THESIS FOR THE DEGREE OF LICENTIATE OF ENGINEERING

TOWARDS SHOULDER INJURY ASSESSMENT FOR SAFER CYCLING: DESCRIBING CLAVICLE VARIABILITY AND MECHANICAL RESPONSE

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Göteborg, Sweden, 2026

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Thesis for Licentiate of Engineering

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Cover: Illustration by Rahul R. Pai.

Schematic representation of a cyclist with a detailed inset highlighting the shoulder complex, generated using Gemini; the clavicles shown are derived from the results of Paper A.

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Ain't about what's waiting on the other side
It's the climb

Miley Cyrus

Abstract

Cycling is both a key mode of sustainable urban mobility and a popular sport. Yet crashes expose cyclists to severe injuries that impose substantial costs on healthcare systems. Clavicle fractures are among the most common skeletal injuries sustained in bicycle crashes and are associated with a risk of permanent medical impairment. Within a Ph.D. project aimed at developing methods and tools for shoulder injury risk evaluation in bicycle accident scenarios, this licentiate thesis presents two foundational steps toward that goal.

In the first study, a statistical shape model (SSM) of the right clavicle was derived from 97 clinical computed tomography (CT) scans using principal component analysis (PCA) to describe surface geometry and cortical bone thickness. Twenty-three principal components were required to explain 80% of the total morphological variance. Multivariate linear regression was used to link the variation to sex, stature, age, and body mass index (BMI). The regression model did however only explain 25% of the total variability, demonstrating that gross anthropometric descriptors are weakly correlated with individual clavicle morphology and that population sampling is necessary to capture the full range of anatomical variation.

In the second study, a morphable finite element (FE) clavicle model was developed from, and linked to, the SSM and validated in axial compression and three-point bending against published experimental tests. Sampling from the full SSM variability generated synthetic populations whose simulated response corridors captured from 60 to 160% of the experimentally observed spread, establishing anatomical variability in geometry and cortical bone thickness as a driver of inter-individual differences in mechanical response.

The framework established in this thesis provides the methodological foundation for that population-informed approach to shoulder injury assessment and will aid the design of countermeasures protecting cyclists in bicycle crashes. Accounting for morphological diversity is essential for developing and designing effective and robust protective countermeasures.

Keywords: Finite Element Human Body Model; Bicyclist; Shoulder; Injuries; Clavicle

Publications

This thesis is based on the following appended papers:

Paper A:

Chiara R. Fichera, Samyuktha Neeluru, Johan Davidsson, Jonas Östh, Jingwen Hu, Johan Iraeus
Investigating Clavicle Morphology: A Statistical Model of Clavicular Cortical Bone Thickness and Geometry
Under review after conditional acceptance
Author's Contributions: Conceptualization, Data Curation, Formal Analysis, Methodology, Writing – original draft, Visualization, Validation, Writing – review & editing

Paper B:

Chiara R. Fichera, Johan Davidsson, Jonas Östh, Johan Iraeus
Population Variance in Clavicle Response to Bending and Axial Compressive Loading
Draft Manuscript
Author's Contributions: Conceptualization, Data Curation, Formal Analysis, Methodology, Writing – original draft, Visualization, Validation, Writing – review & editing

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Abbreviations

AIC	Akaike Information Criterion
ATD	Anthropomorphic Test Device
BMI	Body Mass Index
CT	Computer Tomography
FE	Finite Element
FE-HBM	Finite Element Human Body Model
GHBMC	Global Human Body Models Consortium
HBM	Human Body Model
IRF	Injury Risk Function
PC	Principal Component
PCA	Principal Component Analysis
PMHS	Post-Mortem Human Subject
PPE	Personal Protective Equipment
SD	Standard Deviation
SSM	Statistical Shape Model
SVD	Single Value Decomposition
THUMS	Total Human Model for Safety

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CHAPTER 1

Introduction

Cycling contributes to sustainable urban mobility by reducing greenhouse gas emissions, alleviating traffic congestion, and promoting health through daily physical activity (WHO, 2023). To achieve sustainable and resilient urban transport systems, transportation modes such as cycling, known to be less safe than traveling in cars or public transport, need to become a more attractive and a safer mode of travel (Kjeldgård et al., 2020; Scarano et al., 2023).

