THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING IN
MACHINE AND VEHICLE SYSTEMS

Towards the Inclusion of Pelvis Population Variance in Human Body Models

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ABSTRACT

With a future large-scale introduction of autonomous vehicles, the proportion of intersection crashes on the total number of motor vehicle crashes is expected to increase. The pelvis is frequently exposed to high loads in several of these impacts. In addition, autonomous driving is expected to result in new seating positions where reclined seating increases the risk of the pelvis sliding under the lap belt, producing *submarining* induced injuries. If unaddressed, submarining may result in an increased prevalence of abdominal and spinal injuries, and if addressed by advanced restraint systems, the risk of pelvic fractures may increase due to higher pelvis loads.

Finite Element Human Body Models (FE-HBMs) represent the most advanced tool available to use in the design of safety systems for current and future vehicles. FE-HBMs represent the human anatomy, anthropometry, and physical properties to predict a biomechanical response to external loading via computer simulations. To date, these models are typically defined based on an average male or female subject in terms of global measurements like age, stature, and weight. However, individual variability is an intrinsic property of humans that must be considered in order to capture the vulnerable population and maximise the efficiency of vehicle safety systems. FE-HBMs provides the opportunity to include both geometrical and material variability in the analysis.

In this thesis, methods/tools that enable inclusion of pelvis population variance in HBMs were developed. As part of this work, the population variance in pelvis shape has been described and a morphometric model capable of predicting pelvis shape was developed. A new generic pelvis FE-model was generated from the average pelvis geometry, which can be morphed to the population variance in pelvis shape. The model was validated for lateral impacts followed by a sensitivity analysis on model response to input variance. Results show that while 90% of the population shape variance was captured in the analysis, only 29% was predicted by a morphometric model using sex, age, stature, and BMI, as independent variables. The sensitivity analysis found that material properties account for the majority of the response variance (≈50-65%) in pelvis lateral impacts, and that input variables controlling shape contribute by a similar magnitude (≈35-40%).

Increased knowledge about population variability, and inclusion in future safety evaluations, can result in more robust systems that would reduce the risk of pelvis injuries in real-world accidents.

Keywords: Finite Element Human Body Model; Global Sensitivity Analysis; Pelvis; Population Variance; Sparse Principal Component Analysis

PREFACE AND ACKNOWLEDGEMENTS

The work presented in this licentiate thesis was conducted at the Division of Vehicle Safety, Department of Mechanics and Maritime Sciences, Chalmers University of Technology in Gothenburg, Sweden, at SAFER – The Vehicle and Traffic Safety Centre at Chalmers. The work was performed within the project *"Pelvis and spine injury predicting models for women and men in a variety of sitting postures in future autonomous cars (Injury-HBM step 4)"* in collaboration with Autoliv, Volvo Cars, and Sahlgrenska University. The work was funded by FFI (Strategic Vehicle Research and Innovation), by VINNOVA, the Swedish Transport Administration, the Swedish Energy Agency, and the industrial partners, including Autoliv, Volvo Cars, and Sahlgrenska University Hospital. Simulations were performed on resources at Chalmers Centre for Computational Science and Engineering (C3SE), provided by the Swedish National Infrastructure for Computing (SNIC). All organisations are situated in Sweden.

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Erik Brynskog
March 2022

LIST OF APPENDED PAPERS

Paper A

E. Brynskog, J. Iraeus, M. Reed, J. Davidsson

Predicting Pelvis Geometry Using a Morphometric Model with Overall Anthropometric Variables

Published in:
Journal of Biomechanics, Volume 126, 20 September 2021, 110633

Author contribution: Methodology, Formal analysis, Data Curation, Writing - Original draft, Visualisation

Paper B

E. Brynskog, J. Iraeus, B. Pipkorn, J. Davidsson

Population Variance in Pelvis Response to Lateral Impacts – A Global Sensitivity Analysis

Abstract accepted and manuscript under review for publication and presentation at:
Proceedings of the IRCOBI Conference 2022, Porto, Portugal

Author contribution: Modelling, Validation, Methodology, Formal analysis, Writing – Original draft, Visualisation

ABBREVIATIONS

AIS	Abbreviated Injury Scale
ASIS	Anterior Superior Iliac Spine
BMI	Body Mass Index = weight/(length)^2 [kg/m^2]
CT	Computed Tomography
FE	Finite Element
GM	Geometric Morphometrics
GPA	Generalised Procrustes Analysis
GSA	Global Sensitivity Analysis
HBM	Human Body Model
LASSO	Least Absolute Shrinkage and Selection Operator
LHS	Latin-Hypercube Sampling
MC	Monte Carlo
M-DRM	Multiplicative Dimensional Reduction Method
MVC	Motor Vehicle Crash
PC	Principal Component
PCA	Principal Component Analysis
PMHS	Post-Mortem Human Subject
PSIS	Posterior Superior Iliac Spine
RBF-TPS	Radial Basis Function with Thin-Plate-Splines
SI	Sacroiliac
SPCA	Sparse Principal Component Analysis
SSM	Statistical Shape Models
UMTRI	University of Michigan Transportation Research Institute

CONTENTS

1 INTRODUCTION

Historically, the efforts made to increase safety in new vehicles have been largely successful, with reduced risk for both serious and fatal injuries. However, the risk of injury is not evenly distributed within the population nor between different body regions (Forman et al., 2019; Kullgren et al., 2020). Pelvic fractures specifically have been identified as the 3rd most common Abbreviated Injury Scale (AIS)2+ injury in motor vehicle crashes (MVCs) (Weaver et al., 2013), and the dominating AIS2+ lower extremity injury in side impacts (Pipkorn et al., 2020). Furthermore, pelvic fractures are associated with the highest early mortality rate of patients with orthopaedic injuries (Tile et al., 2015). In addition, real-life MVC data have shown that factors such as sex, age, stature, and Body Mass Index (BMI), are associated with pelvic fracture risk (Schiff et al., 2008; Sochor et al., 2003; Stein et al., 2006), and pelvic fracture tolerance from Post-Mortem Human Subjects (PMHS) experiments is known to show significant variability (Bouquet et al., 1998; Cesari and Ramet, 1982; Guillemot et al., 1998; Salzar et al., 2009). This indicates that pelvis population variance can have a significant effect on the injury outcome.

The most advanced tools available in the design of vehicle safety systems via computer simulations are Finite Element Human Body Models (FE-HBMs). FE-HBMs represent the human anatomy, anthropometry, and physical properties to predict a biomechanical response to external loading. While FE-HBMs provide the opportunity to include both geometrical and material variability in the analysis, state-of-the-art models of today are typically defined based on an average female or male subject in terms of global measurements like age, stature, and weight (Gayzik et al., 2011; Shigeta et al., 2009). Average representations do not capture the individual variability which could be required in order to protect the vulnerable population and maximise efficiency of vehicle safety systems. This is particularly true for the complex geometry of the pelvis which is described as the most distinct skeletal difference between females and males (Standring, 2008). A call has been made for HBM development to focus on concussion, rib, and pelvic fractures (Pipkorn et al., 2020), and to specifically include subject-specific factors such as pelvic shape and position (Richardson et al., 2020).

