belt restraints to mitigate obesity effect for rear-seat occupants in frontal crashes.

However, in all these previous simulation studies only a single stature (mid-size male) was used, consequently the interaction between stature and body shape effects on occupant injury risks were not investigated. Furthermore, the effects of obesity on occupant driving postures have not been considered. Therefore, the objective of the current study was to investigate the stature and body shape effects on driver injury risks in the US NCAP frontal crash condition using a parametric FE human model capable of simulating a diverse population.

II. METHODS

Baseline FE Human Model

In this study, the midsize male simplified occupant model from the Global Human Body Model Consortium (GHBMC M50-OS V1.8.4) was used as the baseline model, which was morphed into six FE human models, including three models corresponding to the three sizes of adult crash dummies (small female, mid-size male, and large male) and three obese models with the same three reference statures of adult dummies but a BMI of 40 kg/m^2. The GHBMC M50-OS model was created from the same source geometry as the original GHBMC model, but with a comparatively coarser mesh to provide faster run times. Bones were assumed to be rigid, except for the ribcage, and mechanical joints were defined for the hip, knee, ankle, shoulder, elbow, and wrist for easy positioning and posturing of the human model. The GHBMC M50-OS model has been validated extensively against cadaver tests, including a 23 kg hub impact to the thorax with an initial velocity of 6.7 m/s, a 48 kg bar impact to the abdomen with an initial velocity of 6 m/s, a 23.4 kg plate side impact to the right arm with an initial velocity of 12 m/s, a lateral sled test condition with an initial velocity of 6.7 m/s, and a frontal sled test condition with an 11.1 m/s crash pulse. In the frontal sled condition similar to the simulation condition in the current study, the CORrelation and Analysis (CORA) ratings for the body excursions ranged from 0.55 to 0.83. More details of the model validation can be found in [44].

Diverse FE Human Models through Mesh Morphing

Fig. 1 shows the basic steps of developing the six human FE models used in this study representing drivers with varied stature and body shape. The process begins with statistical skeleton models, including ribcage, pelvis, femur, and tibia, along with external body shape models of human geometry that describe morphological variations within the population as functions of overall parameters (typically age, sex, stature, and BMI). Mesh morphing methods developed at UMTRI are then used to rapidly morph a baseline human model into target geometries while maintaining high geometry accuracy and good mesh quality. Given a target sex, age, stature, and BMI, the statistical human geometry models developed previously predict thousands of points that define the body posture [27,45,46], the size and shape of the external body surface [47], and ribcage [48,49] and lower extremity bone geometries [50,51]. The skeleton and external body shape geometries are integrated together based on the landmark and joint locations shared in both skeleton and external body shape models [52]. Once the target geometries are developed, the baseline model is morphed to match the target geometries using a landmark-based 3D non-linear interpolation technique based on radial basis functions (RBF). To better control the obesity effects on abdominal adipose tissues, the abdominal wall along with the thoracic and abdominal organs were morphed by the ribcage and pelvis, and the abdomen flesh and adipose tissues were morphed by the abdominal wall and the external body surface. This arrangement ensured a relatively constant thoraco-abdominal cavity, but the intrabdominal or visceral fat was not considered in the morphing process. More details on the parametric FE modelling methods have been published previously [42,43,52-55]. Because the target geometry is based on the statistical human geometry models developed previously, the geometry of the morphed mid-size male model is slightly different from the GHBMC baseline model.

