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Evaluation of Morphed Human Body Models for Diverse Occupant Safety Analysis

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Abstract

Female, obese, and elderly occupants are at increased risk of injury in vehicle accidents. Human Body Models (HBMs) are used to represent the human anatomy and to study injury mechanisms in mathematical crash test simulations. HBM morphing methods can adjust the anatomical geometry of existing HBMs, enabling HBMs to represent the diverse occupant population, beyond the traditionally considered body sizes.

The aims of this thesis were to define and select a diverse population of occupants. Thereafter, select an HBM morphing tool for morphing of the SAFER HBM to individuals in this population; Finally, this population of morphed HBMs was to be validated.

The defined target population to be represented by HBMs in occupant injury risk evaluations included individuals of both sexes. The selection was based on occupant injury risks and biomechanical risk factors. The male and female sub-populations include individuals of a wide range of statures and weights and ages from 20 to 80 years. A sample of 27 female and 27 males were selected as the initial population.

The parametric HBM morphing tool, developed by University of Michigan Transportation Research Institute, was selected for morphing the SAFER HBM.

Sled test results from individual male and female Post Mortem Human Subjects (PMHSs) of a wide range of body sizes were used for validation of morphed HBMs.

The SAFER HBM was parametrically morphed to each individual PMHS. Predictions from both morphed and the baseline SAFER HBM were collected in reconstructions of the PMHS tests. HBM kinematics, chest deflections and interaction forces were compared to corresponding test results using CORA cross-correlation rating. Comparison of morphed and baseline HBM results showed that correlation rating was not consistently improved for morphed HBMs. For large, obese, and small female subjects in frontal impacts, and in lateral impacts, morphed HBMs were stiffer than the corresponding PMHSs.

To improve morphed SAFER HBM predictions for diverse occupants, future work will identify and mitigate the sources of the stiff responses through model updates. Sex and age dependent biomechanical properties, as available in literature will be included.

Biofidelity criteria for morphed HBMs will be defined and with morphed HBMs meeting these criteria, protective principles increasing the protection of all occupants will be investigated.

Keywords: Human body model; Morphing; Diversity; Safety; Virtual testing; Validation

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Abbreviations

AIS	Abbreviated Injury Scale
ATD	Anthropomorphic Test Device (commonly, crash test dummy)
BMI	Body Mass Index = weight/(length^2) [kg/m^2]
FE	Finite Element
HBM	Human Body Model
PMHS	Post Mortem Human Subject
UMTRI	University of Michigan Transportation Research Institute

1 Introduction

Every year, road traffic accidents cause 1.35 million deaths and tens of millions of injuries. Among the fatally injured, almost a third are vehicle occupants (World Health Organization, 2018). Comparing frontal crash occupant injury risk in pre- and post-2009 vehicles, (Forman et al., 2019) found that the injury risk was reduced in the newer vehicles. However, head, upper extremity and thoracic skeletal injuries (especially for elderly occupants) remained as the most prevalent injuries. It was also found that the injury risk increases with age, body mass index (BMI, weight/stature^2) and was higher for females compared to males. In fact, occupant injury statistics shows that females, elderly and obese (BMI > 30 kg/m^2) are at increased risk of injury when compared to other demographic groups (Bose et al., 2011; Ridella et al., 2012; Viano et al., 2008).

The many injuries and the fact that up to 94% of vehicle accidents are due to human actions (National Center for Statistics and Analysis, 2015) are both major driving factors for the development of autonomous vehicles, or self-driving cars. Such vehicles, with advanced crash avoidance technology, may reduce the number of accidents, but some crashes are expected to be unavoidable (Klinich et al., 2016; Östling et al., 2019b, 2019a). Among these crashes are frontal impacts and oblique intersection crashes, which today have head, pelvis and rib fractures as common injuries (Pipkorn et al., 2020). In self-driving cars, it may become possible to relax, work or socialize in the vehicle, which possibly introduces new seating configurations or seating postures that are not considered in occupant safety today.

1.1 Contemporary Occupant Safety Evaluation

Occupant safety evaluation and safety system development have traditionally been performed using Anthropomorphic Test Devices (ATDs) as occupant substitutes in vehicle crash tests. These are commonly known as crash test dummies.

Each vehicle must meet certain legal requirements with respect to occupant safety. Regulations, such as the Federal Motor Vehicle Safety Standards (United States) or United Nations Economic Commission for Europe regulations (European Union) define standardized crash tests that the vehicle and its safety equipment must pass. The regulatory tests represent the minimum level of occupant crash safety performance. Consumer information organizations, such as the New Car Assessment Programs, also test the safety performance of vehicles to promote a high safety level. Each vehicle is rated on several safety related aspects, where occupant safety as measured by ATDs in crash tests is one. Regulatory and NCAP crash tests are standardized tests specifying impact speed, object to impact and which ATD to use as occupant substitute. The crash tests included represent common impact configurations, such as frontal and side impacts.

The advancement of computing power has enabled performing virtual crash tests by mathematical simulations. Using numerical methods, such as the Finite Element (FE) method, the vehicle, the ATD and the safety devices (e.g. seatbelts, airbags) are modelled and subjected to virtual crash tests in computer simulations. This allow designers and engineers to evaluate several different vehicle and safety system designs before a prototype vehicle is constructed for a physical crash test.

1.1.1 Crash test dummies

ATDs are mechanical representations of humans that are used to estimate injury risk through recorded forces, moments, deformations and accelerations at different body regions during a crash test. As they are measurement equipment that reliably should reproduce the same measurements in repeated crash tests, they have a simplified, mechanically robust, anatomy can withstand the forces of crash tests.

An injury risk estimated as low by an ATD in a crash test does not always mean that the corresponding injury does not occur in real-world accidents (Brumbelow and Farmer, 2013). Possible reasons are that the real-life accident scenarios differ from the tested crash configuration (Brumbelow and Farmer, 2013), the ATD and corresponding risk estimates are too simplified to represent the true human injury mechanisms (Kent et al., 2003), or the seating posture and/or anthropometry of the ATD used did not represent the occupants who suffered the injury.

The ATDs representing the population of adult occupants come in three sizes; a 5th percentile (small) female, a 50th percentile (midsize) male and a 95th percentile (large) male. The percentiles refer to the stature and weight in the male or female populations. The midsize male ATD has been the most widely used in regulatory and NCAP crash testing (Linder and Svensson, 2019). The ATD reference sizes are based on population measurements performed in U.S. in the 1970s and are now outdated for the 50th and 95th percentile male sizes. The 78 kg and 102 kg weights of the 50th and 95th percentile male ATDs now represents the 33rd and 81st percentiles of male weights in the U.S. population (Reed and Rupp, 2013).

The available ATD sizes are limited in their ability to represent different body shapes, such as obese individuals. Since obesity have been related to a poor fit of the lap belt over the pelvis (Reed et al., 2013) and increased excursion in frontal impact (Forman et al., 2009), results obtained from the non-obese ATDs may not be representative for obese occupants.

Many ATDs have a corresponding virtual FE model representation, such that their injury risk estimations can be gathered also from virtual crash tests. However, if only the currently existing ATDs and limited sizes are modelled in the virtual crash tests, the diverse occupant population is not represented.

1.1.2 Human Body Models

The use of numerical methods to perform virtual crash tests have enabled the implementation of FE-Human Body Models (HBMs) as occupant substitutes in crash simulations. HBMs aim to be more realistic representations of human occupants than the ATDs by modelling the actual human anatomy. That is, an HBM intends to model the human occupant, as opposed to a virtual ATD model, which models the corresponding mechanical ATD.

