EFFECTS OF MALE STATURE AND BODY SHAPE ON THORACIC IMPACT RESPONSE USING PARAMETRIC FINITE ELEMENT HUMAN MODELING

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Paper Number 17-0314

ABSTRACT

Among the whole population, small, obese, and/or older occupants are at increased risk of death and serious injury in motor-vehicle crashes compared with mid-size young men. Current adult finite element (FE) human body models (HBM) have been developed in a few body sizes (large male, midsize male, and small female) with reference body dimensions similar to those of the available physical anthropomorphic test devices (ATDs). The limited number of body sizes available has resulted in part because the time needed to develop an FE HBM using typical methods is measured in months or even years. The objective of the current study was to apply a recently developed FE HBM morphing method to generate hundreds of FE human models for occupants with a wide range of stature and body shape and using the diverse human models for impact simulations.

The midsize male THUMS and GHBMC models were used as the baseline models to be morphed into occupants with different combinations of stature and body shape. The target geometries were predicted using statistical geometry models of external body shape and the skeleton (ribcage, pelvis, femur and tibia) developed previously based on 3D body scan and CT data from a total of more than 500 subjects. A landmark-based radial basis function (RBF) interpolator was used to morph the baseline models into target geometries. Anthropometric targets for 112 men were sampled based on US population statistics for age, stature and body mass index (BMI). Using these targets, 100 HBMs were developed by morphing THUMS and 12 by morphing the GHBMC model. Pendulum thorax impact conditions were applied to 36 morphed THUMS models and 12 morphed GHBMC models to investigate effects of occupant characteristics on chest impact responses.

The morphed models were all automatically generated without any manual adjustment, and their mesh quality was reasonable and suitable for impact simulations. The mesh morphing process required about 10-30 minutes per model on a contemporary PC. Peak impact forces and chest deflections in the chest pendulum impact simulations varied substantially with different models, confirming the need to consider population variation in evaluating the occupant responses. The age, stature, BMI, and weight effects on chest impact responses were found to be complex but consistent between the morphed THUMS and GHBMC models. The method developed in this study can help future safety designs for occupants with a wide range of stature and body shape.

INTRODUCTION

Elderly and obese people are at greater risk of death and serious injury in motor-vehicle crashes (MVCs), than midsize, young occupants. Kent et al. [1] reported that if the injury risks for people of all ages were the same as for people at age 20, in the U.S. alone there would be 1.13 to 1.32 million fewer occupants injured each year. This is nearly half the number of total annual injuries in MVCs. Increased age in adults is reported to be associated with increased serious injury risks to almost every body region and in every crash mode, but the age effect is especially significant for thoracic injuries [2-4]. Several studies using crash injury data have also shown that obese occupants are at higher risk of injury to the thorax [5-9] and lower extremities [5,10-13] in frontal crashes, as compared to normal-weight individuals.

Due to increasing life expectancy and decreasing birth rates, the proportion of the older population in the US, Japan, China, and many other countries is increasing, and this increase is expected to continue for the next several decades. By 2030, 20% of the US population will be age 65 or older (http://www.census.gov). Similarly, the proportion of people who are obese 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 worldwide. In the U.S., the prevalence of obesity was 35.7% in 2009-2010, compared with 22.9% in 1988-1994 [14].

The documented evidence that age and obesity are strongly related to risks of injury in MVCs, together with the projected increase in older and obese populations, highlight the potential benefit of safety systems specifically optimized for these vulnerable populations.

Finite element (FE) human body models (HBMs) are among the most widely used injury assessment tools. However, the state-of-the-art FE HBMs, such as THUMS v4 [15] and GHBMC models [16], have typically been constructed to simulate the same small number of body sizes and shapes currently represented by the anthropomorphic test devices (ATDs), in particular the midsize male, small female, and large male. Over the past few years, several studies have investigated using mesh morphing method to rapidly change the geometry of an existing FE human model to occupants with varied age, stature, and body mass index (BMI). Shi et al. [17] developed four FE human models 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). Schoell et al. [18] developed a 65 year-old midsize male model by morphing the GHBMC midsize male model. The geometries of the brain, head, ribcage, pelvis, femur, and tibia were predicted by statistical geometry models, and the material properties of the head, thorax, pelvis, and lower extremities were adjusted based on the literature. More recently, Hwang et al.[19] and Hu et al. [20] morphed THUMS v4 and GHBMC models to represent occupants with a wide range of age, stature, and BMI. In all these previous studies, the mesh morphing approach eliminated the costly and time-consuming process of building entirely new human models for each desired occupant size and shape, but only a few morphed models were generated and they have not yet been used to study the human impact responses considering the stature, age, and body shape effects. In addition, it is not clear whether different baseline models would affect the general trends of occupant characteristics (e.g. stature, age, and body shape) effects on their impact responses provided by the morphed models.

Therefore, the objective of this study was to (1) demonstrate the feasibility of rapidly generating a large set of FE human models for occupants with a wide range of stature and body shape by morphing different existing human models and (2) use the diverse human models to investigate the effects of stature, body shape, and age on thorax impact response using a standardized test protocol.