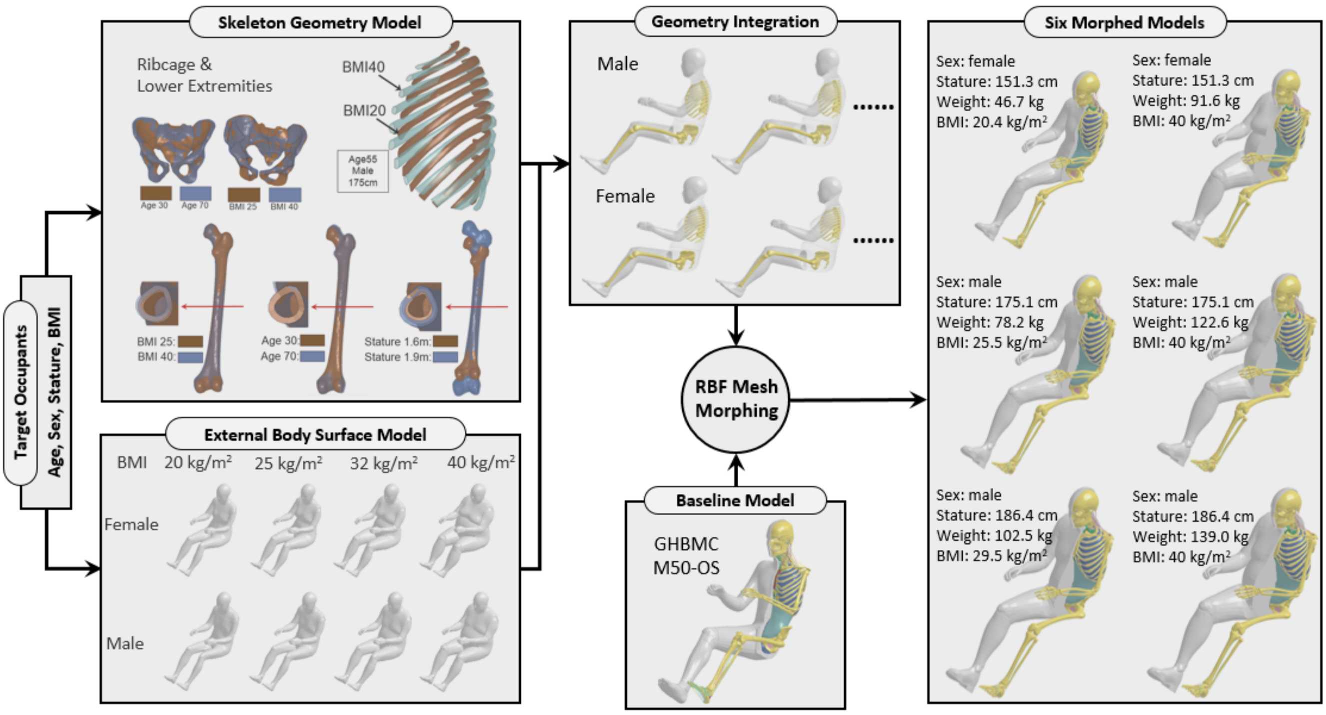

Fig. 1. Rapid development of human FE models for a diverse population by mesh morphing

Vehicle Model for Crash Simulations

In this study, an FE model of a typical midsize sedan was used for all crash simulations. This vehicle was equipped with a driver airbag, a crushable steering column (3 kN), a constant load limiter (2.85 kN), a retractor pretensioner (2 kN) and an anchor pretensioner (2 kN), but no knee airbag. The vehicle package factors are seat height (H30=294 mm), steering wheel X (L6=534 mm), and seat track angle (A19=4.5°). This model has undergone extensive validation against vehicle crash test data, including both midsize male and small female dummies in both driver and front seat passenger locations in US NCAP frontal crash (35 mph) and FMVSS 208 unbelted crash (25 mph) conditions. The average difference in joint (i.e., combined) injury probability (using absolute values) is 3.2% for belted dummies in the US NCAP frontal crash condition and 2.3% for unbelted occupants in FMVSS 208 conditions. An example of model validation with midsize male belted dummy on the driver side in the US NCAP frontal crash condition is shown in Fig. 2, and more validation results can be found in a study by Hu et al. [56]. All the main injury measures predicted by the dummy model are highly correlated with the test data.