For example, ATDs use durable and simplified mechanical representations of the spine and chest, while an HBM can include each vertebra in the spine and each individual rib in the ribcage. The deformation, and resulting material stress and strain, throughout each included entity can be solved for with the FE method. HBMs thus have the potential for evaluating injury risk at the individual organ or tissue level by evaluating localized loading measures, such as pressure, stress or strain in the modelled anatomical structures. The HBMs also have the potential to be omni-directional occupant substitutes, representing human kinematics and injury risk in all impact directions since they accurately model the human joints, and are, unlike ATDs, not limited by mechanical robustness design constraints.

There are several challenges with creating detailed HBMs for injury prediction in vehicle impact scenarios (Wismans et al., 2005). The geometry of the human body, including internal structures must be obtained in sufficient detail, and constitutive (material) descriptions must be characterized. Biological tissue properties are often non-linear, viscoelastic and anisotropic, and for impact application the high deformation speeds (strain rates) properties should be known. Furthermore, anatomical geometry and material properties vary with age and sex and there is also high inter-individual variation. What constitutes sufficiently detailed geometry and constitutive modelling depend on what physiological processes the biological model should represent, or consequently, what questions the model should be able to answer. For example, limited models at scales ranging from sub-cellular, cellular, tissue, organ, body region to whole-body level exist (Roberts, 2013), but whole-body models including sub-cellular details of the roughly 30-40 trillion cells making up the human body does not.

For investigating vehicle occupant injury risk, whole-body HBMs incorporating details down to the organ level have been developed, such as the Global Human Body Models Consortium (GHBMC) (Gayzik et al., 2012) and Total Human Model for Safety (THUMS) (Shigeta et al., 2009) and SAFER HBM (Iraeus and Pipkorn, 2019). These HBMs are intended for predicting the whole-body occupant interaction with the vehicle and safety systems and the resulting organ blunt trauma injury risk.

The GHBMC (M50-O) and THUMS (v4) external and internal geometries are based on 3d-imaging of individual subjects that fitted the midsize male anthropometry. The models include the skeleton and several soft organs, such as the heart and liver of those individuals (Gayzik et al., 2012; Shigeta et al., 2009). The SAFER HBM v9 includes a detailed ribcage model corresponding to a true average male shape but simplified lumped representations of the soft organs in the abdominal and thoracic cavities. The SAFER HBM has been validated for predicting strain in the ribs cortical bone under various impact loading (Iraeus and Pipkorn, 2019) and for strain based rib fracture risk prediction (Pipkorn et al., 2019), and thus have the potential to be a valuable tool in understanding thoracic injury mechanisms, and ultimately designing safety systems that mitigate these injuries.

These HBMs have been based on the same standard anthropometries as the ATDs. For example, GHBMC and THUMS adult occupant models exists in the small female, midsize and large male sizes. The SAFER HBM represents the midsize male ATD size.

1.1.3 Human Body Model Morphing

For HBMs to represent occupants of other anthropometries, a model with a new geometry can be constructed or the geometry of an existing model can be modified. The small female GHBMC was constructed based on new 3d-imaging data from a small female individual (Davis et al., 2016), while the small female THUMS was originally created by scaling the dimensions of the midsize male model, complemented by female specific modeling of the pelvic and thoracic regions (Iwamoto et al., 2003).

For creating the large male GHBMC, external and internal geometry was gathered from a male individual fitting the large male ATD anthropometry. The large male geometry was used to define a set of target landmarks. Corresponding source landmarks were defined on the midsize male geometry. Using the source and target landmarks, the midsize male FE-mesh nodal coordinates was transformed to the large male configuration by a spatially weighted interpolation method (Vavalle et al., 2014). Using this method, the definitions of the two models are the same, with the only exception being that the nodal coordinates describe the geometry of two different individuals. This landmark based HBM mesh interpolation is, within this thesis, called morphing.

Since a significant amount of effort is needed to build a detailed HBM of a new anthropometry, adjusting the dimensions of an already created HBM is an effective option. Representing occupants of a wide range of body sizes for both sexes through morphing of a baseline HBM seems to be a promising method. To obtain a new HBM geometry through morphing, the target landmarks describing the geometry of the target individual is needed. To facilitate this, recent developments have resulted in HBM morphing tools, that provide functionality to define the target landmarks and to perform the HBM morphing.

2 Aim and Objectives

The differences in occupant injury risks existing across the population indicates a need for tools that can evaluate the crash safety for a wider range of occupants than those considered today. The development of self-driving cars, which may introduce new modes of crashing, with occupants in new seating positions and postures, will benefit from omnidirectional occupant safety evaluation tools that can aid in the design of vehicles and safety systems that are safe for all.

The overall aim of the Ph.D. research project is to define and create a population of HBMs, through morphing, that represent the injury risks of a diverse population of adult occupants in current and future vehicle crashes. This population of HBMs will be used to evaluate protective principles that are effective for everyone.

To fulfill the aim, four main objectives have been defined. The first three have been addressed in the present Licentiate thesis:

- Define the target vehicle occupant population, in terms of sex, age, stature and weight, including a sampling strategy
- Select and use a morphing method capable of efficiently adjusting the SAFER HBM to individuals in the target population
- Validate the population of morphed SAFER HBMs with respect to in-crash kinematics and rib fracture injury risk predictability. Also, verify that the morphed HBMs add any additional benefit over average models
- Use the defined population of validated morphed HBMs in evaluations of current and future vehicle crashes and evaluate the benefit of adaptive protective systems for all occupants

In this thesis, Chapter 3 presents the vulnerable populations of today, and a diverse sample of occupants to be represented with morphed HBMs is selected. In Chapter 4, a suitable HBM morphing method, capable of creating the population of occupant models is chosen. In Chapter 5, human body model validation and, as a summary of two appended papers, investigations of how well morphed SAFER HBMs predict the corresponding human outcome in crash conditions is presented. Chapter 6 contains a concluding discussion and, based on results obtained, an outline for future work.

3 The Diverse Occupant Population

To define how a diverse population of car occupants should be represented, occupants that are at greater risk of injury today, and some underlying factors for their increased injury risk, were studied in the literature. The occupant population considered in occupant crash safety today is presented. Based on the same rationale that chose small female to large male as the range of human sizes to consider, the stature and weight range of the considered population is defined. Finally, a sample of individuals is selected to represent the occupant population.

3.1 Diversity and occupant injury risks

Females are more likely than males to get fatally or severely injured in similar accidents. Kahane (2013) studied 1975-2010 accident data and found that, under similar conditions, the fatality risk for females were on average 17% higher than for males of the same age. Limiting the study to more recent year vehicles (model years 2005-2010), the increase in relative risk of fatal injury was 9%. Bose et al., (2011) found that females was 47% more likely than males to sustain AIS 3+ (Abbreviated Injury Scale, severity level 3 or greater) injuries, and 71% more likely at the AIS 2+ level. Belted females had 2.42 and 1.73 times the odds of males to sustain AIS 2+ and AIS 3+ injuries, respectively (Forman et al., 2019).

For obese vehicle occupants, with a BMI > 30 kg/m^2, fatality and injury risks are increased when compared to normal range BMI occupants (18.5 kg/m^2 < BMI < 25 kg/m^2). Viano et al., (2008) found that obese drivers and passengers had increased fatality and AIS3+ injury risks. Jehle et al., (2012) and Rice and Zhu, (2014) studied influence of BMI on fatality risk and found an increased fatality risk for underweight (BMI <18.5 kg/m^2) and obese occupants, compared to normal range BMI occupants. For frontal impacts, an increase in BMI is associated with and increased AIS 2+ and AIS 3+ injury risk (Forman et al., 2019).

Ageing have been found to provide the strongest contribution to increasing AIS3+ occupant injury risk compared to both sex and BMI (Carter et al., 2014). In fact, ageing increases AIS 3+ injury risk for almost all body regions in all types of crash configurations (Ridella et al., 2012). The risk of becoming fatally injured when involved in an accident increases by approximately 3% per year of aging, starting from age 21, independent of type of impact (Kahane, 2013).