In the past decades, protecting vulnerable road users—including cyclists—has drawn on a range of strategies, from infrastructure design and legislation to personal protective equipment. For instance, on the infrastructure side, the separation of bicycle lanes from motor traffic has shown to reduce collision risk (Reynolds et al., 2009; Teschke et al., 2012). However, collisions with motor vehicles represent only a fraction of cycling injury events. In Sweden, nearly 80% of hospital-reported cyclist injuries involve single-bicycle crashes—falls or collisions with fixed objects in which no other road user is involved (Rizzi et al., 2013). These crashes are typically caused by loss of control on slippery or uneven surfaces, collisions with infrastructure elements such as curbstones, or evasive maneuvers to avoid obstacles and other road users (Rizzi et al., 2020; Eriksson et al., 2022). Thus, given the prevalence and varied circumstances of single-bicycle crashes, infrastructure improvements alone are unlikely to eliminate them completely, making personal protective equipment an essential complementary strategy.

To date, the development of protective equipment for cyclists has focused predominantly on head protection, driven by epidemiological evidence demonstrating that head injuries account for a large share of both cycling fatalities and severe, life-altering injuries (Thompson et al., 1989; Sacks et al., 1991; Thompson et al., 1996; Thompson et al., 2000). Helmet adoption has since been linked to reductions in head injury rates (Cripton et al., 2014; Olivier et al., 2017; Høye, 2018; Büth et al., 2023), demonstrating how evidence-based intervention can translate into meaningful safety gains.

Head injuries are not the only type of injuries experienced by cyclists. Upper extremity injuries also represent a substantial proportion of injury cases (Kjeldgard et al., 2019; Eriksson et al., 2022). Although generally less critical than head injuries in terms of severity, they remain highly relevant (Stigson et al., 2025). Epidemiological studies show that upper extremity injuries—predominately affecting the shoulder and wrist—account for a major proportion of injuries associated with long-term disability (Rizzi et al., 2013; Stigson et al., 2025). Fracture registry data from Sweden (Frakturregistret) reported that bicycle accidents account for a large proportion of traffic-related injuries and that the resulting fracture panorama is dominated by the upper-extremity, with the clavicle being among the most frequently fractured skeletal sites in adults (Postacchini et al., 2002; Kihlström et al., 2017).

Clavicle fractures are not unique to cycling, representing a clinically relevant injury also in sports-related trauma such as American football, ice hockey and skiing (Postacchini et al., 2002; Kihlström et al., 2017). In some of these sports, upper body protective equipment incorporating shoulder padding is already in use—shoulder pads are standard in ice hockey (Jang et al., 2020)—and upper body protectors are increasingly adopted in mountain biking. However, no such protective equipment is currently used among commuter cyclists.

While epidemiological data establish the magnitude and distribution of these injuries, it does not elucidate the underlying mechanical mechanisms and injury tolerance level—information that is critical for developing effective protective countermeasures. Characterizing injury mechanisms requires controlled, reproducible testing, and Anthropomorphic Test Devices (ATDs) have historically served this purpose. However, ATDs are mechanical surrogates whose biofidelity remains limited in anatomically complex regions such as the shoulder, and the injury criteria derived from them therefore carry inherent limitations.

More recent studies have investigated injury mechanisms specific to bicycle falls and car–bicycle collisions. The variability in cyclist kinematics observed across these scenarios was substantially high (Klug et al., 2017; Trube et al., 2023; Carroll et al., 2025a; Carroll et al., 2025b). These limitations drive an encouraging shift toward computational Finite Element Human Body Models (FE-HBM) capable of capturing the anatomical complexity that ATDs cannot.

FE-HBMs have emerged as a complementary and increasingly preferred tool precisely to address the bio-fidelity constraints of ATDs. Compared to ATDs, FE-HBMs accurately represent human anatomy, anthropometry, and physical properties to predict a bio-fidelic response in terms of kinematics, kinetics, and internal strains, under omnidirectional external loading. Initially developed to represent vehicle occupants, they have in recent years increasingly been applied to vulnerable road user scenarios (Paas et al., 2015; Maier et al., 2022; Asensio-Gil et al., 2024; Jayathirtha, 2026). Key advantages of FE-HBMs over ATDs is their capacity to be morphed and repositioned (without any restrictions)—allowing systematic variation of posture, body size, impact configuration, and use of protective equipment—without the logistical and ethical constraints of physical testing (Larsson et al., 2023; Leledakis et al., 2023; Brynskog et al., 2024; Brynskog et al., 2025).