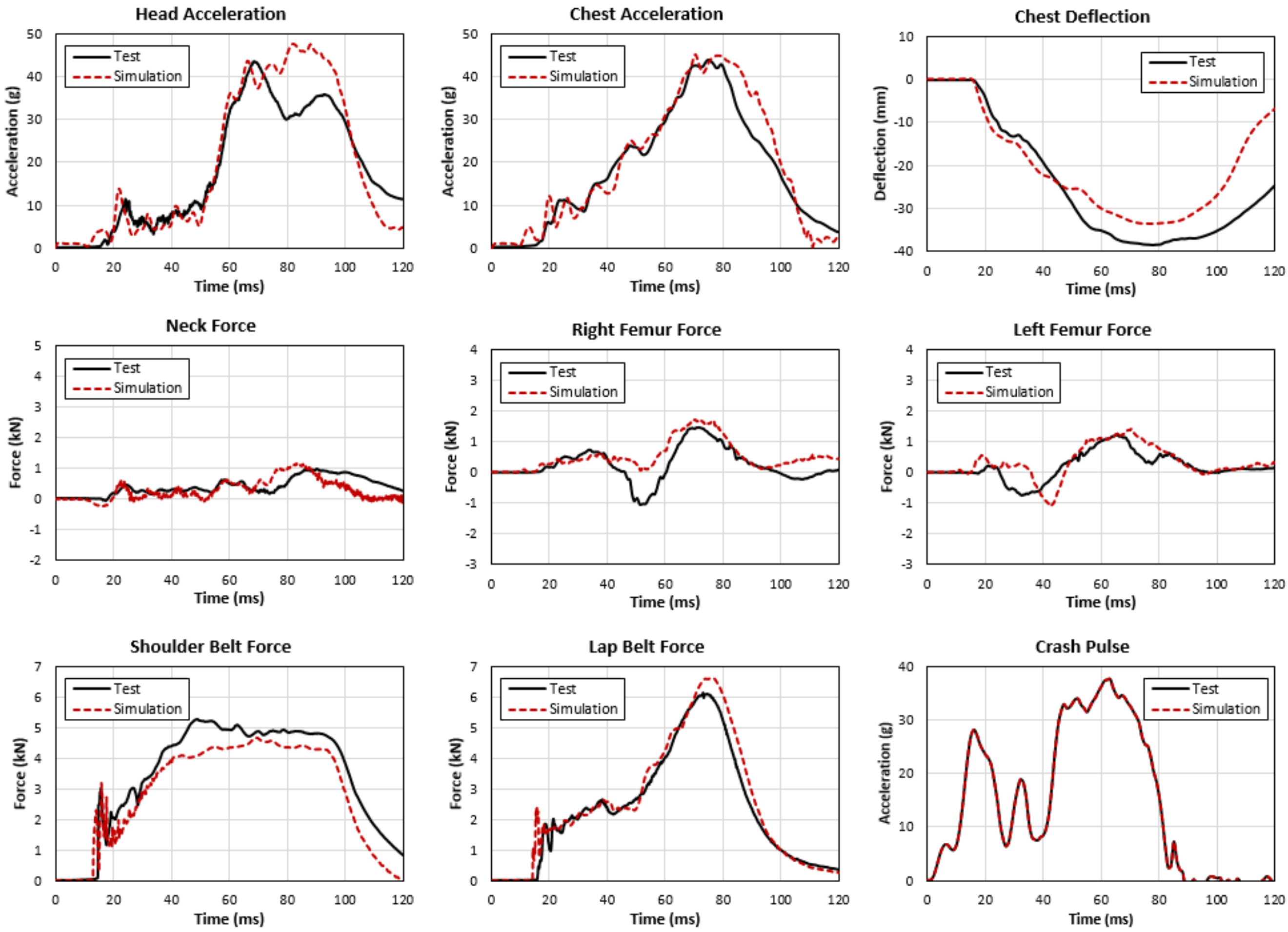

Fig. 2. Vehicle model validation example – US NCAP frontal crash belted midsize male dummy on the driver side

US NCAP Simulations using Morphed Human Models and Injury Risk Prediction

For each simulation, the occupants were positioned as drivers according to a driving posture model developed previously based on measurements from 68 volunteers [27]. The driving posture model predicts a range of occupant posture and position variables as a function of occupant body dimensions and vehicle package factors. In this study, the model-predicted driver hip and eye locations were used to position the morphed human models, and the predicted seat H-point location was used to position the driver seat before each simulation. For each simulation, the driver's hands were positioned onto the steering wheel by adjusting the shoulder and elbow angles, and the right and left feet were positioned onto the gas pedal and the floor, respectively, by adjusting the hip, knee and ankle angles.