Accident statistics reveals that females, obese and elderly are vulnerable occupants. Compared to other demographic groups, they all have an increased risk of injury in vehicle crashes, but the injury outcomes alone do not reveal any causes of why that is the case.

3.1.1 Risk factors for different sub populations

Females have up to 3 times the odds of males to sustain lower extremity injuries in frontal impacts (Forman et al., 2019). Females tend on average to be shorter than males, and thus tend to have the seat positioned more forwards, which could be a contributing factor. However, the elevated lower extremity injury risk remains, also when controlling for stature, indicating other sex related biomechanical factors contributing to this increased risk (Forman et al., 2019; Welsh et al., 2003). Independent of sex, the risk of head injury in vehicle accidents is influenced by stature, with higher risk for short (predominantly female) and tall occupants (Welsh et al., 2003).

Even when adjusting for differences in overall size, females have more slender long bones, with a thinner cortical layer (Russo et al., 2003; Schlecht et al., 2015). Testing on human ribs have revealed that while the individual variation is large, male ribs are on average stiffer than female ribs (Agnew et al., 2018; Kalra et al., 2015).

On the other hand, tensile material coupon testing of rib cortical bone material revealed no sex dependency in the bone material properties, but demonstrated significant decreases in ultimate stress and failure strain with age (Katzenberger et al., 2020). This partly explain why rib fracture risk due to blunt loading increase significantly with age (Kent and Patrie, 2005). The costal cartilage connects the ribs to the sternum, and increasing calcification of this cartilage with age (Holcombe et al., 2017a) stiffens the cartilage, which might alter the load distribution across the ribcage (Forman and Kent, 2014).

Ageing reduces bone mass and increases bone porosity, degrading bone stiffness and ductility (Zioupos, 2001). For males, the age associated deterioration of bone resulting in lower bone density and increasing fragility (osteoporosis) is a gradual process. However, for females, this this process is accelerated post-menopause, since the post-menopause related estrogen deficiency impairs the normal bone remodeling process (Ji and Yu, 2015).

Obese occupants are at increased risk of thoracic and lower extremity injuries compared to non-obese occupants (Brown et al., 2005; Carter et al., 2014; Forman et al., 2019). Results from frontal impact tests using obese and non-obese post mortem human subjects (PMHSs) revealed that the obese subjects obtained increased seatbelt forces and greater forwards excursion, especially in the hip (Forman et al., 2009). High BMI also correlates to poor seat belt fit, by positioning the lap segment of the seatbelt more upwards and forwards relative to the pelvis (Reed et al., 2013). This introduces more slack in the lap belt and increase the risk of the pelvis sliding under the lap belt, causing the seatbelt to load the soft abdominal region (i.e. submarining).

Morphological studies have found that age, sex and weight influence the shape of the ribcage (Holcombe et al., 2017b; Kent et al., 2005; Wang et al., 2016), and ribcage morphological parameters affect the ribcage structural response and rib fracture risk (Ejima et al., 2016; Kent et al., 2005).

To summarize, females tend to have more slender bones than males and are more likely to become osteoporotic as they age, which suggests that the female population have a lower tolerance to external forces before injury occurs, compared to the male population. Ageing degrades the quality of bone, which increases the risk of fractures. Obesity reduces seatbelt pelvic restraint capability and increase belt forces and excursions. Ribcage shape trends by sex, age and weight have been identified, which can alter the structural response and rib fracture risk.

3.2 Current occupant substitute population

The range of human variability represented in occupant crash test evaluations today is defined by the statures and weights of the three standard ATD sizes. The 5th percentile female (151 cm, 47 kg), the 50th percentile male (175 cm, 77 kg) and the 95th percentile male (186 cm, 102 kg) as defined by 1971-1974 U.S. population measurements (Schneider et al., 1983). The rationale for selecting stature and weights from 5th percentile female up to the 95th percentile male was to bracket 90% of the of the adult population variation in stature and weight (Schneider et al., 1983). It is implicitly assumed that any individual with a weight and stature falling in between the 5th female and 95th male values is represented.

Following the rationale that led to the ATD sizes but using updated population data, the 5th to 95th percentiles (from both the male and female sub-population) could be used to define the boundaries of the male and female target populations. However, when the aim is to include 90% of the female and 90% of the male populations, stature and weight cannot be treated as independent measures, since these measures are correlated (e.g. taller individuals tend to have higher body weights).

3.3 Defining range of statures and masses

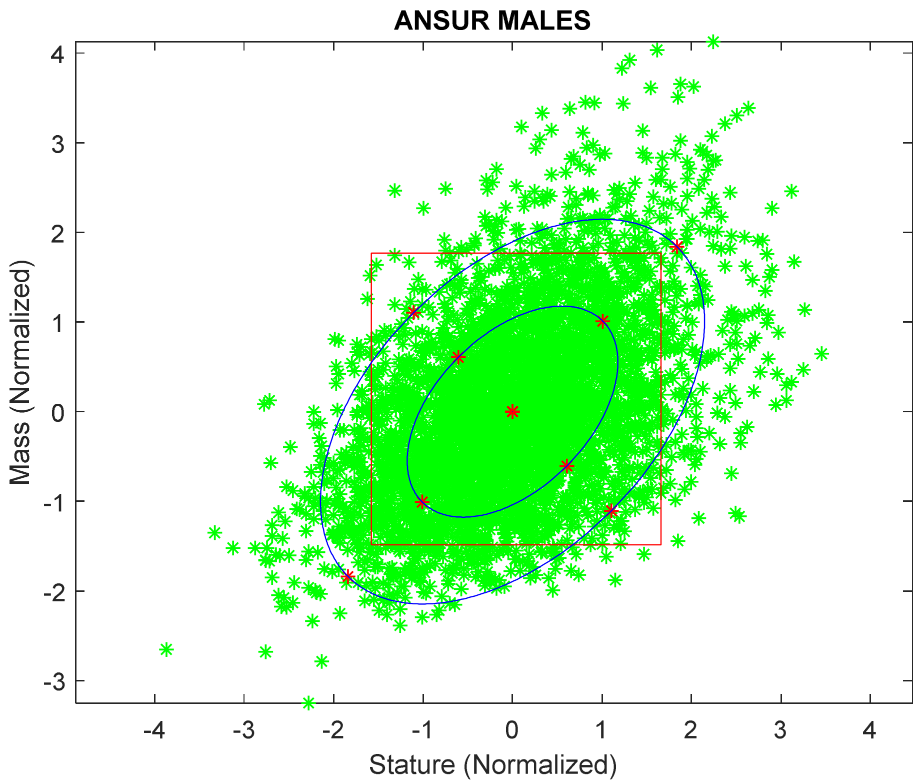

Figure 1. Mass and stature (normalized by standard deviation) of males in the ANSUR II anthropometric database. The green dots are measured individuals. The box defines the range of 5th to 95th percentiles of statures and mass in the sample. The ellipses are confidence ellipses, where the inner is set to accommodate 50% of the variation between individuals and the outer is set to accommodate 90% of the variation. The red dots are boundary cases for 0% (the mean of stature and body weight), 50% and 90% ellipses.

When describing population variation in several correlated variables, a multivariate confidence region is more suitable than the univariate confidence intervals for each variable. For the case of two normally distributed variables, this confidence region is shaped like an ellipse in a scatter plot. Confidence ellipses can be scaled to any desired accommodation level (the percentage of a population that should be included, or 'bracketed') (Brolin et al., 2012). For confidence ellipses, the analog to select extreme values for bracketing is called the boundary case method, where individuals are selected from the boundary of the ellipse.

The difference between considering separately the univariate stature and mass percentile bounds and the confidence ellipses is best demonstrated by a visual example (Figure 1). Stature and mass of males in the ANSUR II (Gordon et al., 2014) database was used since it contains a population representative sample suitable for visualization. The population in this example is, however, U.S. Army personnel, which likely cannot be considered representative of the general population.