Recent studies predict that future autonomous vehicles will reduce the total number of accidents, while simultaneously increase the relative frequency of intersection crashes (Östling et al., 2019). It is also hypothesised that self-driving vehicles could result in the use of non-traditional seating positions, such as fully reclined, as passengers choose to rest during travel (Jorlöv et al., 2017). Using computer simulations with FE-HBMs, reclined seating has been shown to increase the risk of submarining (Rawska et al., 2020a), an event where the occupant slides under the lap-belt, which could induce injurious loads to the abdomen and spine. Tests on PMHSs have shown that submarining in reclined postures can be prevented. However, prevention has only been achieved at the expense of high restraining forces causing multiple pelvic, sacrum, and lumbar fractures (Richardson et al., 2020).

An increased ratio of intersection crashes for future autonomous vehicles might accentuate the risk of pelvic fractures due to lateral loading of the pelvis. In addition, the pelvis has been shown to be a key load bearing structure to prevent submarining for all belted occupants, which could also increase the risk of occupant pelvic fractures in future autonomous vehicles. Currently, a pelvis FE-model accounting for population shape variance is not publicly available. This motivates further research on pelvis anthropometry, development of pelvis FE-HBMs, and the use of these models to address both current and future challenges in traffic safety.

2 RESEARCH OBJECTIVE

The main objective of my Ph.D. degree is to develop methods/tools that enable pelvis related injury risk evaluations for a population of female and male vehicle occupants. As part of this research, a generic FE model capable of morphing to the population variance in pelvic shape, was developed and validated using published PMHS data. The model will be implemented in a state-of-the-art HBM, the SAFER HBM (Pipkorn et al., 2021), for use by academia and the vehicle industry. To fulfil the main objective, five sub-objectives have been defined.

This Licentiate thesis addresses the first two sub-objectives as a step towards the inclusion of pelvis population variance in HBMs:

- Describing the pelvic bone population shape variance and developing a morphometric model for shape predictions based on anthropometric variables
- Developing and validating a generic morphable FE-model of the human pelvis capable of running evaluations based on both shape and material variation

The following three sub-objectives will be the focus of the remainder of my Ph.D. degree and are not addressed in this Licentiate thesis:

- Generating an Injury Risk Curve (IRC) for pelvic fractures
- Validating the full body HBM for submarining scenarios and developing a method for submarining evaluation
- Studying the effect of varying seated postures and variance in anthropometry on the submarining scenario

2.1 General Method Description

To work towards the main objective of my Ph.D., and to meet the two sub-objectives presented in this Licentiate thesis, the first step was to obtain a general understanding of pelvis anatomy, biomechanics, and typical injury mechanics. This includes population variance in pelvis geometry and the expected difference between females and males. This background knowledge is summarised in Chapter 3 of this thesis.

The next step was to consult the literature on traffic related pelvis injuries and study the state-of-the-art in pelvis FE-models, which concluded that a pelvis FE-model accounting for population shape variance was, at the time, not publicly available. To provide such a model for academia and the vehicle industry, identified the requirement of a mathematical description of the pelvis shape variance. This led to a collaboration with the University of Michigan Transportation Research Institute (UMTRI), which provided 3D pelvis geometries based on Computed Tomography (CT) data. Subsequently, the need to study these 3D shapes and to describe them statistically, resulted in the methods presented in Chapter 4 of this thesis.

With the mathematical description of pelvis shape variance, an average geometry could be generated from which the generic FE-model was developed. Since the second sub-objective states that the FE-model should be capable of running evaluations based on shape variation, the need to link the mathematical description of pelvis shape to the generic FE-model became apparent. This was done through a MATLAB morphing script which enables the generation of an FE-model matching any shape in the identified population shape space. The development of the new pelvis FE-model is summarised in Chapter 5 of this thesis.

Finally, to enable evaluations based on both shape and material variability, the next step required a method suitable to study output response variance for computationally demanding models. This led to the sensitivity analysis methods described in Chapter 6 of this thesis.

With the methods and tools described in this thesis, it is possible to include and evaluate the effect of pelvis population variance in HBMs.

3 BACKGROUND

Pelvis is the Latin word for basin, which can easily be understood by its shape and how it supports the organs of the lower abdomen. The pelvis also acts as a load transferring structure as it connects the upper body, via the sacrum, to the lower body. Its deep, basin like structure is formed by two innominate bones (also called hip bones or coxal bones), the sacrum, and the coccyx, which together are referred to as the bony pelvis. The bones are connected in a ring like structure at the anterior pubic symphysis joint and posteriorly at the two sacroiliac (SI) joints.

3.1 Anatomy and Biomechanics

The innominate bones consist of three separate parts: a superior ilium, an inferior-anterior pubis, and an inferior-posterior ischium, see Figure 1. The three bones are fused together by the age of 16 at a deep hemispherical socket called the acetabulum (hip socket), giving it the structure of a single bone.

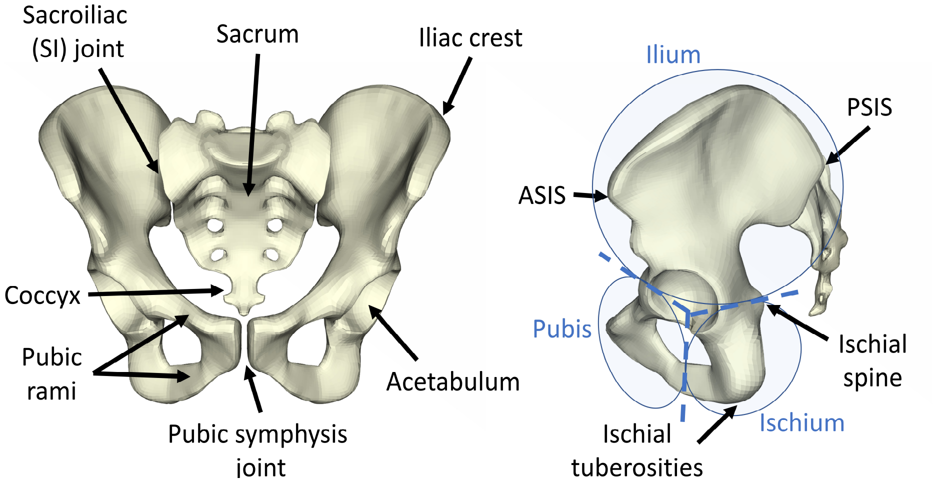

Figure 1 – Anatomical features of the pelvis.

The ilium is the largest of the three bones, composed of a body and a large wing-like section called the ala. The thickened superior margin of the ala is called the iliac crest and can easily be felt at the lateral top edge when you rest your hands on your hips. Two distinct landmarks are: the anterior superior iliac spine (ASIS) and posterior superior iliac spine (PSIS). On the posterior medial side of the ilium, a roughened auricular surface can be found that articulates with the corresponding surface of the sacrum to form the SI joint.

The ischium comprises a superior body that connects to the ilium and the thinner inferior ramus which connects to the pubis anteriorly. Two distinct landmarks are: the ischial spine and the ischial tuberosity. The ischial tuberosity is the strongest part of the innominate bone and when we sit it holds our entire weight.