METHODS

Two Baseline FE Human Models

In this study, two state-of-the-art FE human models, THUMS v4 and GHBMC v4.4 midsize male models (Figure 1), were used as the baseline model to be morphed into occupants with a wide range of stature and body shape. The geometry of the THUMS midsize male model is based on a 39-year-old man with a stature of 173 cm and a weight of 77.3 kg. The model has 1.8 million elements with a final stature of 175 cm and weight of 77 kg. The geometry of the GHBMC midsize male model is based on a 26-year-old man with a stature of 174.9 cm and a weight of 78 kg. The model has 2.2 million elements with a final weight of 76.8 kg. Both models contain detailed anatomical structures of the human body, including the skeleton, cartilages, internal organs, ligaments, muscles, major arteries and veins, and other soft tissues. Both models have also been validated extensively against test results from post-mortem human subjects (PMHSs) [15,16,21-23]. Overlaying the skeletons and external body shapes between the THUMS and GHBMC (Figure 1) by matching their hip joints and eye fore-aft locations demonstrates that their geometries are different. More specifically, the THUMS model has slightly longer femur bones, but shorter torso than the GHBMC. The rib angles in GHBMC are slightly flatter than the THUMS, resulting in slightly deeper ribcage. The GHBMC model also seems slightly more muscular than the THUMS model based on the shapes of the chest, abdomen, and thigh. These differences highlight the variations among human geometry even with the same target stature and weight.

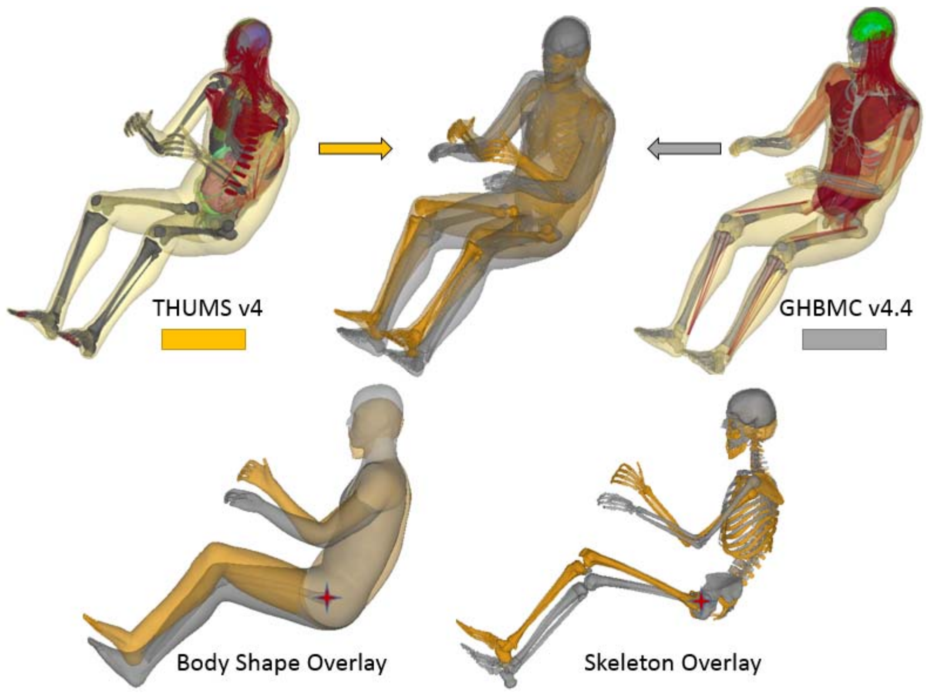


Figure 1. Comparison between THUMS v4 and GHBMC v4.4 midsize male models

Parametric Human Models through Mesh Morphing

The steps for morphing the THUMS and GHBMC models were similar (Figure 2). The process began with statistical shape models for the 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). These statistical models have been developed previously based on 3D body scan and CT data from a total of more than 500 subjects. Mesh morphing methods developed previously were 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 predict thousands of points that define the body posture [24-26], the size and shape of the external body surface [27], and ribcage [28,29] and lower extremity bone geometries [30,31]. The skeleton and external body shape geometries were integrated together based on the landmark and joint locations shared in both skeleton and external body shape models [19]. Once the target geometries were developed, the baseline model can be morphed to match the target geometries using a landmark-based 3D non-linear interpolation techniques based on radial basis functions (RBF). More details on the mesh morphing methods have been published previously [17,19,20,32-34].