The method for calculating confidence ellipses and selecting boundary cases as detailed by Brolin et al. (Brolin et al., 2012) was followed to create Figure 1. Using a 90% confidence ellipse, that theoretically accommodates 90% of the population (assuming stature and weight are normally distributed), will lead to considering combinations of statures and weights more extreme than those of the 5^{th} to 95^{th} percentile bounds, but still representative of individuals that exists within the 90% variation of the population. In this example, only 83% of the studied population was inside the 5^{th} to 95^{th} stature and mass box.

3.4 Definition of target population and initial sample

A female occupant of similar weight and stature is more likely than her male counterpart to become injured, all other parameters being equal. A sex-based difference in injury tolerance may have implications for the design of protective systems. Therefore, it is questionable to represent female occupant injury risk using a male occupant substitute of similar stature and shape, as it is done today. Furthermore, obese and elderly occupants have increased injury and fatality risk and should be represented.

Measurements of adult individuals (age over 20 years) from the National Health and Nutrition Examination Survey (NHANES) data from 2011-2014 (Fryar et al., 2016) were used to create the range of anthropometries for the target occupant population,. This data represents the U.S. population and describes a population with a wide range of statures (5^{th}-95^{th}: females: 150-174 cm, males: 163-188 cm) and weights (females: 50-116 kg, males 62-125 kg). NHANES is not based on a random sample. Certain subgroups of the population are oversampled, and thus weighting must be used to create a sample representative of the true population. Male and female confidence ellipses of 50% and 90% accommodation was calculated for three age groups; 20-40, 40-60 and 60-80 years (Figure 2). The ellipses reveal that younger females (20-40 years) describe a larger variation in mass than the older (60+ years) females. The 60+ years females and males tend to be of smaller stature than the younger groups.

To define the initial sample of target individuals, ellipse boundary cases were sampled at the ends of the main axes of the 90% and 50% ellipses for each age group and at the mean. The specific age in years of each target individual was determined randomly from a uniform distribution of ages within the corresponding age group. The initial target sample can be seen in Figure 3. In total, the sample consist of 27 female and 27 male individuals of varying age, stature, weight and BMI.

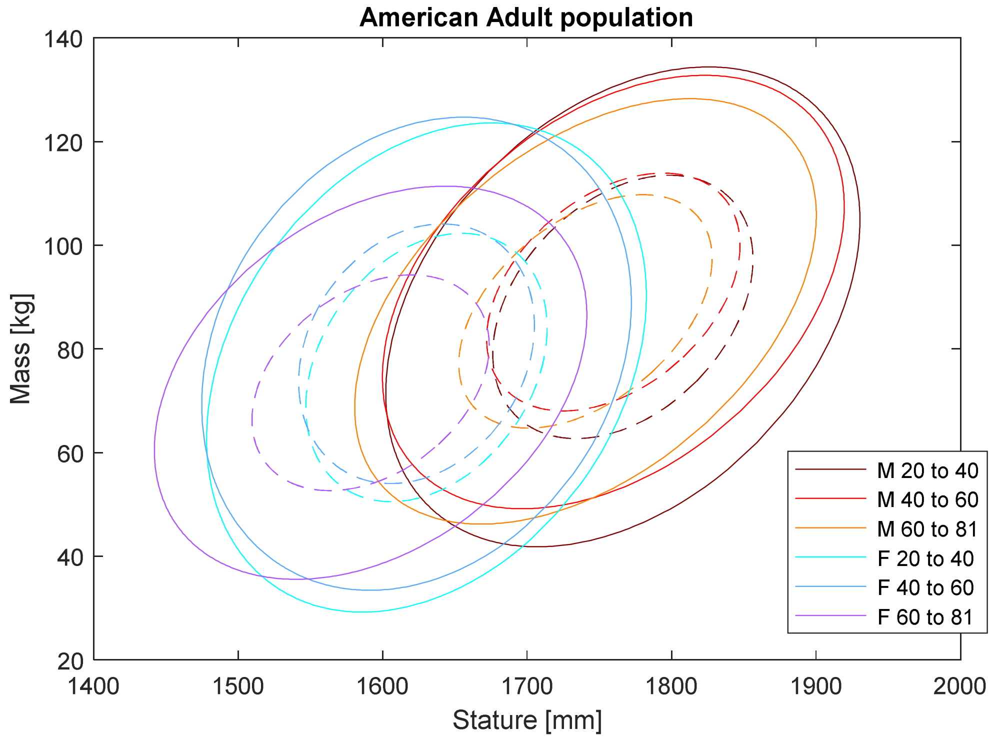

Figure 2. Stature and Mass variation in the U.S. population for males (M) and females (F) in three age groups. Solid ellipses describe 90% of the variation, dashed ellipses 50% for the respective sex and age group.

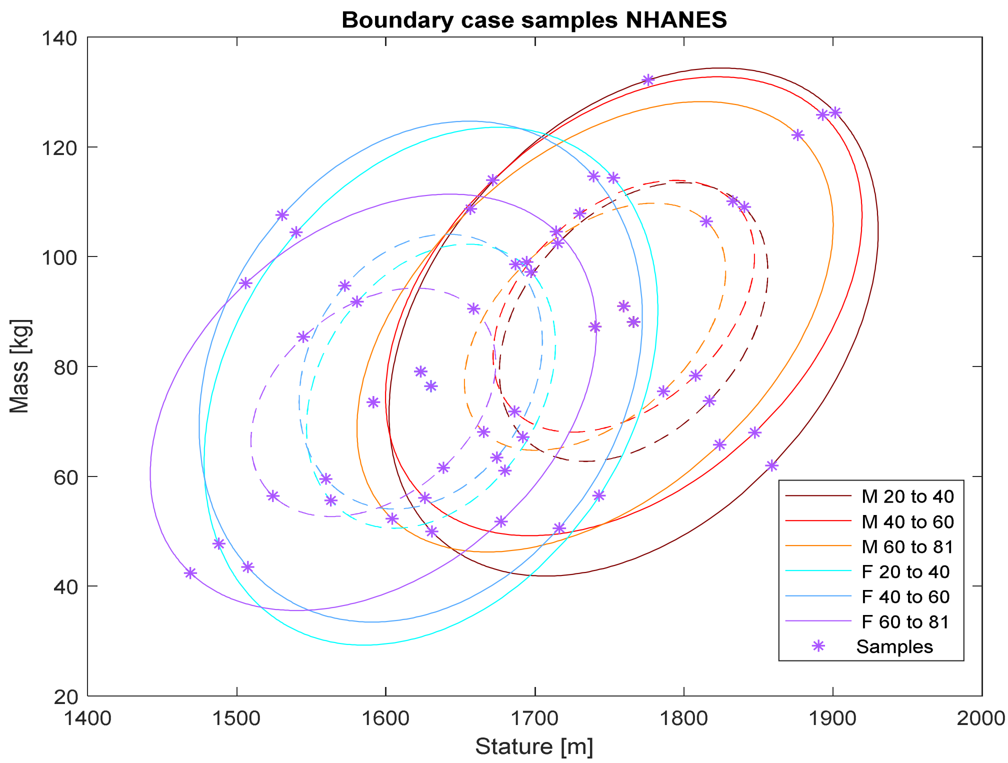

Figure 3. Initial sample of target individuals (*)

4 Selection of Human Body Model Morphing tool

The target population contains individuals of both sexes, with a wide range of ages, stature and weights. To create HBMs matching the target population, a method capable of transforming the baseline SAFER HBM to the anthropometry of the various individuals is needed.

Broadly speaking, two applicable methods have previously been used to change the shape of a whole body HBM to represent a new anthropometry; geometrical scaling and landmark-based mesh morphing.