The pubis is a V-shaped bone comprising a body and two rami, the superior and inferior ramus. The inferior ramus connects to the ischial ramus and the superior ramus connects to the ischium and ilium at the acetabulum. At the junction of the left and right pubic bones in the median plane is the pubic symphysis joint. These rami constitute the weaker regions of the pelvis but represent an important load path for lateral forces.

In adults, the sacrum is fused together as one triangular bone by the sacral vertebrae (S1-S5). It articulates superiorly with the L5 vertebrae, inferiorly with the coccyx, and laterally with the innominate bones, creating the SI joints. The vertebral canal continues inside the sacrum as the sacral canal, guiding blood vessels and spinal nerves.

Biomechanically, and when classifying injuries, the pelvis is often categorised into the pelvic girdle and the acetabulum/hip joint. The pelvic girdle is a ring structure consisting of sacrum and left and right innominate bones. The ring can be thought of as a posterior arch, consisting of the upper sacral vertebrae and the bone connecting the SI joint with the acetabulum, and an anterior arch, consisting of the pubic bones and their superior rami. However, in total the pelvic ring should be considered as a single anatomical structure.

The stability of the pelvic girdle is achieved by strong ligaments, primarily by the posterior ligaments called the posterior tension band. The major posterior ligaments are interosseous SI, posterior SI, anterior SI, sacrotuberous, sacrospinous, iliolumbar, and lateral lumbosacral. These must work together to assure a stable posterior pelvis and have been described as the most powerful ligaments of the body. The anterior ligaments are called inguinal and pubis ligaments. The pubis ligaments help stabilise the pubic symphysis joint in external rotation and anterior shear forces.

The acetabulum is connected to the rest of the pelvis via its anterior and posterior columns, which provide structural support. The two columns connect at a 60° angle at a concave arch, which forms the dome of the acetabulum socket. The posterior wall of the acetabulum is larger and protrude more laterally than the anterior wall.

3.2 Injury Mechanisms

Pelvic fractures can cause both direct loading to the soft tissue and visceral damage by bony fragment penetration and laceration. Given the major nerves, blood vessels, and organs inside the pelvic girdle, such injuries are associated both with a high acute mortality rate and a high degree of residual disability (Tile et al., 2015). Every biomechanical structure has a number of injury mechanisms depending on differences in geometry, tissue properties and the expected loading scenario. As such, it is logical to separate the injury mechanism for the pelvic girdle and the acetabulum.

Pelvic gridle

The severity of a pelvic injury often refers to the degree of instability, either from fracture or from dislocation, caused by the trauma. The instability can be described as stable, partially unstable, or completely unstable, and the degree of instability correlates with the energy of the trauma and the patient's physiological status (Tile, 1988). In the case of fracture, the resulting fracture pattern will be governed both by direction and magnitude of the force applied. For general pelvic fractures, three main force patterns can be identified as anteroposterior compression, lateral compression, and vertical shear (Burgess et al., 1990). For each of these cases, different injuries to the pelvic structure can be expected. Due to the ring-like arrangement of the three pelvic bones, a fracture in a single location is highly unusual (Tile, 1988; Tile et al., 2015). Hence, a patient who has been identified to have sustained an anterior pelvic fracture, should also be assumed to have suffered a concomitant posterior fracture or ligament injury. Fracturing both of the pubic rami will have a significant effect on the pelvic stability and its ability to maintain shape (Tile et al., 2015).

Acetabulum

Acetabulum fractures are caused by the interaction between the acetabulum socket and the femoral head. Injuries are usually a result of either a direct impact to the greater trochanter or an impact to the foot or knee, which produces an axial force along the femoral shaft. Since the acetabulum is composed of two columns and two walls that meet at a dome, all fracture types are variations involving these anatomical structures. The type of fracture is highly dependent on both the position and the orientation of the femoral head at the moment of impact (Rupp et al., 2003). An axial load through the femoral shaft is often seen in dashboard injuries, where the force is applied through the flexed knee of a seated occupant, resulting in posterior wall and column fractures. Due to its greater distance from the supporting arch, the posterior wall is the most vulnerable part of the structure when loaded via the femoral head, making it the most commonly and easily fractured region of the acetabulum.

3.3 Anthropometry

Sexually dimorphic measurements have been analysed by several authors, e.g., (DelPrete, 2019; Luis and Carretero, 1994), and books on anatomy and physiology offer descriptions of the female and male pelvis as; *"strikingly different"* (Marieb and Hoehn, 2010); *"a difference in features of bones are readily apparent"* (Tortora and Derrickson, 2009); and *"the pelvis provides the most marked skeletal differences between male and female"* (Standring, 2008).

The differences between females and males are linked to function where the female pelvis has adapted to enable childbirth while the male pelvis, generally, has to transfer greater locomotive forces. Hence, a clear distinction between the average male and average female pelvis geometry should be expected. However, since the range of most features overlap between the sexes**,** the inter-individual differences can sometimes be more pronounced than the sex differences (Standring, 2008). Common anatomical differences from the above sources are presented in Table 1. In general, the female pelvis is smaller than the male, it has a wider sub-pubic angle, thinner pubic bones, it is broader and shallower, its pelvic brim is wider and more oval, and the sacrum is shorter, wider, and less curved. A difference in average shape, or size, can probably also be expected for people of different ethnicity, but has not been the focus of this thesis.

Table 1 – Example of morphological differences between the female and male bony pelvis as described in anatomical textbooks (Marieb and Hoehn, 2010; Standring, 2008; Tortora and Derrickson, 2009)

Characteristic	Male	Female
General structure	Heavy, thick, less tilted forward	Light, thin, tilted forward
True (lesser) pelvis	Narrow, deep	Shallow, broad
Pelvic inlet (brim)	Narrow, heart shaped	Wide, more oval
Acetabulum	Large, faces laterally	Small, faces anteriorly
Sub pubic angle	More acute angle (50°-60°)	Broader angle (80°-90°)
Ilium	More vertical	Less vertical
Greater sciatic notch	Narrow (mean 50.4°)	Wide (mean 74.4°)
Sacrum	Long, narrow, more curved	Short, wide, less curved
Ischial tuberosity	Long, close	Short, further apart

4 CAPTURING POPULATION SHAPE VARIANCE

Historically, anthropometrical studies have focused on analysing a limited set of distances and angles that describe the geometry of a body part. A more modern approach is to study a much larger set of anatomical points defined by Cartesian coordinates. By shifting the focus to coordinate data, the complete spatial arrangement of the anatomical points, e.g., the shape, is captured, and any distance (or angle) between them is automatically retained. By adopting this approach, a large set of data is usually attained, and statistical analysis methods are warranted. One collection of such methods, defined by multivariate statistics on dense sets of corresponding anatomical points, are known as Geometric Morphometrics (GM) or Statistical Shape Models (SSM) (Slice, 2007).