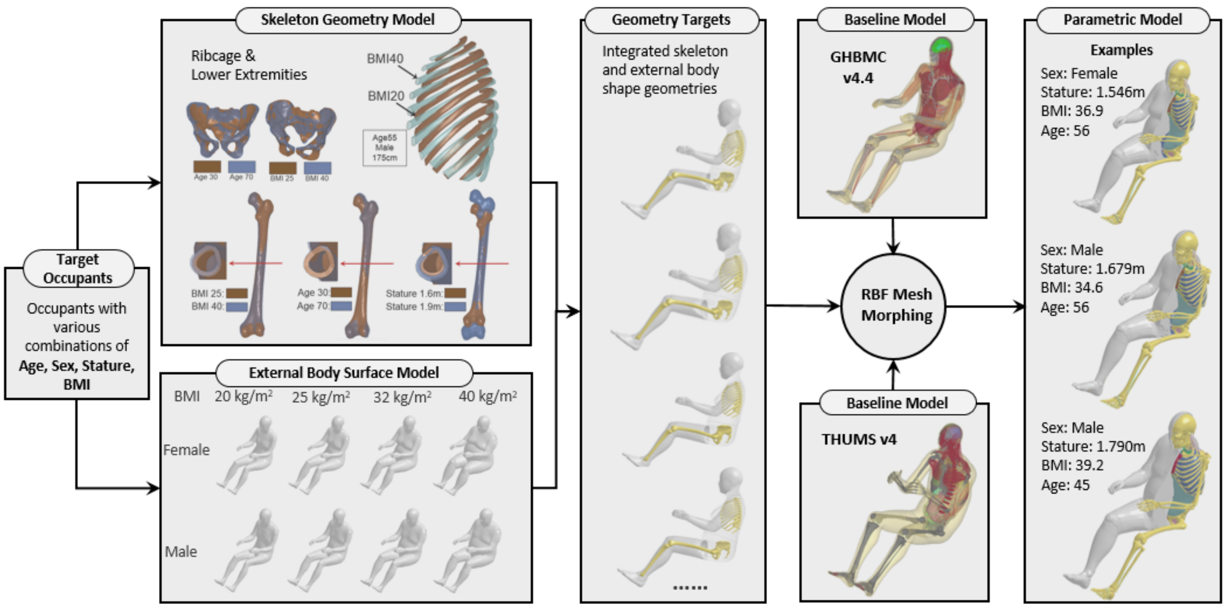


Figure 2. Methods for rapid development of parametric human FE models for a diverse population

To morph different baseline models (i.e. THUMS and GHBMC) into geometries predicted by the same set of statistical skeleton and body shape models, each of the baseline models has to be linked to the statistical geometry models. To do that, each baseline model was treated as a subject in the same way as that used for collecting the geometry data. Specifically, landmarks were first identified on each of the 24 ribs, sternum, pelvis, femurs, tibias, and the external body shape on the baseline models. Then the template meshes used to develop the statistical geometry models were morphed and projected onto the corresponding skeleton and body shape surface meshes of the baseline models. This mesh mapping process set up the correspondence between the template meshes of the statistical geometry models and the surface meshes from the baseline models. After that, with any given age, sex, stature, and BMI, the surface meshes of the ribcage, pelvis, femur, tibia, and the external body shape in the baseline model could be morphed into the statistical-model-predicted geometry. These morphed meshes for the skeleton and external body surfaces served as the landmarks for morphing all the other components in the whole body.

The whole-body mesh morphing methods were slightly different between the THUMS and GHBMC models due to their differences of mesh density in the skeleton and external body shape. In particular, the THUMS model was divided into ten regions with each region being morphed separately first and the combined. As for the GHBMC model, because of the high mesh density on the skeleton and external body surfaces, the regional morphing approach still required over 30,000 landmarks in some regions, which significantly increased the computational time. To solve this problem, a sequential mesh morphing method was used for the GHBMC model, in which the mesh morphing was conducted component by component. The components typically represent a single bone, ligament, muscle, or internal organ. For morphing a single component, the surface nodes of that component were first used to search a set of the nearest landmarks around the component. The landmarks are either from the morphed skeleton or body shape based on the statistical geometry models or from the previously-morphed components. The mesh morphing was conducted one-by-one sequentially until all the components were morphed. Because only a limited number of landmarks were used for each mesh morphing, the total computational time was significantly reduced compared to the regional mesh morphing. In all the morphed models, material properties were unchanged to allow consideration of exclusively geometric effects.

Human Model Sampling

A total of 100 male human models were developed by morphing the THUMS to all combinations of five statures (162, 170, 175, 180, and 188 cm), five BMI levels (20.4, 24.2, 27.4, 31.2, and 39.2 kg/m^2), and four ages (20, 40, 60, 80 years old). A total of 12 human models were developed by morphing the GHBMC to all combinations of two statures (175 and 188 cm), three BMI levels (25, 30, and 35 kg/m^2), and two ages (30 and 70 years old). All the morphed models were run without loading for 1 ms to verify their integrity.

Thorax Pendulum Impact Simulations

Thorax pendulum impact simulations were conducted with 36 morphed THUMS models (three statures, three BMI levels, and four ages) and all 12 morphed GHBMC models. The pendulum impact condition followed that used in a study with PMHSs by Kroell et al. [35], in which a 23.4-kg and 15-cm-diameter cylindrical hub impactor was used to impact the PMHS at the mid sternum with an impact velocity of 6.7 m/s. The model-predicted thorax impact responses (force vs. chest deflection) were compared among the morphed models. The chest deflection was calculated based on the bone deformation on the mid sternum relative to the ribcage depth. The age, stature, BMI, and weight effects on the peak force and peak deflection were analyzed.

RESULTS

Morphed Human Models

The mesh morphing for both THUMS and GHBMC models was finished automatically without any manual adjustment. Per model, it took 10-15 minutes for morphing the THUMS and about 30 minutes for morphing the GHBMC model on a contemporary PC. Examples of the morphed human models based on THUMS and GHBMC are shown in Figure 3. The weights of all the morphed models were slightly lower than the theoretical values based on BMI, but the discrepancies are all less than 2% of the total target weight. This is consistent between the morphed THUMS and GHBMC models. The mesh quality of the morphed models is slightly lower than the baseline THUMS and GHBMC models. The smallest Jacobian values of the solid elements in all morphed models range from 0.03 to 0.25, compared with 0.30 in the baseline THUMS and GHBMC models. The number of solid elements with <0.3 Jacobian for each of the 112 morphed models is typically less than 100 (out of ~2 million elements in the THUMS and GHBMC models). For all the models, no error occurred in the 1-ms no loading simulation.