Geometrical scaling is carried out by multiplying the nodal coordinates of the HBM with one or several scaling factors. These factors can be applied to the X, Y, and Z nodal coordinates separately or combined. Scaling all coordinates together represent scaling the model size up or down, while scaling separately the X, Y and Z coordinates will stretch the model in the different dimensions. For example, the THUMS HBM was scaled and evaluated in a pedestrian impact scenario (Paas et al., 2015). Scaling is an effective and straightforward method for changing the global size of a model. However, for more complex transformations, that cannot be achieved by a combination of size scaling and stretching, the scaling approach is not applicable.

The landmark-based mesh morphing techniques are mathematically more complex than applying a simple scaling factor. However, through suitable definitions of source and target landmarks, this method can achieve complex, non-linear transformations.

To aid in HBM morphing work, two major HBM morphing tools have been developed: PIPER (www.piper-project.eu), and the University of Michigan Transportation Research Institute (UMTRI) parametric HBM morphing method (Hwang et al., 2016a). Both tools modify the shape of an existing HBM by interpolation of FE mesh nodal coordinates between source and target landmarks but differ in how they define the target landmarks.

4.1 PIPER

PIPER is an open source, freely available, software framework developed to aid users with the positioning and personalization of FE HBMs. The framework consists of several modules integrated into a graphical user interface.

For morphing of an HBM to represent another anthropometry, the Scaling Constraints Module can be used to define a hierarchical set of anthropometric measurements on the HBM, e.g. sitting height and chest circumference. The collection of these measurements is termed a 'simplified scalable model'. Along the measurements, source landmarks are defined. For each measurement in the simplified scalable model, a new target measurement can be defined. Either the user manually enters all target measurements, or defines a few key measurements, and then lets the Anthropo module compute statistically likely remaining measurements from an anthropometric database. To be able to use the computed measurements, the measurements defined in the simplified scalable model should correspond to measurements existing in the anthropometric database.

Giving new measurements will scale the simplified scalable model and the source landmarks to a new size, and this new size the defines the target landmarks. Each landmark can be considered to belong to bone, skin or both skin and bone. In this way it is possible to morph the skin and bones independently. With a set of source and target landmarks, the morphing is done by the Kriging module. The PIPER morphing tool can be seen as a framework implementation of the HBM morphing method applied in (Beillas and Berthet, 2017)

The PIPER morphing tool gives the user control over specific anthropometric measurements, such that a morphed HBM can e.g. obtain a specific shoulder width. However, there is no control that the morphed geometry of internal structures, for example the ribcage, will represent sex, age and BMI dependent geometrical features when morphing to a diverse set of occupants. For that to be included, a user will have to implement additional landmarks, and a method ensuring that the target locations are realistic.

4.2 UMTRI parametric HBM morphing

The UMTRI parametric HBM morphing tool, and in particular the target landmarks, uses parameterized statistical human shape geometry models. Currently, such geometry models are implemented for the femur, the tibia, the pelvis, the ribcage and the external body surface. These geometry models have been parameterized with respect to sex, age, stature and BMI.

There are some benefits of using the UMTRI morphing tool, over the PIPER morphing tool. Since the human shape-based target geometries are defined for both the external and some internal shapes, an HBM morphed with the UMTRI tool, will have both an external body shape and internal structural geometry that is realistic and representative of the corresponding human geometry.

The way the UMTRI HBM morphing tool is parameterized, i.e. using parameters age, sex, stature and BMI, is particularly suitable for creating HBMs that represents a variety of elderly, female and obese human shapes that can facilitate investigating the mechanism of injury for these vulnerable occupants. The drawback with the parametric HBM morphing method is that there is no user control of specific anthropometric measurements, e.g. it is not possible to create specific subjects, for example for a specific crash reconstruction.

4.3 Selected morphing tool

After morphing the SAFER HBM into small females and large males using both tools, the UMTRI parametric morphing tool was judged to be the easier to work with, as it was simply a matter of defining the targeted sex, age, stature and BMI, after an initial adaption of the HBM to the tool. There were also some issues with stability with the PIPER software (v.1.0.0) available when the work presented in this thesis was started. Although the user interface software bugs did not invalidate the effectiveness of underlying morphing methods, the access was hindered from a user perspective.

More importantly, the UMTRI parametric tool ensures that internal geometry of a morphed HBM is determined by the human-shape based statistical models, rather than being driven by changes of the external measurements. This is potentially important for predicting geometry dependent injury risk.

For the HBM morphing in this thesis, the UMTRI parametric HBM morphing tool was used.

5 Validation of morphed HBMs

Before using morphed HBMs or any other HBMs, these should be validated, in order to understand how well they predict the corresponding human occupant kinematics and injury risk. In this chapter, classical human impact model validation procedures are described, and an alternative approach to validate morphed HBMs. The morphed HBMs validations performed are then presented in brief summaries of two appended papers.

5.1 Human Impact Model Validation

Model validation is the process of comparing model results to independent real-world measurements, such that the predictive capabilities of the model can be understood. For models of humans under potentially injurious conditions, such as ATDs or HBMs, the acquisition of validation data poses some special problems. Due to ethical considerations, it is not possible to perform experiments on volunteers. Instead, PMHS, or human cadavers, are used to gather information of the kinematics, kinetics, and injury outcomes of human subjects in controlled impact experiments (Yoganandan et al., 2011).

Due to natural biological variation, humans are rarely alike; neither in terms of anthropometry nor in injury tolerance. Therefore, a PMHS test is commonly repeated with several subjects, together forming a test series. Since the subjects usually deviate from each other in mass or other anthropometric dimensions, it is common to apply mathematical scaling methods to the results, that accounts for the subject differences. Common scaling methods assume that the PMHS experiment impact responses can be modelled as responses from a mass-spring system. Using this assumption, results from each individual subject can be normalized to a targeted reference anthropometry, such as the midsize male ATD size (Yoganandan et al., 2014). A corridor is often defined by taking ±1 standard deviation around the mean of the normalized PMHS responses. If a human impact model produces a result that is within this corridor when subjected to the same test conditions it is said to be biofidelic, or true to the response of the biological system it represents.

For the objective comparison of alternative impact models, biofidelity rating procedures have been developed. For example, the ISO/TR 9790:1999 standard defines a set of experiments and a calculation method for objectively quantifying the biofidelity of a 50th percentile male side impact surrogate. In this standard, pre-selected human response corridors (generated from PMHS results normalized to the midsize male reference size) from the included experiments are used to describe the human responses.

Another biofidelity rating procedure, the Biofidelity Ranking System, have been proposed by Rhule et al. (Rhule et al., 2013). The method starts from PMHS data normalized to the investigated reference stature and weight and then details how mean and ±1 standard deviation PMHS reference signals should be calculated from the data from several subjects. Through pre-defined calculation methods, the corresponding human impact surrogate results are then rated for correlation with the PMHS reference signals.

The benefits of using pre-defined biofidelity rating procedures is that a pre-determined method of calculating correlation to the reference test data allows for objective rating of models. If an alternative ATD or HBM is proposed as a new human surrogate, it is possible to compare its biofidelity to the previously rated surrogates and thus obtain an objective measure of the relative performance of the different models.

5.2 Morphed Human Body Model Validation

For morphed HBMs representing a wide range of body sizes of both sexes, comparing the model predictions to corridors created from testing with subjects close in anthropometry and age of each morphed HBM can be an applicable method. However, PMHS tests are limited in numbers and such corridors are generally not available.

For example, the large male GHBMC HBM was validated using midsize male experimental reference corridors, by normalizing the large male HBM predictions to the midsize male reference (Vavalle et al., 2014). Additionally, due to a lack of small female PMHS reference data, the validation of the small female GHBMC HBM was done with midsize male reference data using two approaches (Davis et al., 2016). First, the reference experiments were simulated with the small female HBM and the model results were normalized to a midsize male, using the same scaling methods that was used to create the respective reference data corridors. In the second approach, the small female HBM was morphed to the external anthropometry of a midsize male, and the morphed HBM results was directly compared to the midsize male reference corridors. The HBM morphed to the midsize male size produced better correlation to the test data than the normalized small female HBM results. This indicates that the simplified result normalization methods are limited in describing the effects of body-size variation, at least for this HBM.