A common method utilised in GM studies is called Principal Component Analysis (PCA). This method captures the mean shape and the covariance structure of the data around that mean. As a mathematical method, PCA identifies the orthogonal set of vectors that most efficiently captures the sample variance. This can be used as a dimension-reduction technique by transforming the data into an orthogonal set of loading vectors and only retain the Principal Components (PCs) that capture variance up to a predefined threshold, see Figure 2 for a 2D visualisation. Once the reduced set of PCs are known, correlation of shape with other factors can be explored to find new associations (Slice, 2007).

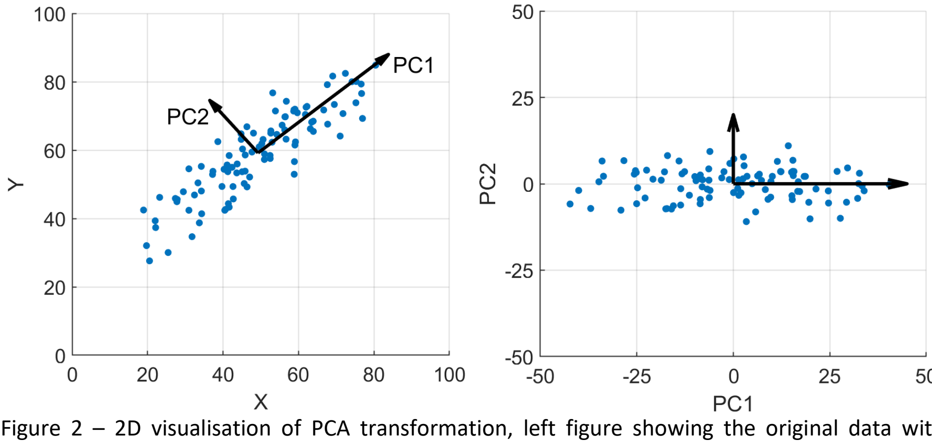

Figure 2 – 2D visualisation of PCA transformation, left figure showing the original data with significant variance in both the X and Y direction, right figure showing the transformed data with majority of variance (≈95%) captured by only PC1.

One drawback with PCA is that the PCs are global in nature which can make shape interpretation difficult, especially for the non-dominating PCs (Zou et al., 2006). The PCs are considered global since they are defined by a variance-maximising criterion on the entire dataset. This means that local variations in the data might get mixed over several PCs and therefore be difficult to distinguish. An extension to PCA called Sparse Principal Component Analysis (SPCA) has been developed to address this problem. SPCA frames the PCA problem as a regression-type optimisation problem and utilises variable selection techniques from multiple linear regression, to penalise the weight of distant data points to zero. This results in sparse loading vectors that describe localised variance in the data (Zou et al., 2006). The general problem formulation can be expressed as:

$$\begin{gathered}(\widehat{\mathbf{A}}, \widehat{\mathbf{B}}) = \underset{\mathbf{A},\mathbf{B}}{\arg\min} \sum \|\mathbf{X} - \mathbf{A}\mathbf{B}^{\mathrm{T}}\mathbf{X}\|^2 + \psi(\mathbf{B}) \\ subject\ to\ \mathbf{A}^{\mathrm{T}}\mathbf{A} = \mathbf{I},\end{gathered} \tag{1}$$

where $\mathbf{B}$ is a sparse weight matrix, $\mathbf{A}$ is an orthonormal matrix and ψ denotes a sparsity inducing regularisation such as the Least Absolute Shrinkage and Selection Operator (LASSO) or the elastic net (Zou et al., 2006). The principal components $\mathbf{Z}$ are formed as:

$$\mathbf{Z} = \mathbf{X}\mathbf{B} \tag{2}$$

and the original data can approximately be recreated using:

$$\widetilde{\mathbf{X}} = \mathbf{Z}\mathbf{A}^{\mathrm{T}} \tag{3}$$

To solve this optimisation problem a method has been presented by (Erichson et al., 2020), implemented as an R-package “*sparsepca*” (Erichson et al., 2018).

By design, SPCA is not suited for capturing global effects like volume and these should be removed a priori, as noted by (Sjöstrand et al., 2007). This can be achieved by including both translation and scaling when registering the set of data points to a common reference using Generalised Procrustes Analysis (GPA). The scaling variable includes the volumetric difference between samples and can be studied separately from the shape effects. This approach is further motivated by (DelPrete, 2019), who states that geometric normalisation prior to shape analysis is important to be able to understand how the shape of male and female pelvises differ.

Usage of geometric morphometrics and SPCA in this thesis follows as:

- Describing the population shape variance of the pelvic bones, **Paper A**
- Development of a morphometric model predicting pelvis geometry, **Paper A**

5 FINITE ELEMENT MODEL DEVELOPMENT

The pelvis FE model developed in this thesis consists of both innominate bones and the sacrum, with separate representations for trabecular and cortical bone. The bone models were connected anteriorly with a model of the pubic symphysis joint and posteriorly by models of the two SI joints. The former consists of a fibrocartilage disc and the surrounding ligaments. The latter consists of articular cartilage, interosseous ligaments, anterior ligaments, and posterior ligaments. The inferior sacrum and the ischial bone were connected via the sacrospinous and sacrotuberous ligaments. Finally, elements that make up for the articular cartilage were modelled on the lunate surface of the acetabulum. See Figure 3 for a model overview and Paper B for a more detailed overview.

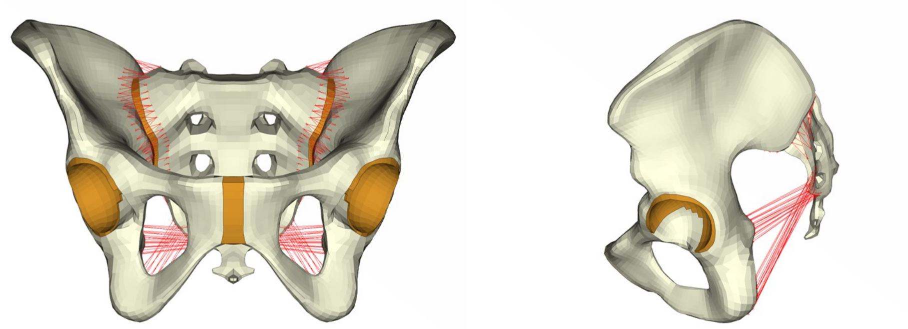

Figure 3 – Medial (left) and sagittal (right) view of the pelvis FE-model.

One sub-objective of this thesis was to develop and validate a generic morphable FE-model of the human pelvis, capable of running shape variation evaluations. To meet this objective, the model was developed based on the outer surface of an average generic pelvis geometry described in Paper A. The average of the complete sample, including both females and males, was chosen as baseline to minimise the overall morphing distance and mitigate mesh distortion when covering the entire shape space. In addition, mesh quality and structure were highly prioritised to allow for significant variations in geometry while retaining a numerically stable and runnable model. Details on the mesh quality achieved are outlined in Paper B.