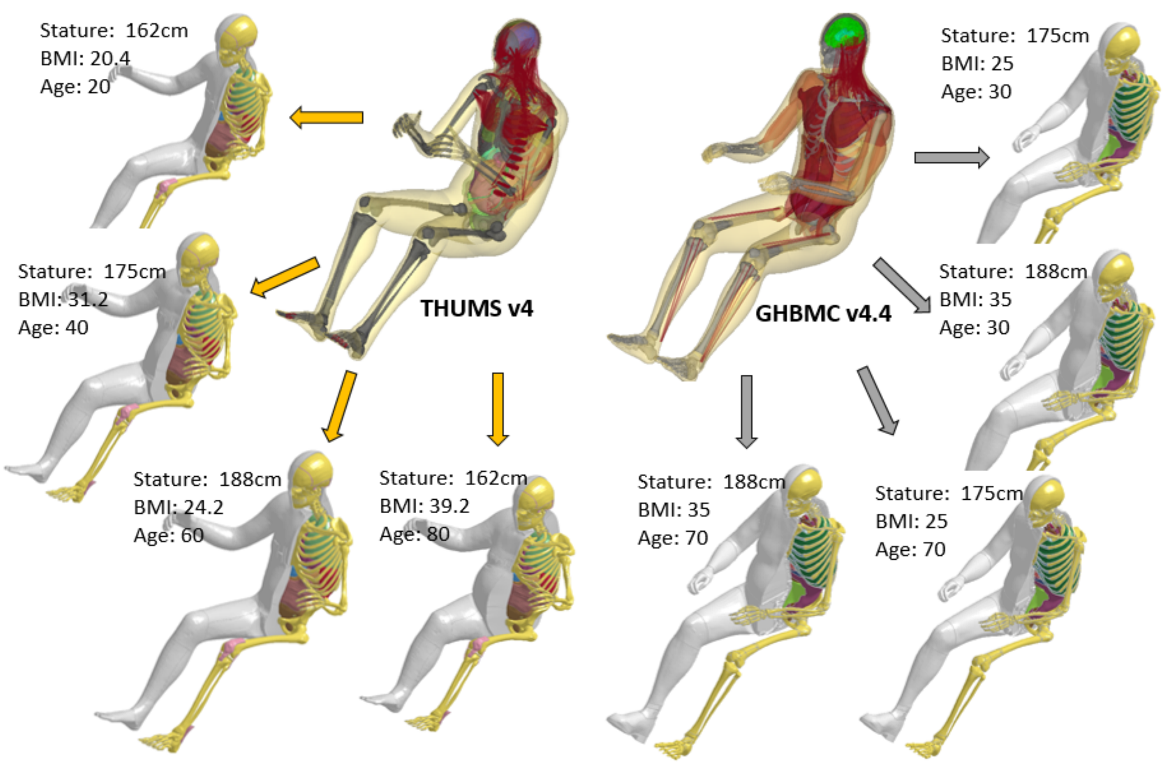


Figure 3. Examples of morphed THUMS and GHBMC models

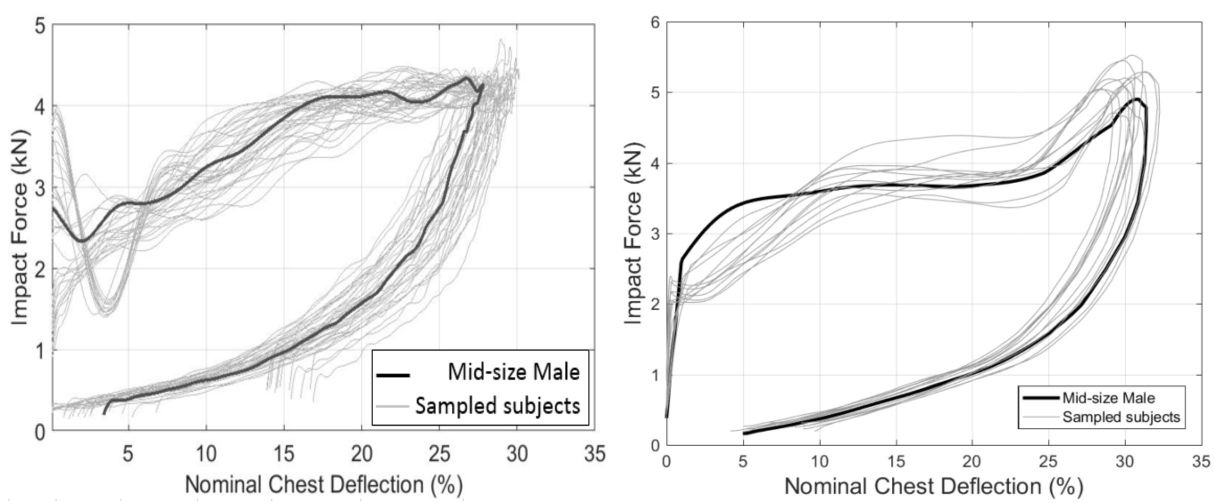
Pendulum Impact Simulations

All thorax pendulum impact simulations finished without error. Figure 4 shows the impact force vs. chest deflection curves from the 36 morphed THUMS models and 12 morphed GHBMC models. Generally speaking, the thorax impact responses were similar between the morphed THUMS and GHBMC models, although the morphed GHBMC models showed slightly higher impact force and chest deflection. The model-predicted peak impact forces and chest deflections varied substantially with different morphed models, confirming the need to consider population geometry variation in evaluating the occupant response. The morphed THUMS models showed larger variations in the impact responses than the morphed GHBMC models likely due to their wider ranges of age, stature, and BMI.