An alternative validation approach for morphed HBMs is to perform subject specific validations (Beillas and Berthet, 2017; Hwang et al., 2020, 2016b). In this approach, the HBM is morphed to represent an individual PMHS (subject specific HBM). The experiment is then reconstructed using the subject specific morphed HBM, and the morphed HBM results are compared to the test results from the modelled PMHS. This reduces the need of having a multitude of subjects of similar anthropometries tested in the same experimental set-up for the creation of response corridors. A drawback of using the results from a single PMHS is that it is questionable how well a single individual represents its subpopulation, as it is well known that testing several subjects of similar anthropometry will result in some variability. The benefit is that the HBM will be compared to real-world measurements from a subject it is intended to represent.

In this thesis, the subject specific approach to validation of morphed HBM has been used. To study the benefit of morphing the current version of the SAFER HBM (v9), the predictions of the baseline SAFER HBM have also been compared to the morphed HBM predictions as well as the PMHS results. To facilitate objective model comparison the CORA cross-correlation rating metric (Gehre et al., 2009) has been used to rate HBM to PMHS result correlation.

5.3 Summary of Appended Papers

Paper I

Larsson, K.-J., Pipkorn, B., Iraeus, J., Bolte IV, J. H., Agnew, A. M., Hu, J. Reed, M. P., Sunnevång, C. (2019): Evaluation of the benefits of parametric human body model morphing for prediction of injury to elderly occupants in side impact, *Proceedings of IRCOBI Conference 2019*, Florence, Italy.

Author's Contributions: Methodology, Validation, Formal Analysis, Writing original draft, Visualization

Paper II

Larsson, K.-J., Pipkorn, B., Iraeus, J., Forman, J. (2020): Evaluation of a Diverse Population of Morphed Human Body Models for Prediction of Vehicle Occupant Crash Kinematics, *Manuscript intended for submission to Journal of Computer Methods in Biomechanical and Biomedical Engineering*

Author's Contributions: Conceptualization, Methodology, Validation, Formal Analysis, Writing original draft, Visualization

5.3.1 Paper I

The parametric HBM morphing method was used to morph the SAFER HBM v9 (Baseline HBM) to the age, sex, stature and BMI parameters of two elderly female PMHS (Parametric HBMs). Each Parametric HBM was further morphed to match the ribcage, shoulder and external torso geometry of the individual PMHS, creating Personalized HBMs. Two side impact sled tests previously performed with the elderly female PMHS were reconstructed using the Baseline and corresponding Parametric and Personalized HBM in each test. In the sled tests a production seat, door intrusion, a pre-tensioning seatbelt and a side impact airbag was included.

Parametric and Personalized HBMs were positioned in the seat model targeting measured anatomical landmark coordinates from each PMHS. The Baseline HBM, that was larger than the two PMHS, was positioned according to a driver posture model predicting the posture of a midsize male driver. CORA cross-correlation rating was used to rate correlation of the Baseline, Parametric and Personalized HBM kinematics and normalized chest deflections to the corresponding PMHS physical test results. Strain in the HBM ribs was extracted at locations corresponding to strain gauges in the PMHS ribs. A probabilistic, age-adjusted rib facture risk was calculated from each HBM simulation, and the rib fracture risk predictions were compared to the number of fractured ribs in each test.

Results showed higher average kinematic CORA ratings for morphed Parametric (ratings: 0.88, for test 1, 0.83 for test 2) and Personalized HBMs (0.85, 0.87), compared to the Baseline HBM (0.83, 0.76). The morphed HBMs showed lower magnitude chest deflections than both PMHS and the Baseline HBM, which obtained the highest correlation rating. For the test with strain gauges positioned laterally on the ribs, all HBMs showed greater lateral compressive rib strains in several ribs, compared to the subject in the test.

In the tests, the 83-year-old PMHS fractured 12 ribs, and the 61-year-old fractured 5 ribs. The corresponding Parametric and Personalized HBMs predicted 0% risk of fracturing one or more ribs in both tests. The Baseline HBM predicted a 7% risk of two or more fractured ribs for the test condition with the 61-year-old subject, and 18% risk for the 83-year-old subject test condition.

The Parametric and Personalized HBMs improved, as judged by a higher CORA rating, prediction of the individual elderly female kinematics in lateral impacts, compared to the Baseline HBM. The personalization morphing did not provide any additional benefits in prediction of kinematics, chest deflections, rib strain or rib fracture risk, compared to the parametric morphing. This was consistent with results from a previous study of parametrically morphed and further personalized HBMs for modelling males in a simplified lateral impact scenario (Hwang et al., 2016b).

The Baseline HBM was larger and had a wider chest than the two female PMHS, thus, the Baseline HBM chest was closer to the intruding door, which could partly explain why this HBM obtained greater chest deflections than the smaller, Parametric and Personalized HBMs. Since the morphed HBMs, especially the Personalized HBMs, had a more similar geometry to the test subjects, the underprediction of chest deflection was suspected to be related to the mechanical stiffness parameters of the materials in the HBMs. The sensitivity of HBM chest deflection to boundary condition (door intrusion at chest height) and HBM torso flesh material modelling was investigated for Personalized HBMs, and the flesh material model had the greatest influence on resulting chest deflections. Potentially, morphed HBMs need to consider adaption of also material mechanical parameters, in addition to the geometrical morphing, to predict chest deflection for elderly females in side impact.

Compared to the number of fractured ribs in the tests, all HBMs predicted low risks of fractured ribs. The HBMs predicted higher compressive lateral strains than was measured in the PMHS test, indicating a locally greater loading, but this did not translate to a higher rib fracture risk being predicted. The rib maximum principal strain magnitudes predicted in the morphed HBMs ribs were lower than rib cortical bone ultimate strains from the literature.

Conclusions from this study are:

Parametric morphing of an HBM to a specific individual anthropometry improved prediction of individual kinematics in side impact. Parametric HBMs performed as well as Personalized HBMs.

Parametric morphing of an HBM to a specific elderly female individual did not improve prediction of the individual thoracic injury risk in side impact.

5.3.2 Paper II

In this study, a total of 22 whole-body PMHS tests previously performed with 19 PMHS (7 female) were reconstructed with the Baseline HBM and Parametric HBMs. The Parametric HBMs were created by parametric morphing of the Baseline HBM to the sex, age, stature and BMI of each individual PMHS.

Age, stature, mass and BMI of the modelled PMHS ranged between 33-87 years, 152-189 cm, 39-124kg and 14-40 kg/m^2. Impact directions included near-side lateral, frontal oblique 30° near-side, frontal, and frontal oblique 60° far-side impacts.

For the tests including a seatbelt, a seatbelt model approximating the shoulder belt path from the test was modelled. Since the Parametric HBMs were statistical averages of the corresponding PMHS body shapes, and the Baseline HBM was a midsize male, torso shape-driven differences in initial shoulder belt routing was hypothesized to influence the HBM predictions. Therefore, three additional initial shoulder belt paths were investigated; High Mid and Low, defined as crossing the sternum at the 1st,3rd and 6th rib levels.

The Parametric HBMs were positioned in the corresponding test environment model targeting the corresponding PMHS initial posture in pre-simulations. To create the initial posture targets for the Baseline HBM, the coordinates of the positioning targets for the Parametric HBMs were scaled according to the stature ratio of PMHS to Baseline HBM. This was to ensure that the Parametric and Baseline HBMs had the comparable initial posture.

CORA cross-correlation rating was used to objectively compare Baseline and Parametric HBM predictions of kinematics, seatbelt or impactor forces and normalized chest deflections to the corresponding PMHS physical test data.