The pelvis cortical bone thickness is not uniform over the pelvis surface, and it is important to include this variability to accurately describe the structural stiffness. Unfortunately, the data used in Paper A does not provide the cortical bone thickness associated with each subject. To include cortical bone thickness in the model, a separate study on cortical thickness distributions of the innominate bones from 10 normal controls (5 females, 5 males) (Harris et al., 2012), was conducted. The distribution of nodal thicknesses within each subject was found to be lognormal with a mean of 1.64 mm. Hence, a lognormal distribution was fitted to the nodal thicknesses of each subject and the subject with the closest distribution to the average lognormal curve was chosen as baseline, see Figure 4 for cortical thickness of the baseline subject. Since the minimum cortical thickness was 0.5 mm, a solid mesh was deemed unfeasible to comply with restrictions on minimum time step length in the explicit solver. A quadrilateral shell mesh was hence implemented for the cortical bone on the surface of the hexahedral solid elements of the tetrahedral bone. To have the shell element placed in the midplane of the cortical bone, the outer cortical surface of the average generic pelvis geometry was offset in the normal direction by half the baseline cortical thickness of each element.

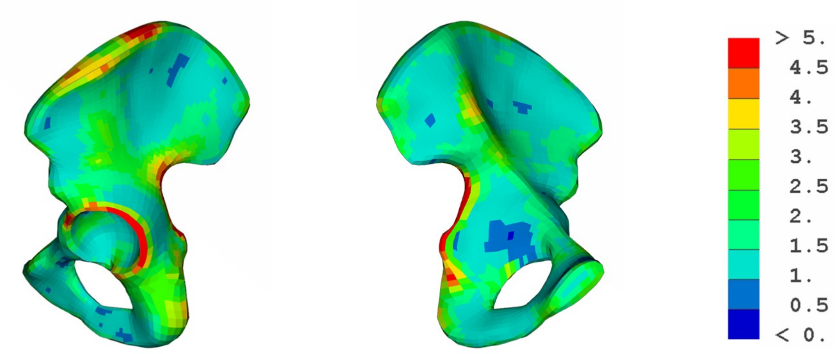

Figure 4 – Cortical bone thickness in baseline mode from a lateral (left) and a medial (right) view.

Morphing the FE model based on the geometrical shape variance results from Paper A was done by a MATLAB script, developed in collaboration with UMTRI. The script utilises a Radial Basis Function with Thin-Plate-Splines (RBF-TPS) interpolation and sets the outer cortical surface of the average generic pelvis geometry as source. The target for the morphing was the outer cortical surface of the pelvis geometry as predicted by the SPCA results. The FE model was then morphed based on the displacement needed to move from source to target in 3D space. For further details on morphing see Paper A.

Presentation and usage of the pelvis FE model in this thesis follows as:

- Development of the pelvis FE model, **Paper B**
- Running a parametric evaluation based on shape, **Paper B**

6 GLOBAL SENSITIVITY ANALYSIS

To gain confidence in computational biomechanical models, a thorough assessment of model sensitivity is crucial such that not only the average is considered, but also the distribution of possible outcomes (Cook et al., 2014). In addition to providing confidence in the model, sensitivity analysis also enables us to answer questions like: *"How much does a specific variable contribute to the predicted response?"* and *"Which variable could result in a predicted response exceeding a predefined threshold?"*. Given the significant variability in biological systems, Cook et al. encouraged the biomechanical research community to broaden its current scope and make parameter variation a standard component of their analysis.

The literature includes several sensitivity analysis methods (Borgonovo and Plischke, 2016; Saltelli et al., 2008). These can broadly be distinguished as local, where one parameter at a time is varied, and global, where all parameters are varied simultaneously (Saltelli et al., 2019), but should not be confused with the local/global terminology used to describe shape components. While being intuitive and easy to set up, local sensitivity analysis is only valid if the model is linear with no interactions, and only explore a limited range in a multi-dimensional space. Global Sensitivity Analysis (GSA) on the other hand, is also valid when the model response is both nonlinear and include interaction effects amongst parameters.

Sensitivity analysis aims to quantify the contribution of each input variable on the random response of a system. A common approach is a variance-based decomposition, where the total variance of the output response is defined by the sum of the contribution of each input variable. Given a function $Y = h(\boldsymbol{X})$, where $\boldsymbol{X} = [X_1, X_2, \dots, X_n]^T$ are n independent random variables, the variance of the output can be decomposed as

$$V_Y = \sum_{i=1}^{n} V_i + \sum_{i<j} V_{ij} + \cdots \tag{4}$$

where V_i is the variance from variable X_i, V_{ij} is the variance due to the interaction of variables X_i and X_j, and the dots represent higher order (more than two variables) interactions, as presented by (Zhang and Pandey, 2014). Dividing Equation (4) with the total variance V_Y, one obtains the Sobol's sensitivity indices as

$$1 = \sum_{i=1}^{n} S_i + \sum_{i<j} S_{ij} + \cdots \tag{5}$$

where S_i is referred to as the primary (or first-order) sensitivity index. For a model with no interaction between input variables, $\sum S_i$ equals one since all higher-order terms are zero, for all other cases $\sum S_i < 1$.

The most effective GSA method of a general response function is Monte Carlo (MC) simulations (Zhang and Pandey, 2014). However, the method is time consuming and typically requires tens of thousands of model evaluations, making it unrealistic for computationally demanding models. An approximation for variance-based GSA with sensitivity indices called the Multiplicative Dimensional Reduction Method (M-DRM) was first presented by (Zhang and Pandey, 2014). The method approximates high-dimensional integrals associated with the variance analysis by a product of one-dimensional functions, and computes the primary sensitivity indices as

$$S_i \approx \frac{\theta_i/\rho_i^2 - 1}{\left(\prod_{k=1}^{n} \theta_k/\rho_k^2\right) - 1} \tag{6}$$

where ρ_i and θ_i are one-dimensional integrals. As such, these can be computed numerically by Gaussian quadrature as

$$\begin{aligned} \rho_i &= \int_{X_i} h(X_i, \boldsymbol{C}_{-i}) f_i(X_i) dX_i \approx \sum_{j=1}^{N_{GP}} w_{ij} h(X_i^j, \boldsymbol{C}_{-i}) \\ \theta_i &= \int_{X_i} [h(X_i, \boldsymbol{C}_{-i})]^2 f_i(X_i) dX_i \approx \sum_{j=1}^{N_{GP}} w_{ij} \left[h\left(X_i^j, \boldsymbol{C}_{-i}\right)\right]^2 \end{aligned} \tag{7}$$

where $f_i(X_i)$ is the distribution function for parameter X_i, $\boldsymbol{C}_{-i}$ is the cut point vector with all variables but X_i fixed to their nominal values, $h(X_i^j, \boldsymbol{C}_{-i})$ is the functional evaluation for each input variable, and w_{ij} are Gaussian quadrature weights. Using Gaussian quadrature with N_{GP} Gauss-points and n variables the total number of simulations are at most nN_{GP}, which is several orders of magnitude less than the MC method.

Usage of GSA with the M-DRM approximation in this thesis follows as:

- Assessing shape and material variability on pelvis response to lateral impacts, **Paper B**

7 SUMMARY OF APPENDED PAPERS

7.1 Paper A

The objective of Paper A was to describe the population shape variance of the pelvic bones using SPCA and to develop an associated morphometric model using overall anthropometry (sex, age, stature, and BMI) as independent variables. The study was performed to define the pelvic bone geometrical variance and to facilitate the development of FE-HBMs capable of representing the pelvis shape for assessment of future restraint systems.