The age, stature, BMI, and weight effects on the peak impact force and peak chest deflection based on the morphed THUMS models are shown in Figure 5, in which several preliminary but interesting trends can be found. First, the BMI, stature and weight effects on both the peak force and deflections are generally consistent. In particular, the shorter, leaner or lighter subjects tended to have slightly higher peak force and chest deflections than tall and heavy subjects. This is especially true for the shortest and leanest subjects on peak force, but the trend is not always consistent. Second, the age effect may be opposite to our expectation, as the increase in age led to stiffer thorax with higher peak force and lower chest deflection. Note that the material properties in these models were not changed. Therefore, the trend shown here only reflected the age-related geometry effects, but not the material property effects. Third, there are complex nonlinear and interaction effects among the occupant characteristics, as many lines in Figure 5 are curved and sometimes their slopes are in opposite directions.

The age, stature, BMI, and weight effects on the peak impact force and peak chest deflection based on the morphed GHBMC models are shown in Figure 6. The general trends are similar to those based on the morphed THUMS models, although all the trends are less evident due to the smaller ranges of age, stature, and BMI in the morphed GHBMC models.

These results highlight the capability of parametric human models for exploring and understanding the variation and complexity of human impact responses.



a) 36 Morphed THUMS models b) 12 Morphed GHBMC models

Figure 4. Pendulum impact simulation results

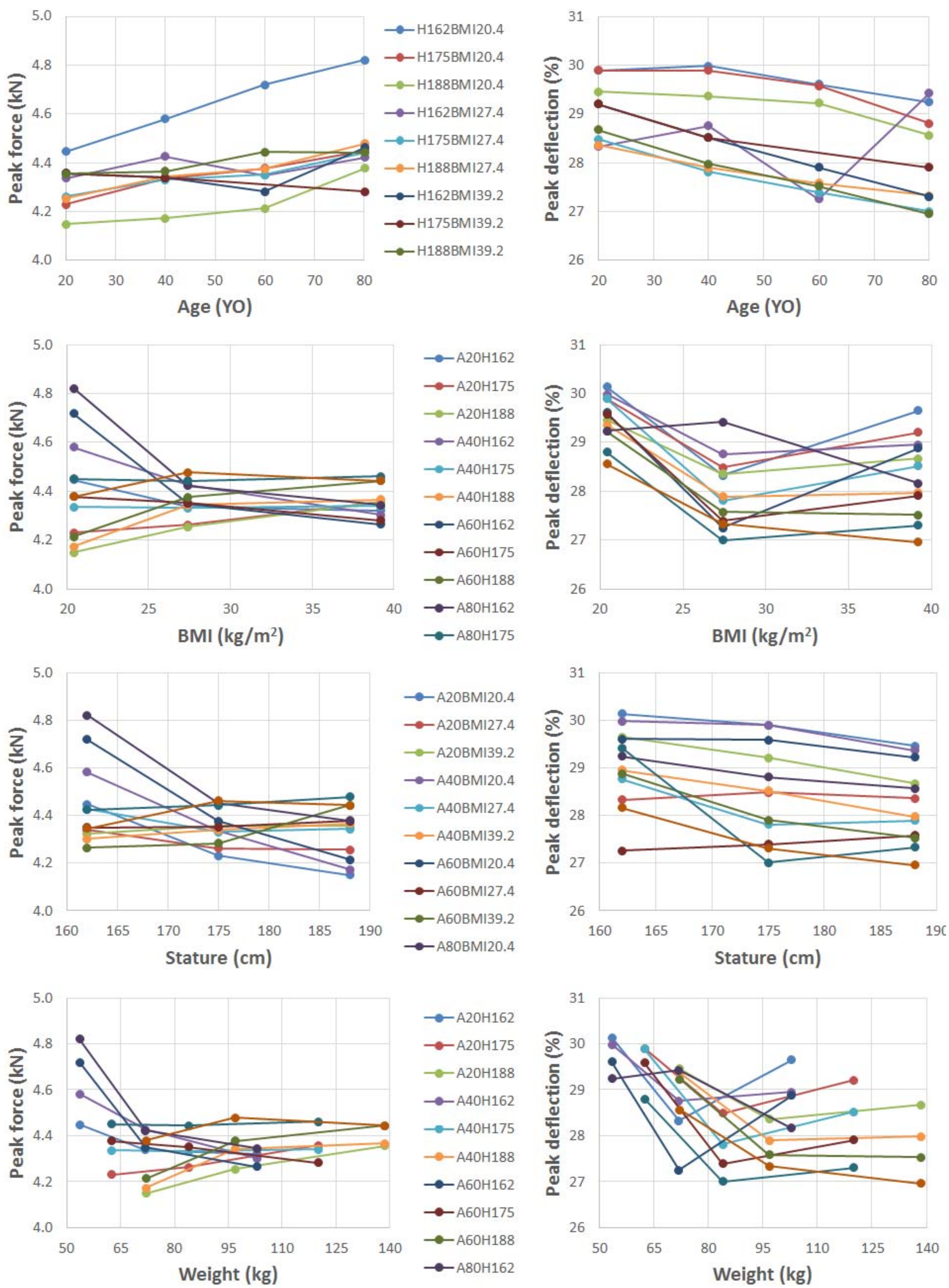


Figure 5. Occupant characteristic effects on chest impact responses based on the morphed THUMS models
A: Age(year-old), H: Height(cm), and BMI: Body Mass Index(kg/m^2)