Frontal crash simulations of a US NCAP, 56 km/h (35 m/h) full barrier crash test with a duration of 120 ms were conducted with each of the six human models using Ls-Dyna 971-R810 (LSTC, USA). For each simulation, injury measures for the head (HIC), neck (force), chest (deflection), and lower extremities (femur force) were output. We did not use Nij for neck injury risk prediction, because the injury risk is not zero at zero Nij and the neck/cervical spine has the lowest risk of injury in field crashes compared to other body regions. The injury risks were calculated based on the injury risk curves corresponding to the three occupant statures provided by US NCAP, all of which are shown in Table . A single joint probability of injury (Eq. 1) combining all four injury risks, as used in the current US NCAP test star rating, was calculated as the main output.

$$P_{joint}=1-(1-P_{head})\times(1-P_{neck})\times(1-P_{chest})\times(1-P_{KTH}) \quad (1)$$

In this study, we used the same injury risk curves for obese and non-obese occupants with the same stature, because the effects of obesity on injury risk are not yet well quantified.

TABLE I
INJURY RISK CURVES USED IN THIS STUDY

	Midsize Male	Small Female	Large Male
Head (HIC15)	$P_{head}(AIS3+)=\emptyset\left(\frac{ln(HIC15)-7.45231}{0.73998}\right)$ Where Φ=cumulative normal distribution		
Neck (tension / compression in kN)	$\begin{cases} P_T(AIS3+)=\frac{1}{1+e^{10.9745-2.375T}} \\ P_C(AIS3+)=\frac{1}{1+e^{10.9745-2.375C}} \\ P_{neck}=Max(P_T,P_C) \end{cases}$	$\begin{cases} P_T(AIS3+)=\frac{1}{1+e^{10.9745-3.770T}} \\ P_C(AIS3+)=\frac{1}{1+e^{10.9745-3.770C}} \\ P_{neck}=Max(P_T,P_C) \end{cases}$	$\begin{cases} P_T(AIS3+)=\frac{1}{1+e^{10.9745-2.003T}} \\ P_C(AIS3+)=\frac{1}{1+e^{10.9745-2.003C}} \\ P_{neck}=Max(P_T,P_C) \end{cases}$
Chest (deflection in mm)	$P_{chest}(AIS3+)=\frac{1}{1+e^{10.5456-1.568*D^{0.4612}}}$	$P_{chest}(AIS3+)=\frac{1}{1+e^{10.5456-1.7212*D^{0.4612}}}$	$P_{chest}(AIS3+)=\frac{1}{1+e^{10.5456-1.488*D^{0.4612}}}$
Knee Thigh Hip (femur force in kN)	$P_{femur}(AIS2+)=\frac{1}{1+e^{5.795-0.5196F}}$	$P_{femur}(AIS2+)=\frac{1}{1+e^{5.7949-0.7619F}}$	$P_{femur}(AIS2+)=\frac{1}{1+e^{5.7949-0.4090F}}$

III. RESULTS

Morphed Human Models

The six morphed human models are shown in Fig. 1, in which the non-obese occupants are on the left and obese occupants are on the right. The weights of the two female models are slightly higher than the theoretical values based on BMI, while the weights of the four male models are slightly lower than the theoretical values based on BMI. The mesh quality of the morphed models is slightly lower than the baseline GHBMC M50-OS model. The smallest Jacobian values for shell and solid elements in the six morphed models are 0.38 and 0.20, respectively, compared to 0.7 and 0.3 in the GHBMC M50-OS model. The number of solid elements with <0.3 Jacobian for each of the six morphed models is less than 30 (out of over 350k elements in the GHBMC M50-OS model).

Driver Posture

Table II shows the hip and eye locations of the morphed human models predicted by the driving posture model based on volunteer data [27]. Fig. 3 illustrates the driving position and posture variations among the four models with the small female and large male statures. Generally speaking, the hip and eye locations for obese occupants are more forward and slightly higher than the non-obese occupants with the same stature, and obese occupants seated with a slightly more reclined posture than the non-obese occupants.