1.1 Research objectives

The main objective of my Ph.D. project is to develop methods/tools that enable shoulder-related injury risk evaluations for bicyclists and to aid the development of countermeasures. To fulfil the main objective of the Ph.D., five sub-objectives have been defined:

- Describing the clavicle bone geometric and cortical bone thickness population variance and developing a statistical shape model linked to anthropometric variables.
- Developing and validating a generic morphable FE-model of the clavicle capable of running evaluations based on both shape and cortical bone thickness variations.
- Developing and validating FE models of the shoulder joints soft tissue structures, such ligaments, cartilage and integrate the following models into an HBM.
- Generating Injury Risk Functions (IRFs) for shoulder related injuries.
- Design test methods for evaluating shoulder injuries to guide the development of restraint and protective devices based on typical boundary conditions in single bicycle fall scenarios.

The initial focus of this thesis was placed on the clavicle, motivated by epidemiological evidence, identifying it as one of the most frequently fractured skeletal sites in bicycle crashes. Thus, this Licentiate thesis addresses the first two sub-objectives as a step towards the inclusion of clavicle population variance in HBMs, while the remaining sub-objectives will be the focus of the subsequent phase of my Ph.D. degree.

CHAPTER 2

Background

2.1 Anatomy of the shoulder

The shoulder girdle comprises three bones—the scapula, the clavicle, and the humerus—along with their associated musculature, collectively connecting the upper limb to the axial skeleton. Its architecture prioritizes range of motion over stability, making it the most mobile joint complex in the human body. This mobility arises from the coordinated interaction of four articulations—the glenohumeral, acromioclavicular, and sternoclavicular joints, together with the scapulothoracic gliding mechanism—and from the surrounding musculature each contributing to the full arc of upper limb movement (Figure 1). Passive stability is provided primarily by the glenohumeral capsule and its associated ligaments, while dynamic stability relies on the rotator cuff muscles—the supraspinatus, infraspinatus, teres minor, and subscapularis (Marieb et al., 2000; Standring, 2016).

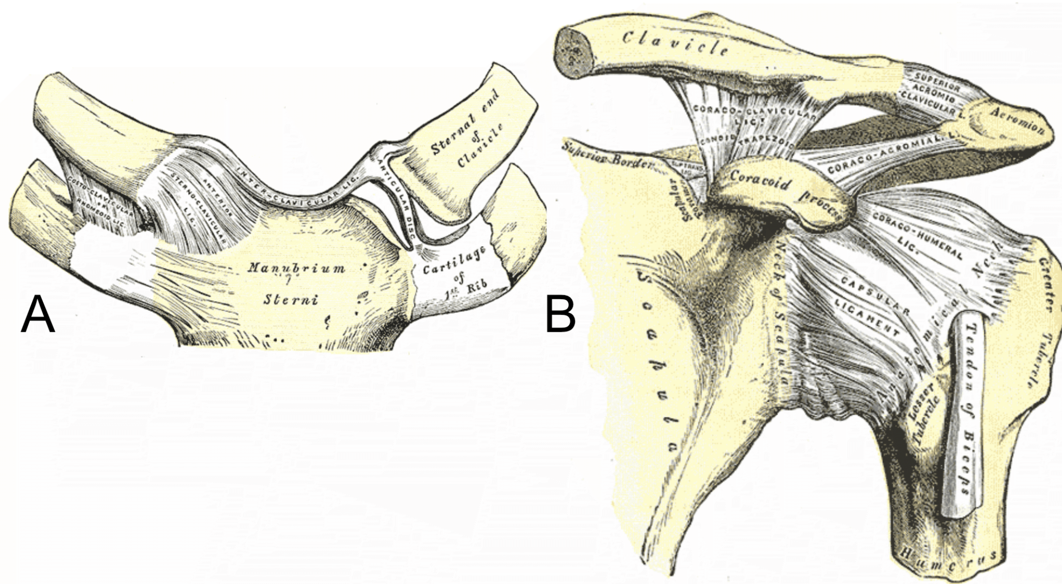

Figure 1: Shoulder joints. (A) Anterior view of the sternoclavicular articulation, with the right joint opened to expose the articular disc. (B) Acromioclavicular and glenohumeral joint and ligaments. Reprinted from (Gray, 1918).