The results showed CORA ratings ranging from 0.55-0.92 for prediction of seatbelt forces and 0.61-0.86 for kinematics across frontal, oblique near- and far-side impacts.

In most cases, correlation ratings were similar for Parametric and Baseline HBMs. Exceptions were two obese subjects in a frontal impact scenario, where correlation to the PMHS kinematics was higher for the Parametric, obese, HBMs, regardless of initial shoulder belt location. The obese HBMs predicted greater magnitude excursions than the Baseline HBM, but still underpredicted the individual obese PMHS pelvis forward excursions. Further, for two small female subjects in frontal impact, the Parametric, small female, HBMs underpredicted the peak forward excursion of the corresponding test subjects. The Baseline HBM overpredicted the forwards excursions in both tests. For one of these tests, this resulted in lower kinematics CORA rating for the Parametric HBM, regardless of shoulder belt position, and in the other test the initial shoulder belt routing influenced which of the Parametric or Baseline HBM obtained the highest kinematics CORA rating.

For the lateral impacts the CORA ratings ranged from 0.57 to 0.88 for impact forces. The kinematic CORA ratings ranged from 0.63 to 0.89 for lateral velocity and 0.18 to 0.82 for chest deflections. The major difference between the Baseline and the Parametric HBMs was seen for chest deflections, where the Baseline HBM showed results closer to PMHSs for most of the cases. A general trend for the lateral impacts, for both the Baseline and the Parametric HBMs, was that the impactor force was overestimated, and the chest deformation was underestimated.

Several results indicated that the Parametric HBMs were stiffer than corresponding PMHS. For the obese test subjects in frontal impact, the lap belt penetrated deep into the abdomen. No such penetration of the lap belt occurred for the obese HBMs, which restricted the pelvis forward excursions in the HBMs. For two small females in frontal impact, both Parametric HBMs underpredicted the PMHS forward excursions. Since the subject mass, sled acceleration and seatbelt load limiting force was matched between the tests and the simulations, this smaller excursion indicates a stiffer, more elastic, force-deformation behavior in the small female HBMs than in the PMHS. In the lateral impacts, where impactor force and chest deflection measurements were available from the tests, both the Parametric and Baseline HBMs exhibited a stiffer force-deflection response than the PMHS. For improving the predictions of the SAFER HBM v9 as parametrically morphed, future work need to address the stiffness of the HBM.

Conclusions from this study are:

Resulting kinematic CORA cross-correlation ratings of HBMs ranged from 0.61-0.89.

Parametrically morphed HBMs obtained higher correlation rating for obese PMHS frontal impact kinematics by predicting increased forward excursions.

Parametrically morphed HBMs underpredicted small female PMHS forward excursion in frontal impact.

In lateral impacts, baseline HBMs predicted chest deflection magnitudes closer to the PMHS.

A general trend of too high stiffness in the HBM impact responses was identified and addressing this stiffness may provide additional benefits in morphed HBM predictive capabilities.

6 Discussion

With the overall aim of representing the population of vehicle occupants in future cars, the work presented in this thesis has taken some critical steps.

Main contributions are:

A definition of a diverse occupant population, including males and females of a wide ranges of age, stature and weight.

The selection and implementation of a morphing tool capable of morphing the SAFER HBM to the individuals in the diverse occupant population

A comparison of morphed and baseline SAFER HBMs to corresponding PMHS experimental results.

6.1 The Diverse Occupant Population

A method to define the target population was proposed. The general idea of bracketing 90% of the population at interest inside the bound (similar to ATD sizes) was followed. With the chosen method, the correlation between stature and weight is respected. Since it is known that a female occupant is at greater risk of injury than a male of same stature and weight, there is potential for different protective strategies being suitable for males and females. Therefore, it is recommended that females should not be considered represented by male HBMs of similar stature and weight, and separate male and female populations were derived.

The initial sample contains 27 female and 27 male individuals of a wide range of body sizes. Ages between 20 and 80 years are considered. The population contains individuals more extreme in terms of stature and weight than the traditional 5th and 95th univariate percentile limits. However, these individuals still exist within the 90% stature and mass variation among individuals. The sample also contains a variation of more common individuals, existing within the 50% variation. Several individuals are close in stature and weight, but differs in age and/or sex, which means that they are expected to be different in terms of injury risk. Including extreme and more common individuals in the sample is beneficial for the evaluation of protective principles, since the range of protection in terms of stature, weight or age can be investigated by evaluating also intermediate statures and weights.

The sample was taken from the NHANES database, which describes the American population. Therefore, this does not necessarily describe the likely distribution of individuals from other regions. However, the range of weights and statures bracketed within this sample covers a large range of individuals and is therefore likely to contain many individuals from other populations. Region or country specific anthropometric data must be consulted to confirm this.

A 90% inclusion still excludes 10% of a studied population. One in ten individuals is still a quite significant proportion of a population to exclude. However, the chosen method to define the boundaries for considered statures and weights can be adapted to any accommodation level, effectively by creating a larger ellipse.

If the initial sample of 27 individuals of each sex is a complete, or perhaps even a redundant description of occupant injury risks in future cars is not yet known. Simulation studies varying the occupant anthropometry with morphed HBMs in vehicle crash simulations can partly answer that question, at least for the studied vehicle and crash scenario. However, the conclusions from such HBM studies will depend on how well the HBMs can represent the corresponding human response and injury risk. It is therefore important to show that the morphed HBMs are valid for the diverse population of occupants, i.e. within the target population. Another answer is to use the injured occupant population from real-world accidents. Females, elderly and obese, as described in this thesis, are however very coarse descriptions of occupants, and more in-depth analysis of injured occupant anthropometry can possibly reveal if there are typical individuals suffering injuries within the vulnerable occupant groups. However, with the introduction of automated vehicles, where occupants can be seated in new configurations and postures, historical injury data may not be representative of the future crashes and related injuries.

6.2 Selection of Human Body Model Morphing method

A tool capable of morphing the SAFER HBM v9 to both male and female anthropometries within the previously defined bounds was selected.

The UMTRI parametric HBM morphing tool (Hwang et al., 2016a) use sex, age, stature and BMI as input. This was suitable for generating a set of HBMs that are representative of individuals within the targeted population in this study. A benefit of this morphing tool is that it includes sex, age and BMI dependent changes to the geometry of internal structures.

In the current version, the parametric morphing tool uses statistical geometry models for describing the shapes of pelvis, ribcage, femur, tibia and external body surface. The shape of other parts in the HBM, e.g. cervical spine or bones in the shoulder and upper extremities, are determined by interpolation from the baseline to the morphed configuration. Including human-shape based statistical models for the remaining skeletal structures will further enhance the realism of the morphed HBMs generated.

The parametrically morphed HBM represents an “average individual” given the specific sex, age, stature and BMI parameters. However, there can be significant individual variations that are overlooked when only the representation of an “average individual” is considered. For example, the statistical ribcage geometry model included in the parametric HBM morphing can only describe 51% of the geometric variation of the 101 subjects it is based upon when parametrized for sex, age, stature and BMI (Wang et al., 2016). It is possible that some shapes of ribcages, other than those close to the average shape, are more susceptible to injury when loaded by seatbelts or airbags. However, including the sex, age, stature and BMI driven geometrical changes, even if only in the average sense, is a big step forward in representing the diverse occupant population, compared to representing only three average sizes.

6.3 Validation of morphed HBMs

The parametrically morphed HBM predictions was compared to individual PMHS test results in simulations recreating the physical PMHS test conditions. As reference, the predictions of the baseline midsize male SAFER HBM v9 was also gathered in each test such that the effect of the parametric morphing on the HBM response could be investigated.