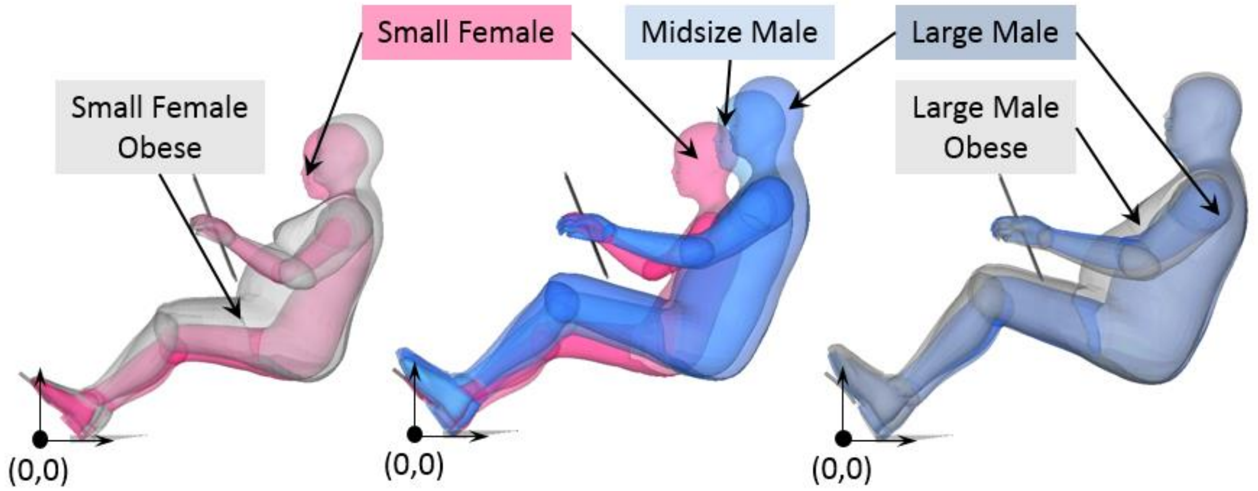

Fig. 3. Driving posture variations due to stature and body shape

TABLE II
DRIVING POSTURE DATA FOR POSITIONING THE HUMAN MODELS (UNIT: MM)

Stature	Body Shape	Driving position data				Seat H-point		Lap belt fit		Shoulder belt fit Y
		Hip-X	Hip-Z	Eye-X	Eye-Z	X	Z	X	Z	
Small female	Normal	770.8	301.7	845.5	851.6	794.0	304.1	51.7	2.6	41.1
Small female	Obese	702.2	325.2	802.4	871.1	794.0	304.1	178.1	70.4	36.3
Midsize male	Normal	856.0	299.7	949.5	930.7	897.1	296.0	79.3	40.8	73.2
Midsize male	Obese	805.3	317.1	920.4	944.5	897.1	296.0	182.5	95.0	57.3
Large male	Normal	891.0	300.7	996.5	969.6	946.0	292.1	125.7	62.7	87.2
Large male	Obese	854.2	313.3	976.4	979.3	946.0	292.1	191.5	98.5	85.6

*The X-axis is pointing rearward and Z-axis is pointing upward. The coordinate system origin is the vehicle package origin point, whose X-zero is determined by the Ball of Foot (BOF) and Z-zero is determined by the Accelerator Heel Point (AHP).

**The belt fit measurements were based on methods shown in Fig. 4.

***The small female obese model was moved slightly rearward in the simulation due to an initial penetration between the abdomen and the steering wheel.