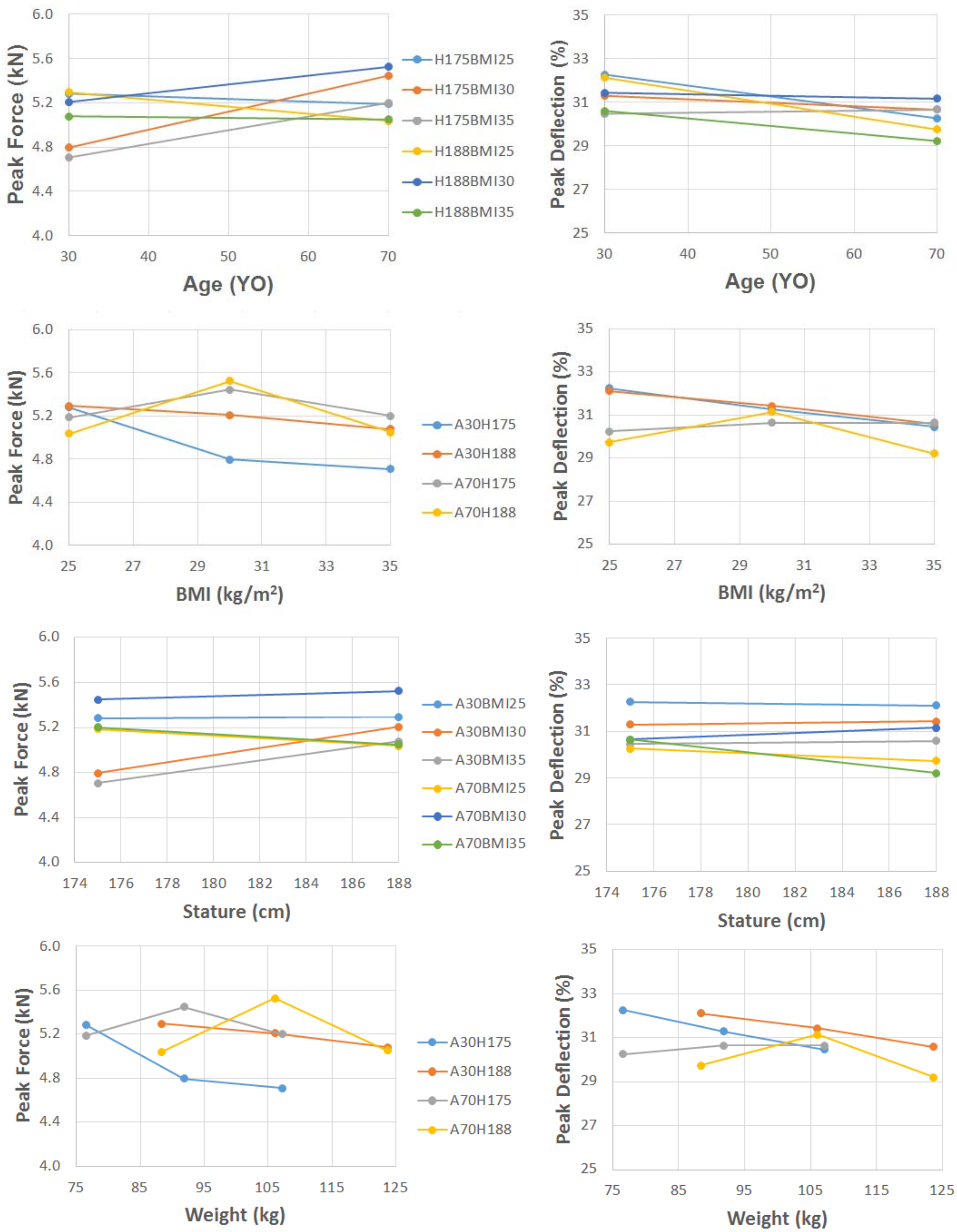


Figure 6. Occupant characteristic effects on chest impact responses based on the morphed GHBMC models
A: Age(year-old), H: Height(cm), and BMI: Body Mass Index(kg/m^2)

DISCUSSION

This study generated a large set of FE human models by morphing two different baseline human models, and demonstrated that the mesh morphing method works well even for baseline models with slightly different posture and skeleton/body shape geometries. Although mesh morphing slightly reduced the mesh quality, the results were sufficient for impact simulations without any manual improvement. This result also indicated that the mesh morphing method used in this study can be applied to any other FE occupant models.

A total of 48 morphed models were used for thorax pendulum impact simulations. The results demonstrated the value of using a large set of human models to study the variations in human impact responses and the age, stature, and BMI effects on those responses. Because the material properties were not varied in the morphed models, the model-predicted response variations mainly reflected the geometry effects associated with age, stature and BMI. Since we focused on the thorax impact responses in this study, the results predicted by the morphed models were varied largely due to the ribcage and body shape geometry variations.