In this study, clinical CT scans from 132 subjects (75 females, 57 males) were retrospectively obtained from clinical imaging studies at the University of Michigan, Department of Radiology. A previous study (Klein, 2015), segmented the pelvic outer 3D surfaces and extracted co-variate data from the medical records of each subject including sex, age, stature, and weight.

A method known as geometric morphometrics was used to study the population variance in pelvic bone geometry. The steps include; landmarking, registration with GPA, morphing of a template geometry to each subject geometry to create corresponding node sets, SPCA on morphed subject-specific models, and generating a morphometric model using multivariate linear regression to predict the nodal coordinates of the subject-specific models.

Conclusions from this study were:

- The population variance in pelvis geometry can only partially be explained (29%) by overall anthropometric variables such as sex, age, stature, and BMI
- Inferior-anterior regions of the pelvis were primarily captured, while local sacrum features, shape and position of ASIS, and lateral tilt of the iliac wings, were not captured
- Shape features overlap for females/males and substantial inter-individual differences remain even after controlling for sex

7.2 Paper B

The objective of Paper B was to build, calibrate, and validate a pelvis FE-model for lateral impact evaluations and to identify and quantify the most influential variables on the pelvis response to side loading using GSA. The variables studied were pelvic bone shape and material properties.

In this study, a new detailed pelvis FE-model was built based on the average geometry in Paper A. The base model was built with average properties from the literature, including cortical and trabecular bone Young's-modulus, a distributed cortical bone thickness, and joints calibrated to generate a response similar to published PMHS experimental results. Using the morphometric model from Paper A, a 50th percentile female (50 years, 162 cm, 63 kg) and male (50 years, 175 cm, 77 kg) baseline pelvis geometry were generated.

The morphable FE-model was validated against published PMHS experimental results (Guillemot et al., 1998) from static (n=10) and dynamic (n=12) lateral loads on denuded pelvises. Latin-Hypercube Sampling (LHS) was utilised to draw 50 random samples around each baseline model from the variable distribution, including both shape and material properties, such that the distribution of possible outcomes was considered and not just the average.

To study model sensitivity to variations in input variables, the GSA approximation M-DRM, was utilised for the dynamic lateral load case. Based on Gaussian integration, each variable was individually drawn from its distribution to generate 78 simulations for each baseline. The shape distributions were taken from Paper A, while material distributions were defined based on the literature.

Conclusions from this study were:

- In lateral impacts to the pelvis, material properties account for the majority of response variance (≈50-65%), while shape controlling variables contribute by a similar, albeit slightly smaller, magnitude (≈35-40%)
- Both material properties and geometrical shape should be considered to accurately model the pelvis response for a general population

8 DISCUSSION

In this Licentiate thesis, steps were taken towards including pelvis population variance in vehicle safety analysis. This is in line with the main objective of my Ph.D. degree, which is to develop methods/tools enabling pelvis related injury risk evaluation, based on a population of female and male vehicle occupants.

In the first study, pelvis shape was analysed through SPCA, and a morphometric model capable of predicting pelvis shape based on anthropometric variables was developed. In the second study, a generic morphable FE-model of the human pelvis, capable of running parametric evaluations based on shape variations, was developed and validated for lateral impacts. In addition, a sensitivity analysis on response variance due to variability in model input variables was performed.

8.1 Population Variance in Pelvis Shape

Previous studies have used PCA to describe global shape variations of the pelvic bone, e.g., (Arand et al., 2018; Audenaert et al., 2019), however, the study presented in Paper A is the first to use SPCA to describe localised shape variations. The analysis technique used resulted in improved interpretability, since the local features were more distinguishable in shape, than their global counterparts. This allowed for a more precise identification of shapes captured by the morphometric model, using overall anthropometry (sex, age, stature, and BMI) as independent variables. It also enables studies with the pelvis FE-model, where only a specific local feature is varied to evaluate the effect on a predicted response.

The strength of the localisation effect is governed by a parameter value in the SPCA solver and there are no discrete boundaries in the model. A local feature should be interpreted as the dominating shape variance in a sub-volume of the pelvis geometry. Variations in shape that are too small to generate their own sub-volume will not be captured by a separate PC, and hence could exist over the entire pelvis surface. To exemplify the SPCA results and size of a local feature, two PCs are shown in Figure 5.

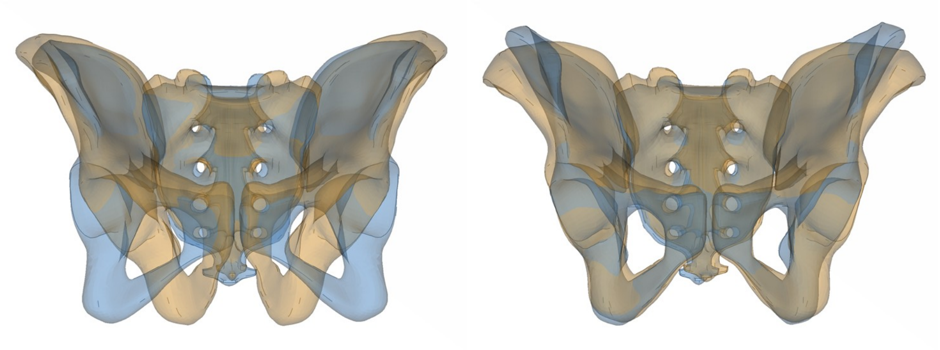

Figure 5 – Local features from SPCA describing width of the ischial tuberosities (left) and lateral tilt of the iliac wings (right). Results represent ±3SD from the studied population in Paper A.

The benefit of describing local features through SPCA is associated with certain disadvantages. In SPCA, the number of PCs is set a priori and are computed through optimisation. Since the variance captured is dependent on the number of PCs specified, the resulting variance captured will be unknown when setting up the problem. Furthermore, since the problem is solved by optimisation, the resulting shapes will also depend on the number of PCs specified. In PCA, the complete variance is always captured, and the retained variance can be decided a posteriori by specifying the number of PCs. In Paper A, one scale parameter and 15 PCs were specified in the SPCA and were found to capture 90% of the total variance. This number of PCs was considered sufficient for the purpose of the study.

For both PCA and SPCA, the resulting PCs are constructed by a variance-maximising criterion based on the analysed coordinate data. However, there is no guarantee that these variations are aligned with the variation relevant to the biological question being addressed (Slice, 2007). For example, the first PC describing most of the shape variance might not correlate with risk for a specific injury. For this injury, a different PC may instead be more relevant despite it describing much less of the total shape variance. In addition, a very localised feature, relevant to a specific injury, could potentially be found in the variance not captured/retained. With regard to the results presented in this thesis, this means that future evaluations would only consider the geometrical variations found in the approximately 90% of variance captured by the analysis.