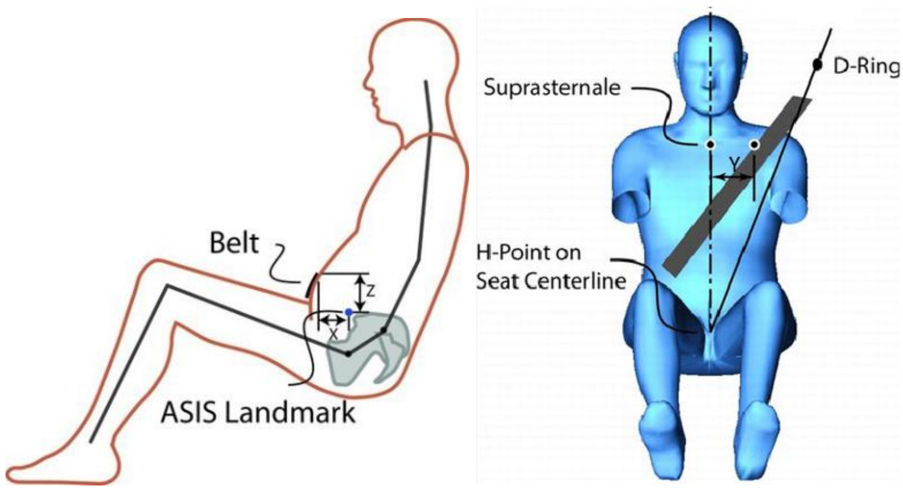

Fig. 4. Lap and shoulder belt fit measurements

US NCAP Simulation Results

The six US NCAP frontal crash simulations were successfully conducted without run-time errors. The simulated driver kinematics for all the morphed models are shown in Fig. 5. Both stature and body shape exhibited significant effects on occupant kinematics. In particular, the torso of taller occupants tended to pitch more forward than shorter occupants, and their head and neck tended to wrap around the airbag. The torso and abdomen of obese occupants pushed the airbag upward, which is most evident for small the female whose abdomen was very close to the airbag before the crash.

The injury risks to the head, neck, chest, lower extremities, as well as the joint injury probabilities for all the six morphed human models are shown in Table III. For both non-obese and obese drivers, short female (Pjoint=11.1% and 19.9%) and tall male (Pjoint=7.3% and 10.3%) had higher injury risks than mid-stature male (Pjoint=6.9% and 7.6%); while at the same stature, simulations of obese drivers always produced higher Pjoint than were observed for the non-obese drivers. The short obese female produced the highest Pjoint among all the six morphed models.

Head injury risks were generally very low, although the risks were higher for the short female and tall male than for the mid-stature male. On the other hand, obese occupants produced substantially higher lower extremity injury risks than non-obese occupants. Among all the body regions, chest injury risks accounted for the highest percentage of the joint injury probability, and the obesity effects on the chest injury risk are the highest for short female.