As the morphed HBMs should be used as human occupant surrogates for a range of individuals within the previously defined target population, it was of interest to investigate the predictive capabilities of the morphed HBMs on a set of PMHS tests performed with subject anthropometries existing within and along the defined variation boundaries. Therefore, PMHS tests available in the published literature were collected with the aim to gather refence data from individuals spanning as much of the population as possible, to maximize variability. The selected PMHS experiments consisted of whole body impacted subjects in sled tests imitating typical accident scenarios, as the morphed HBMs are intended to be used under such conditions.

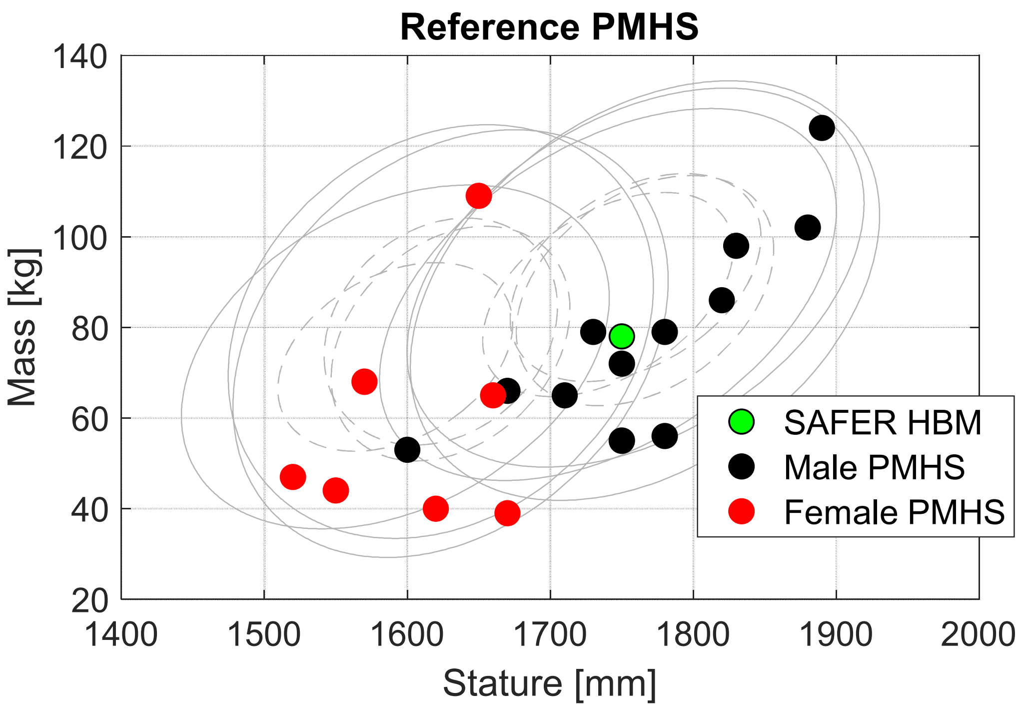

Figure 4. Stature and weight of PMHS used as reference for morphed HBM correlation evaluation, plotted over the male and female confidence ellipses from Figure 2.

In Figure 4 the stature and weight of the 19 PMHS used as validation references are plotted over the previously defined boundary ellipses (Figure 2). The male PMHSs spans the range of male statures well. For the female subjects, all PMHSs are within the 50% variability range of female statures, i.e. there was a lack of females closer to the 90% stature boundaries. Except for one obese female and one obese male, there was also a lack of PMHSs with high BMI, especially for shorter male and female statures.

The comparison of morphed and baseline SAFER HBMs to the individual PMHS test data showed that morphing improved the prediction of kinematics in frontal impacts for obese subjects, by predicting increased forwards excursions. However, the morphed HBMs could not predict the deep penetration of the lap belt into the adipose tissue, that was observed in the corresponding PMHS tests. This means that the HBMs still underpredicted the pelvis forwards excursion. As obesity is associated with increased lower extremity injury risk, a greater hip forwards excursion for obese subjects can be a contributing factor to the injury mechanism. Predicting the forwards hip excursion magnitude is thus of high importance.

For HBMs morphed to small females in frontal impact, it was observed that the forwards excursion was underpredicted.

In the modelled lateral impact tests, the morphed HBMs underpredicted the chest deflections and overpredicted the impactor forces from the corresponding tests, resulting in a predicted force-deflection stiffer than seen in the PMHS results.

All these results, i.e. underprediction of lap belt penetration for obese occupants, underprediction of forwards excursion for small females and overprediction of the stiffness in lateral impacts, indicate that the morphed HBMs are stiffer than the PMHSs.

So far, the work has only focused on the geometrical modification, through morphing, of the SAFER HBM v9 to model the diverse occupant population. However, the geometry is only one aspect of a FE model. The model response is also affected by the material models and material parameters, describing each material response. The age-dependent degradation of bone could be represented in morphed HBMs with changing the material parameters to reflect this effect. Furthermore, the SAFER HBM does not model the distribution of adipose and skeletal muscle tissue, but uses a lumped “flesh” representation, where material properties should represent an average of adipose and muscle tissue. For obese subjects, with a significant amount of abdominal adipose tissue, this modelling assumption may not be valid and further investigation is warranted.

6.4 Future work

The source of the stiff model responses identified for the SAFER HBMs will be identified and mitigated through model updates. This includes investigating the biofidelity of included material models and questioning previous modelling assumptions, for example that the muscle and adipose tissue layers can be lumped into a single layer of “flesh”, and that the material parameters for this “flesh” are independent of BMI. The biofidelity of alternative material models and modelling approaches will be evaluated, preferably starting with material characterization test data. Then in component level tests, and finally assessment at the full human body model level. Preferably, age and sex dependent biomechanical properties, such as cortical bone thickness distribution and material mechanical parameters, as available in published literature should be included in the morphed HBMs.

Due to the wide range of body sizes targeted for morphing, it may be suitable to define separate FE-meshes for high and low BMI HBMs. Since the high BMI HBMs have thicker layers of tissue, more elements through the thickness are needed to keep the element aspect ratios similar.

Validation criteria for the morphed HBMs must be defined, i.e. a definition of what level of correlation to the individual PMHS test data, including rib fracture risk predictability, must be reached before considering the HBM to be a valid representation of the modelled subjects.

Once the population of morphed HBMs considered biofidelic within the target population is generated, protective principles that increase the safety for all will be evaluated in vehicle accident simulation studies.

For example, a vehicle model with contemporary state-of-the-art safety systems can be subjected to the same accident scenario, using every individual from the population sample as occupant substitute. Results from such simulation studies may indicate how robust the safety systems are to different occupant characteristics and indicate alternative protection principles that are more effective across the population. The simulation study can be extended to include several impact configurations, and/or future seating configurations or seating postures.

A further step can involve minimizing injury risk predictors for each individual, e.g. rib fracture risk and occupant to vehicle interior contact forces, by tuning parameters in the restraint systems. This can possibly result in principles for age, sex, stature and BMI adjusted restraint configurations (personalized restraints). Such results can also inform about how useful each of the HBM individuals are to the evaluation and design of safety systems. It is for example possible, that a restraint configuration that is optimal for an elderly occupant, would be optimal also for a younger occupant of same sex and similar stature and BMI.

Furthermore, the defined population is only an initial description of a diverse population. The definition of the population is based on external measurements and age. However, another suitable population for vehicle safety development may be found based on injury outcomes, i.e. individuals that need enhanced protection. Such a population could be found by simulation studies varying the occupant anthropometry, and then grouping individuals based on injury outcomes. One or more typical individuals representing an injury is then created. If this process is repeated for different vehicles and impact configurations, another population, representing typical occupant injury risks and safety system challenges may be found.

With the morphing tool used, only the “average” individuals for the selected parameters are considered. Extending the morphing tool to include more parameters, e.g. extending the variation of possible ribcage shapes included, may further inform about individuals at increased risk of injuries existing in the real population.

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