The complex stature, weight, and BMI effects on the peak impact force are likely due to a combination of inertia and padding effects. That is, the same pendulum transferred less energy to heavier subjects than lighter ones, and more flesh on the chest may have reduced the peak force. On the other hand, taller and more obese subjects have flatter rib angle and deeper ribcages, and consequently their chest deflection ratios (in %) relative to the chest depth would be smaller than the short and lean subjects even with the same chest deflections (in mm). Similarly, older subjects created by these models have flatter ribs and deeper ribcages than young subjects. As a result, their chest deflection ratio (in %) may be lower as well. However, the age effects on the peak impact force are complex and could be affected by at least two geometrical factors. One is that the flatter rib angles in older subjects may increase the ribcage stiffness, yet older subjects also have less flesh tissues on the chest and more adipose tissues in the abdomen. Regardless the reasons for those preliminary trends, both the morphed THUMS and GHBMC models show consistent trends from age, stature, BMI, and weight. The mesh morphing method effectively introduced the geometry variations into the human models, making the morphed models capable of simulating occupant characteristic effects on human impact responses.

This study has substantial limitations. Only the ribcage, pelvis, femur, tibia and external body shape geometries were estimated based on the statistical models, other skeleton geometries, such as the skull and cervical spine, need to be considered in the future. The morphed human models were not validated against any PMHS tests, although a preliminary investigation has suggested that subject-specific modeling of PMHS tests will provide an avenue for validating parametric HBMs [36]. In the current study, material properties were not changed with different age, stature and BMI. Many previous studies have documented significant changes in material properties with age [37-40], but it is not yet clear whether changes in material properties have important effects on response as well as tolerance relative to the effects of geometry across the population. The methodology used here creates "average" HBM given the anthropometric targets. The complexity of the responses even in this simple biomechanical test suggests that considerably more work is needed to understand the relative importance of various factors. HBMs provide the ideal tool for these investigations, because PMHS necessarily individually vary on all factors, making controlled studies of such factors as flesh padding and rib angle problematic. Further research using parametric HBM will allow a greater understanding of the geometric, material, and other factors that result in the observed wide differences in occupant risk in crashes.

CONCLUSIONS

This study generated a large set of FE human models by morphing two baseline human models (THUMS and GHBMC), and demonstrated the feasibility of rapidly generating a large set of FE human models without manual mesh adjustment. Pendulum thorax impact simulations with a subset of the morphed models showed substantial variations in the thorax impact responses with different models, confirming the need to consider population variation in evaluating the occupant response. The age, stature, BMI, and weight effects on the thorax impact responses were complex but fairly consistent between the morphed THUMS and GHBMC models. The method developed in this study can help improve vehicle safety for occupants with a wide range of characteristics.

REFERENCES

[1] Kent, R., Trowbridge, M., Lopez-Valdes, F.J., Ordoyo, R.H., and Segui-Gomez, M. 2009. "How many people are injured and killed as a result of aging? Frailty, fragility, and the elderly risk-exposure tradeoff assessed via a risk saturation model." Ann Adv Automot Med, 53: 41-50

[2] Kent, R., Henary, B., and Matsuoka, F. 2005. "On the fatal crash experience of older drivers." Annu Proc Assoc Adv Automot Med, 49: 371-91

[3] Morris, A., Welsh, R., Frampton, R., Charlton, J., and Fildes, B. 2002. "An overview of requirements for the crash protection of older drivers." Annu Proc Assoc Adv Automot Med, 46: 141-56

[4] Morris, A., Welsh, R., and Hassan, A. 2003. "Requirements for the crash protection of older vehicle passengers." Annu Proc Assoc Adv Automot Med, 47: 165-80

[5] Boulanger, B.R., Milzman, D., Mitchell, K., and Rodriguez, A. 1992. "Body habitus as a predictor of injury pattern after blunt trauma." The Journal of Trauma Injury, Infection, and Critical Care, 33: 228-232

[6] Moran, S.G., McGwin, G., Jr., et al. 2002. "Injury rates among restrained drivers in motor vehicle collisions: the role of body habitus." The Journal of trauma, 52(6): 1116-20

[7] Reiff, D.A., Davis, R.P., et al. 2004. "The association between body mass index and diaphragm injury among motor vehicle collision occupants." The Journal of trauma, 57(6): 1324-8; discussion 1328

[8] Mock, C.N., Grossman, D.C., Kaufman, R.P., Mack, C.D., and Rivara, F.P. 2002. "The relationship between body weight and risk of death and serious injury in motor vehicle crashes." Accid Anal Prev, 34(2): 221-8

[9] Cormier, J.M. 2008. "The influence of body mass index on thoracic injuries in frontal impacts." Accident Analysis & Prevention, 40(2): 610-615

[10] Arbabi, S., Wahl, W.L., et al. 2003. "The cushion effect." The Journal of trauma, 54(6): 1090-3

[11] Rupp, J.D., Flannagan, C.A., et al. 2013. "Effects of BMI on the risk and frequency of AIS 3+ injuries in motor-vehicle crashes." Obesity, 21(1): E88-E97

[12] Ryb, G.E. and Dischinger, P.C. 2008. "Injury severity and outcome of overweight and obese patients after vehicular trauma: a crash injury research and engineering network (CIREN) study." The Journal of trauma, 64(2): 406-11

[13] Zarzaur, B.L. and Marshall, S.W. 2008. "Motor vehicle crashes obesity and seat belt use: a deadly combination?" The Journal of trauma, 64(2): 412-9; discussion 419

[14] Flegal, K.M., Carroll, M.D., Kit, B.K., and Ogden, C.L. 2012. "Prevalence of obesity and trends in the distribution of body mass index among US adults, 1999-2010." Jama, 307(5): 491-497

[15] Hayashi, S., Yasuki, T., and Kitagawa, Y. 2008. "Occupant kinematics and estimated effectiveness of side airbags in pole side impacts using a human FE model with internal organs." Stapp Car Crash J, 52: 363-77