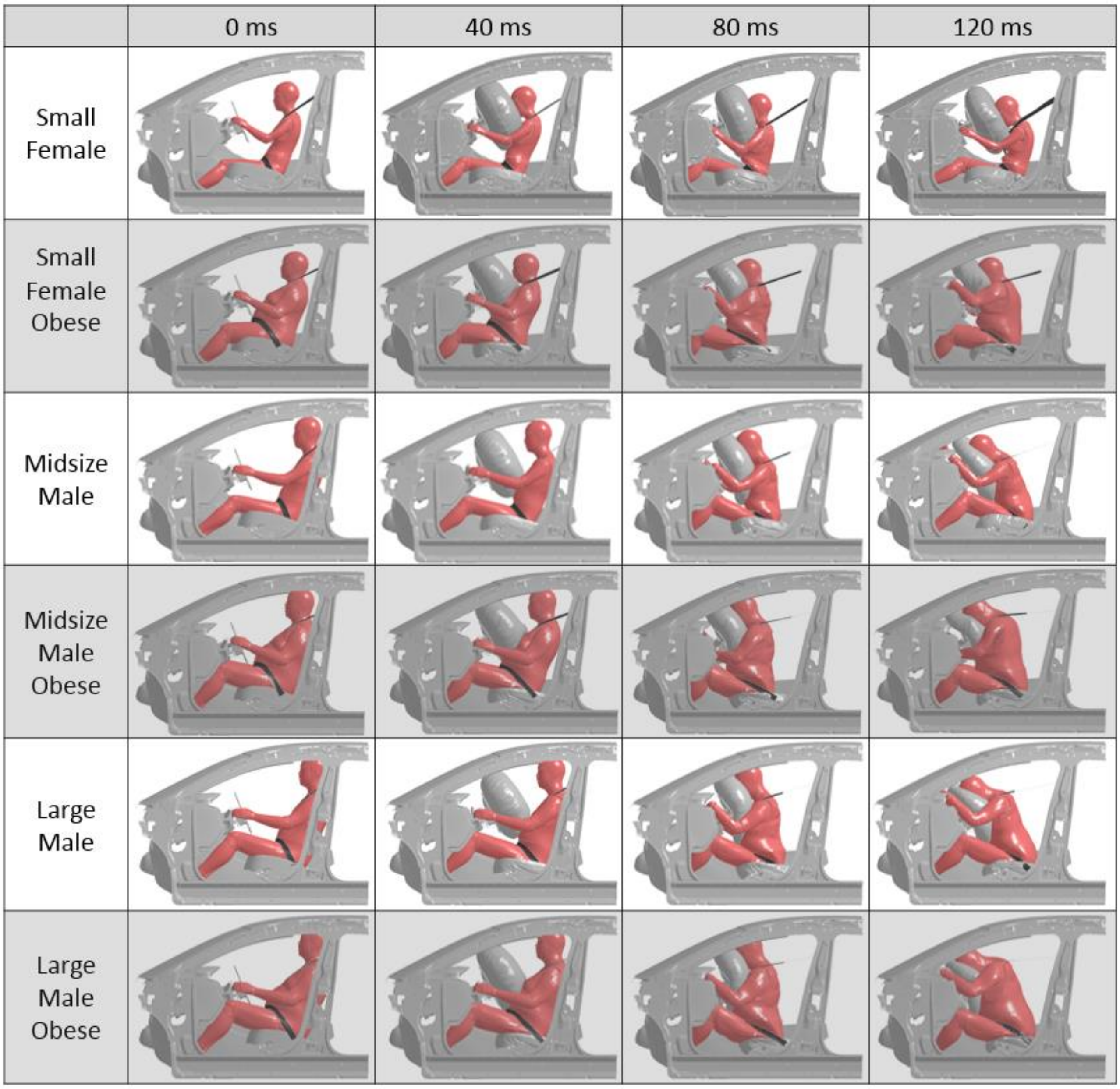

Fig. 5. Occupant kinemactics in US NCAP frontal crash

TABLE III
INJURY RISKS OF THE SIX MORPHED HUMAN MODELS IN US NCAP FRONTAL CRASH CONDITION

Stature	Body Shape	HIC P(Head)	NeckF P(Neck)	ChestD P(Chest)	FemurF P(Femur)	Pjoint	Shoulder Belt F	Lap Belt F
Small female	Normal	261 0.54%	0.33 0.01%	35.3 16.25%	0.00 0.30%	17.0%	3.18	3.68
Small female	Obese	161 0.07%	0.69 0.02%	36.4 18.05%	2.26 2.19%	19.9%	3.05	4.58
Midsize male	Normal	200 0.18%	0.59 0.01%	32.6 6.15%	1.30 0.59%	6.9%	3.19	4.53
Midsize male	Obese	165 0.08%	0.38 0.00%	32.1 5.84%	3.39 1.74%	7.6%	3.02	3.64
Large male	Normal	277 0.67%	0.67 0.01%	36.1 5.92%	2.49 0.84%	7.3%	3.11	4.08
Large male	Obese	279 0.69%	1.05 0.01%	40.3 8.62%	3.31 1.16%	10.3%	3.01	3.87

* The unit of the neck/femur/belt force is kN, and the unit of deflection is mm.

IV. DISCUSSION

This study is the first to use a parametric human body model to investigate the combined effects of stature and high BMI on injury risks in frontal crashes. Generally speaking, the simulations suggested that obese occupants tended to have higher lower extremity and chest injury risks than non-obese occupants in this severe frontal crash scenario. Based on an examination of body kinematics and loading, the increased risk appears to be due largely to higher mass and poor pelvis constraint. The simulations also showed higher joint injury probability for the short female than for the midsize male. These trends in injury risk are broadly consistent with previous analyses of crash data [2,3,10-17].