Even though the SPCA captured 90% of the total shape variance, the developed morphometric model using multivariate linear regression with overall anthropometry as independent variables, only captured 29% of the total. Given the identified range of geometrical variability, and that most of this variance was not captured by the morphometric model, one should not expect a single “average” subject to present a representative pelvis shape. This is an important finding in relation to current state-of-the-art FE-HBMs, which are modelled from CT data of a single subject (Gayzik et al., 2011; Shigeta et al., 2009). While the chosen subject is considered average by certain evaluations on global measurements, the pelvis shape might vary significantly from that of the true average. Similar conclusions have also been made for other body parts (Yates et al., 2016; Yates and Untaroiu, 2018), where selected global measurements did not correlate strongly with geometrical shape.

State-of-the-art methods to include population variance in traffic safety analysis utilise multivariate linear regression with global anthropometric variables (Hu et al., 2019), which further highlights the importance of knowing that sex, age, stature, and BMI, are poor predictors of pelvis shape. While this might be a suitable approach for more one-dimensional structures than the pelvis, such as long bones (Klein et al., 2015), the results from Paper A and other studies on more complex geometries such as the ribcage (Wang et al., 2016), indicate that the variance captured shrinks with increasing dimensional variability. This suggests that local measurements, based on anatomical landmarks that require more intrusive measurement techniques, are needed to reliably predict the population variance in structures such as the pelvic bone.

It has also been noted that certain shape features were better predicted by the morphometric model than other. Plots showing the prediction error of the morphometric model versus the true geometry, show that the inferior-anterior regions and the pelvic brim (except for the sacral promontory) correlate strongest with overall anthropometry (median nodal error ≈4-5mm). A strong coupling with sex for these areas mostly explains this result (DelPrete, 2019; Luis and Carretero, 1994). On the other hand, the morphometric model prediction of the anterior-superior margins of the ilia and the inferior/superior ends of the sacrum were shown to be least correlated with the independent variables (median nodal error ≈9-10mm). A more local measurement would be required to improve the prediction capabilities of these areas.

The shape features found to correlate poorly with overall anthropometry could have important implications for traffic safety analysis. For example, relative distance between the iliac wing and the trochanter can affect impact timing and force transfer from lateral loading, while ASIS relative to sacrum position could affect lap belt to pelvis engagement. The coupling between sacrum position and lap belt engagement can be realised if one considers the connection with the lumbar spine. For a given lumbar spine shape, variations in sacrum endplate angle will cause a tilt of the pelvis in the sagittal plane, effectively shifting the

ASIS position. This shift might cause a correctly placed lap belt, loading the iliac spines, to instead be placed above the ASIS and risk loading the abdomen.

One final limitation of the shape variance presented in Paper A is that it is derived from a limited sample (n=132) and a single source. Based on sex, age, stature, and weight, the sample is representative of a modern US population (Fryar et al., 2016), but further generalisation based on ethnicity, for instance, is not currently possible.

8.2 Pelvis Response to Lateral Impacts

The study presented in Paper B is the first to include population variance from both material and geometrical shape, when analysing lateral impacts to the pelvis. In addition, it quantified the relative importance of different input variables on the pelvis response. Other pelvis FE-models for lateral impact evaluations can be found in the literature, e.g., (Kikuchi et al., 2006; Konosu, 2003; Kunitomi et al., 2017; Untaroiu et al., 2008), but this is the first model to be built based on an average generic pelvis geometry, including a morphometric model that enables parametric evaluations based on shape variance.

Fracture tolerance from lateral impacts to the hip is known to show significant variation in experimental studies using PMHSs (Bouquet et al., 1998; Cesari and Ramet, 1982; Guillemot et al., 1998; Salzar et al., 2009). For example, Cesari and Ramet performed 60 impacts to 22 PMHSs in a seated position, using a rigid spherical impactor centred on the greater trochanter. They found a force tolerance of 10 kN for the 50th percentile male subject and close to 4 kN for the 5th percentile female, and concluded that *"the value of the tolerable impact force varies greatly with anthropometry"*. Paper B confirms the statement by Cesari and Ramet, and quantifies the effect by presenting how much of the response variance that is attributed to the pelvis shape (≈35-40%), when sampling from a random distribution. However, it should be noted that these findings come from a well-defined impact on a denuded pelvis structure. In real-life MVC lateral impact scenarios, with an intruding side structure hitting the soft tissue of a seated occupant, the variability in boundary conditions is expected to be significantly more pronounced. For this scenario, the contribution from pelvis shape in relation to all other sources of uncertainty remains unknown. To visualise the effect of the random distribution in shape, the weakest and stiffest model from the LHS used in Paper B can be seen in Figure 6.

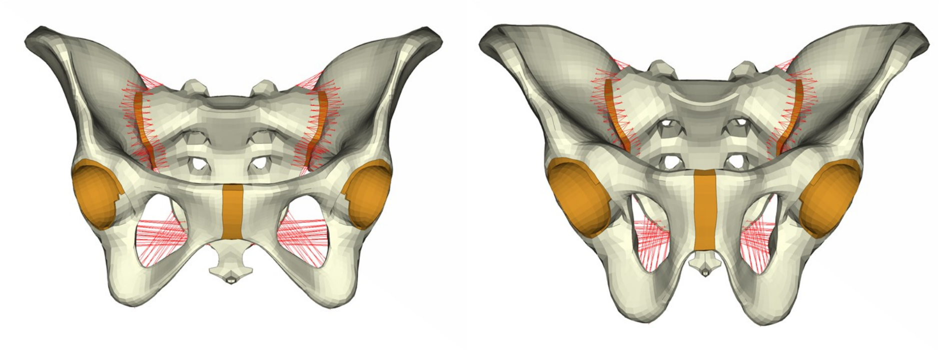

Figure 6 – Weakest (left) and stiffest (right) model from the LHS sub-study in Paper B. The resulting stiffness was achieved by random sampling of both shape and material properties.

A suitable local criterion for fracture in human cortical bone is strain-based, as demonstrated experimentally (Nalla et al., 2003; Trosseille et al., 2008). This has been utilised in prior studies using both 1st principal strains (Iraeus et al., 2019; Pipkorn et al., 2019) and effective plastic strain (DeWit and Cronin, 2012). However, a detailed understanding of the fracture mechanics due to lateral compression of the pelvis is lacking in the literature. Furthermore, the PMHS simulated in Paper B does not present strain measures against which the model could be validated. Therefore, the authors of Paper B chose to perform a sensitivity analysis for both peak applied force, and maximum nodal averaged effective plastic strain, in the superior pubic rami. The force-based sensitivity can be used when evaluating the variance in historical PMHS data, where peak force is typically reported. The strain-based sensitivity, while less validated, was included to provide an indication for future experiments. In both cases the material properties account for the majority of the response variance (≈50-65%), while the input variables controlling shape contribute by a similar, albeit slightly smaller, magnitude (≈35-40%).

The M-DRM computed sensitivity indices are approximations, relying on that a complex function of random variables can be approximated by a product of one-dimensional functions. It also assumes that the sensitivity of the model can be estimated based on a fixed reference (or cut) point. Zhang and Pandey demonstrates that these assumptions make up for a good approximation of sensitivity indices, at a much lower simulation cost, for a number of numerical examples using standard benchmark functions (Zhang and Pandey, 2014). A requirement for this to hold true is that sufficient number of Gauss-points are used when performing the numerical integration as part of the M-DRM. While promising, their results do not guarantee that the assumptions hold also for the current pelvis model and should hence be seen as a limitation. However, both 3 and 5-point Gauss integration was evaluated to check that the results had converged.