[16] Vavalle, N.A., Moreno, D.P., Rhyne, A.C., Stitzel, J.D., and Gayzik, F.S. 2013. "Lateral impact validation of a geometrically accurate full body finite element model for blunt injury prediction." Ann Biomed Eng, 41(3): 497-512

[17] Shi, X., Cao, L., Reed, M.P., Rupp, J.D., and Hu, J. 2015. "Effects of obesity on occupant responses in frontal crashes: a simulation analysis using human body models." Computer methods in biomechanics and biomedical engineering, 18(12): 1280-1292

[18] Schoell, S.L., Weaver, A.A., et al. 2015. "Development and validation of an older occupant finite element model of a mid-sized male for investigation of age-related injury risk." Stapp Car Crash J, 59: 359-383

[19] Hwang, E., Hallman, J., et al. 2016. "Rapid Development of Diverse Human Body Models for Crash Simulations through Mesh Morphing." SAE Technical Paper, 2016-01-1491(doi:10.4271/2016-01-1491)

[20] Hu, J., Fanta, A., Neal, M., Reed, M., and Wang, J. 2016. "Vehicle Crash Simulations with Morphed GHBMC Human Models of Different Stature, BMI, and Age." Proceedings of The 4th International Digital Human Modeling Symposium (DHM2016), Montréal, Québec, Canada

[21] Shin, J., Yue, N., and Untaroiu, C.D. 2012. "A finite element model of the foot and ankle for automotive impact applications." Ann Biomed Eng, 40(12): 2519-31

[22] Untaroiu, C.D., Yue, N., and Shin, J. 2013. "A finite element model of the lower limb for simulating automotive impacts." Ann Biomed Eng, 41(3): 513-26

[23] Iwamoto, M., Kisanuki, Y., et al. 2002. "Development of a finite element model of the total human model for safety (THUMS) and application to injury reconstruction." in *2002 International IRCOBI Conference on the Biomechanics of Impact*: Munich, Germany.

[24] Reed, M.P., Manary, M.A., Flannagan, C.A., and Schneider, L.W. 2000. "Effects of vehicle interior geometry and anthropometric variables on automobile driving posture." Hum Factors, 42(4): 541-52

[25] Reed, M.P., Manary, M.A., Flannagan, C.A., and Schneider, L.W. 2002. "A statistical method for predicting automobile driving posture." Hum Factors, 44(4): 557-68

[26] Park, J., Reed, M.P., and Hallman, J.J. 2016. "Statistical models for predicting automobile driving postures for men and women including effects of age." Human Factors, 58(2): 261-278

[27] Reed, M.P. and Parkinson, M.B. 2008. "Modeling Variability in Torso Shape for Chair and Seat Design." in *ASME International Design Engineering Technical Conferences*: New York, NY. p. 1-9.

[28] Wang, Y., Cao, L., et al. 2016. "A parametric ribcage geometry model accounting for variations among the adult population." J Biomech,

[29] Shi, X., Cao, L., et al. 2014. "A statistical human rib cage geometry model accounting for variations by age, sex, stature and body mass index." J Biomech, 47(10): 2277-85

[30] Klein, K.F., Hu, J., Reed, M.P., Hoff, C.N., and Rupp, J.D. 2015. "Development and Validation of Statistical Models of Femur Geometry for Use with Parametric Finite Element Models." Ann Biomed Eng, 43(10): 2503-14

[31] Klein, K.F. 2015. "Use of Parametric Finite Element Models to Investigate Effects of Occupant Characteristics on Lower-Extremity Injuries in Frontal Crashes " PhD Dissertation, University of Michigan

[32] Hu, J., Rupp, J., and Reed, M. 2012. "Focusing on vulnerable populations in crashes: recent advances in finite element human models for injury biomechanics research." Journal of Automotive Safety and Energy, 3(4): 295-307

[33] Li, Z., Liu, W., Zhang, J., and Hu, J. 2015. "Prediction of skull fracture risk for children 0-9 months old through validated parametric finite element model and cadaver test reconstruction." Int J Legal Med, 129(5): 1055-66

[34] Wang, Y., Bai, Z., et al. 2015. "A simulation study on the efficacy of advanced belt restraints to mitigate the effects of obesity for rear-seat occupant protection in frontal crashes." Traffic injury prevention, 16(sup1): S75-S83

[35] Kroell, C.K., Schneider, D.C., and Nahum, A.M. 1974. "Impact tolerance and response of the human thorax." in *Stapp Car Crash Conference Proceedings*.

[36] Hwang, E., Hu, J., et al. 2016. "Development, Evaluation, and Sensitivity Analysis of Parametric Finite Element Whole-Body Human Models in Side Impacts." Stapp Car Crash J, 60: 473-508

[37] Yamada, H., "Strength of biological materials". 1970, Baltimore: The Williams and Wilkins Company.

[38] Burstein, A.H., Reilly, D.T., and Martens, M. 1976. "Aging of bone tissue: mechanical properties." J Bone Joint Surg Am, 58(1): 82-6

[39] Wall, J.C., Chatterji, S.K., and Jeffery, J.W. 1979. "Age-related changes in the density and tensile strength of human femoral cortical bone." Calcif Tissue Int, 27(2): 105-8

[40] Ito, O., Dokko, Y., and Ohashi, K. 2009. "Development of Adult and Elderly FE Thorax Skeletal Models." in *2009 SAE World Congress*. SAE 2009-01-0381: Detroit, MI, USA.