Compared with previous studies that focused on separate effects from either the stature or obesity on occupant injury risks, the current study investigated both the stature and body shape effects at the same time, and used a validated posture-prediction model to achieve realistic driving postures for each body size. Several interesting findings indicated that the obesity effects may vary for occupants with different statures. Specifically, the increased chest injury risk in obese occupants was the most pronounced for the short female, to a lesser extent for the tall male, but was not apparent for the mid-stature male. Interestingly, based on the occupant kinematics, the obesity-induced higher chest injury risks may be caused by different mechanisms between the short female and tall male. As shown in Fig. 5, because the obese short female is very close to the steering wheel before the crash, her abdomen/chest pushed the airbag up at the early stage of the crash, resulting in a chest contact to the lower edge of the steering wheel, which may contribute to the higher chest injury risk. However, this contact was not observed for the obese tall male. The higher chest injury risk for the obese tall male seemed mainly due to the higher torso excursion associated with the high mass/energy. Similarly, the obesity effects on head injury risks differed among occupants with the three statures. For the short female and mid-stature male, being obese may reduce the head injury risk due to a submarining type of kinematics, while the obese tall male sustained almost the same head injury risk as the non-obese tall male because the obese tall male's head struck through the airbag and contacted the instrument panel. Note that head injury risk calculations considered only linear accelerations (HIC 15) and all predicted head injury risks were very low.

In the current study, a constant load limiter was used for all the simulations. Consequently, similar forces were transferred through the seatbelt to the chest of all occupants. Regardless of the occupant interaction with the airbag, this constant seatbelt force alone may help to explain why short female drivers showed higher chest injury risks due to chest deflection than taller drivers. On the other hand, the airbag design used in this study was optimised for the midsize male ATDs, which may be sub-optimal especially for the obese short female and the obese tall male. These results indicate that restraint system designs that can adapt to occupant stature and body shape have a great potential to improve the occupant protection beyond midsize males.

There are several limitations to this study, which can be considered as future work for this study. First, only one vehicle model was used, therefore the findings in this study only represent that particular vehicle and may not be generalised in the whole vehicle fleet. However, the injury trends suggested by this study are generally consistent with the other studies.

Second, our statistical geometry models only include the ribcage, pelvis, femur, tibia and the external body shape, therefore bones in other body regions, such as the skull, cervical spine, and feet were morphed by the external body surface without accurate bone geometry prediction. Furthermore, the characteristics of the joints and dampers in the hip, knee, and cervical spine were not changed among the 6 morphed models. The morphed human models were not validated against any PMHS tests, and their material properties were not changed with different stature and body shape. To validate morphed human models, the traditional way for human model validation may not be appropriate, because PMHS test corridors generated by scaling method based on the body size and mass may not work for occupants with different body shapes. On the other hand, the mesh morphing technique may enable subject-specific model validations, in which the human model can be morphed into the geometry of a specific PMHS. By accounting for the geometry variations, especially in the body shape, the model validation can be more focused on the material properties. One of our previous studies has shown that the morphed human models can generally produce more accurate results than the baseline model [57], but the biofidelity of the morphed human models requires further investigation.

Third, we also assumed that obesity or body shape does not affect the injury risk curves. Further investigation will be needed to evaluate this assumption. Other injury criteria, such as BrIC, Multi-point thoracic injury criterion, and tibia load could be considered in our future studies for evaluating injury risks.

Finally, posture and position varies widely even among individuals with the same overall stature and body weight, while the driving posture model was used to estimate the average posture given sex, stature, and body weight. Furthermore, the driving posture model was developed based on volunteers with BMI from 16.9 to 33.5 kg/m^2, which may induce errors when extrapolating the results to BMI 40. The non-linear differences in restraint system interaction observed in the current study suggest that a particular difference in torso recline or fore-aft seat position may have little consequence for some occupants but large effects for others. Further research is needed to differentiate between body size and posture/position effects.

V. CONCLUSIONS

This study developed six FE human models with a wide range of stature and body shape by morphing the GHBMC M50-OS model using a mesh morphing method developed previously. US NCAP frontal crash simulations were conducted with these morphed human models considering the driving posture variations with the given ranges of stature and body shape. The simulations suggested that driver body size and body shape affect occupant interactions with the restraints, occupant kinematics, and injury risks in severe frontal crashes. The findings suggest that restraint optimisation should include additional consideration of occupants who differ substantially in size from the ATDs commonly used for vehicle assessment.

VI. ACKNOWLEDGEMENT

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