One of the main challenges with sensitivity analysis is defining the parameter distribution and potential correlations. Knowledge about how a parameter varies within a population, and which distribution it follows, is often lacking and typically require some assumptions. In Paper B, the shape parameters were defined based on the analysis of the population in Paper A (n=132), the cortical bone thickness distribution was defined based on a group of normal controls (n=10) (Harris et al., 2012), the cortical bone stiffness was defined from a coupon tension experiment (n=20 from four subjects) (Kemper et al., 2008), and the trabecular stiffness was defined based on a pelvis related elasticity-density relationship (Dalstra et al., 1993), using lumbar vertebrae apparent density measurements (n=87 from 23 subjects) (Galante et al., 1970). Given the sample sizes, and lacking source for pelvis trabecular bone apparent density, the distribution in pelvis material properties and thickness was not defined with the same confidence level as the distribution in pelvis shape.

To improve knowledge about pelvic fracture mechanics, additional experiments are motivated. Specifically, it would benefit the development of future models if studies were carried out on; the anisotropy of the pelvis cortical bone, osteon orientation over the cortical surface, population distribution of material properties, tuning and validation data for strain-based measurements, and fracture tolerance of pelvis cortical bone in multiple loading directions.

8.3 Research Applicability

The methods and results presented in this Licentiate thesis and the appended papers can be utilised both by academia and the vehicle industry. To begin, the methods described are general and can be applied to any body part where inclusion of population variance is desired. As of today, FE-HBMs do not consider the population variance with regard to shape for most body parts, other than indirectly from global morphing of the entire body. Hopefully, this thesis can spark additional interest and research outside the pelvis area, to allow FE-HBMs to better represent the general population.

The presented pelvis FE-model can be used to improve the understanding of injury mechanics and aid the design of passive safety systems that consider the most vulnerable occupants. This can be achieved by morphing the FE-model to possible shapes from the population and study the response for a specific loading scenario. Subsequently, a critical shape for that particular scenario can then be identified and used in future analyses. Instead of designing a new vehicle safety system against thresholds for an average occupant, the response of the critical shape should be used to make the system more robust for the general population.

The presented model can also be used in simulation pre-studies for future PMHS experiments. By running experiments as computer simulations for a sample of possible pelvis shapes, features potentially critical to the experimental outcome can then be identified a priori. With this knowledge the experiment protocol can be adjusted to make sure that certain related measurements would be recorded for use in future analyses.

While this Licentiate thesis is focused on the inclusion of pelvis population variance in vehicle safety analysis, the methods applied as well as the models developed can be used more generally. The description of pelvis shape variance can be adopted by any field that finds the level of detail sufficient for their application. Furthermore, the pelvis FE-model has been validated for lateral impact scenarios which could make it useful for other applications than just vehicle safety, e.g., fall accidents. To make the model a versatile tool for multiple applications, future research ought to aim at validating the model for additional loading scenarios.

9 CONCLUSION

With the main objective to develop methods/tools that enable pelvis related injury risk evaluations for a population of female and male vehicle occupants, the work presented in this thesis has taken some critical steps.

The steps include:

- A mathematical and visual description of the average shape and population shape variance of the pelvic bone
- A morphometric model capable of predicting pelvis shape based on anthropometric variables (sex, age, stature, BMI)
- A new generic morphable pelvis FE-model that facilitates evaluation based on population shape and material variability

Based on the results from both appended papers, it can be concluded that the population shape variance of the pelvis structure is significant, and that such variations affect the simulated model response. Furthermore, overall anthropometric variables (sex, age, stature, BMI) were found to only capture parts of the variance in pelvis shape, which indicates that HBMs based on a generic pelvis model would be preferred over models based on individual CTs. Future studies should aim to include variability in both material properties and geometrical shape to accurately model pelvis response for a general population. Increased knowledge about population variability, and inclusion in safety evaluations, can result in more robust systems that reduce the risk of pelvis injuries in real-world accidents.

10 FUTURE WORK

The first obvious step in the continuation of my Ph.D. degree, is to integrate the newly developed pelvis FE-model into the full body SAFER HBM. A so far unresolved challenge is the coupling between the predicted pelvis shape and the surrounding body parts. A relationship between sacrum position/orientation and lumbar spine curvature must exist and is needed for a biofidelic integration. Potential collaboration with other partners, performing MRI scans of seated volunteers, is currently being explored to define this relationship.

To address the remaining sub-objectives of my Ph.D. degree, future research will be spent on the submarining scenario. The issue of submarining has been known since the introduction of the three-point seat belt as standard equipment, and has been studied since the 1970s, but has gained increased focus with the expectation of reclined seating in future autonomous vehicles (Boyle et al., 2019; Rawska et al., 2020a, 2020b).

The first step will be to decide on a suitable submarining PMHS experimental setup from the literature, to be used for validation and future sensitivity analyses. Some candidates are available, e.g., (Richardson et al., 2020; Shaw et al., 2018; Trosseille et al., 2018; Uriot et al., 2015; Wiechel and Bolte, 2006), although a more detailed analysis is required before the final decision is made. Subsequently, the updated SAFER HBM must be validated for proper belt interaction in simulated crashes, preferably in both upright and reclined positions. It will be important to verify that the model can capture the transition between submarining and non-submarining cases. In the validation work, prior modelling assumptions regarding the surrounding soft tissue, e.g., muscle/fat modelling, muscle insertions, interaction between bone and soft tissue, will be re-evaluated.

With a model validated for submarining scenarios, the morphable pelvis FE-model will be used to generate a population of vehicle occupants. The significance of pelvis variance and occupant position must be assessed in order to better understand the mechanics of submarining and the relevant variables. The focus will not be on the countermeasures to stop submarining, but rather the fundamental understanding of what causes submarining and how we should validate and correlate models that include population variance for this event. With this knowledge, the possibility for an IRC in submarining scenarios will be explored.

One sub-objective stated for my Ph.D. degree still remains, namely the generation of an IRC for prediction of pelvic fracture risk. However, due to the lack of experimental data on pelvis cortical bone in the literature (Kemper et al., 2008), a criterion based on local strain from material testing has currently been deemed unfeasible. An alternative approach is to reconstruct several PMHS experiments and generate an IRC based on predicted strain from simulation, coupled with injury data obtained in the original experiments. The drawback of this approach is that it will become a model specific criterion, which makes generalisation challenging. Furthermore, it is not guaranteed that the same IRC will be suitable for predicting superior pubic rami fractures from lateral compression, posterior wall acetabular fractures due to axial femur loading, and iliac wing avulsion fractures due to high lap belt loading, given the varying injury mechanics for these events. To still address this objective, the aim is to supervise a Master thesis project that reconstructs lateral loading scenarios with the SAFER HBM and generates a model specific IRC for this particular event. If time and data availability allow, the same will be done within my Ph.D. research for avulsion fractures of the iliac wing from lap belt loading.

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