2.2 The clavicle

The clavicles, also called collarbones, are curved S-shaped bones (Figure 2). The medial end presents an anterior convexity, constituting approximately two-thirds of the bone length, while the lateral end presents a posterior convexity. Medially, the clavicle articulates with the manubrium of the sternum at the sternoclavicular joint. Laterally, it articulates with the

acromion of the scapula at the acromioclavicular joint, a plane synovial joint stabilized by the acromioclavicular and coracoclavicular ligaments (Figure1B). Functionally, the clavicle acts as a stiff beam that transmits forces between the upper limb and the thorax, maintaining the lateral position of the shoulder relative to the trunk. It provides attachment sites for three major muscles: the deltoid and trapezius attach along the superior surface of the lateral third, while the pectoralis major originates from the anterior surface of the medial half.

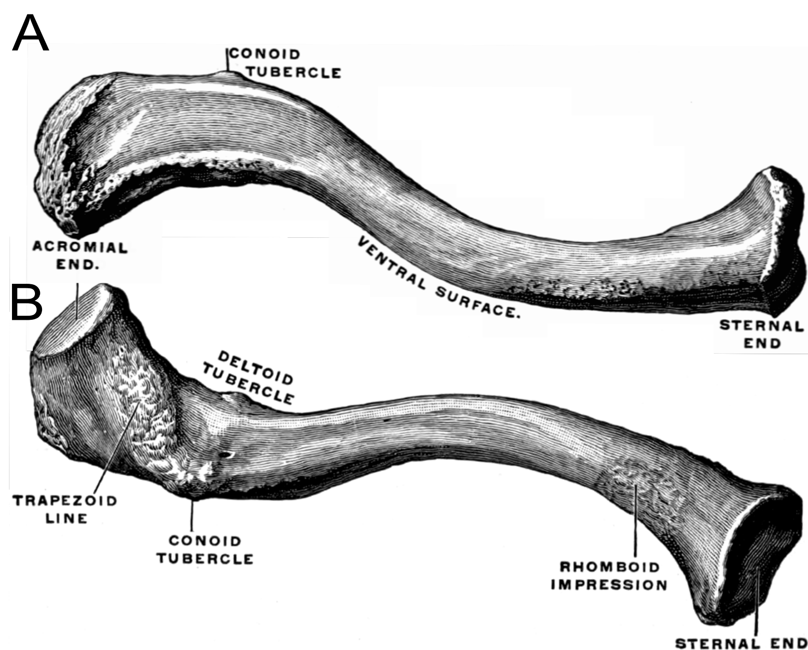

Figure 2: A) Superior and B) inferior view of the right clavicle adapted from (Gerrish, 1902).

2.3 Clavicle fracture injury mechanism

Clavicle fractures are most commonly associated with a direct impact to the lateral shoulder. In a clinical study by Stanley et al. (1988) —including 150 patients that sustained a clavicle fracture—94% of those injuries resulted from a direct blow to the shoulder, whereas only 6% followed a fall on the outstretched hand. Stanley et al. (1988) argued that compressive loading transmitted from the acromion is a more plausible fracture mechanism than pure bending or torsion, given that the clavicle retains mobility at the sternoclavicular joint and can rotate about its longitudinal axis. Two principal load transmission pathways through the shoulder girdle have been identified as potential fracture mechanisms by Scarlat et al. (1999): a medial-lateral path through the acromioclavicular joint, the clavicle, and sternoclavicular joint, and a posterior–inferior path through the glenohumeral joint, scapula, and scapulothoracic articulation.

Robinson (1998) reported that, in young adults, clavicle fractures were commonly associated with sports or road-traffic trauma and were predominantly located in the diaphysis (middle-third), whereas fractures of the lateral fifth were more frequent after simple falls in older individuals. Similarly, Postacchini et al. (2002) reported that road accidents and sports were the leading causes of clavicle fractures. Around 81% of the fractures were located in the middle third, and low-energy falls were more common in children and older adults. Together, these

observations indicate that clavicle fracture mechanisms depend not only on impact direction and the load transmission through the shoulder girdle, but also on age-related differences in exposure, leading to variability in the fracture location.

Understanding fall kinematics is essential for characterizing the loading conditions that lead to shoulder injuries in single-bicycle crashes. Video analyses of real-world cyclist falls have identified several common kinematic patterns, including lateral falls and forward ejections over the handlebars (Gildea et al., 2024). The cyclist's protective response—particularly whether and how the arms are used to brace for impact—significantly influences which body region sustains the primary ground contact (Gildea et al., 2024). When bracing is absent or insufficient, the shoulder takes the direct impact; epidemiological data indicates that approximately 90% of shoulder injuries in bicycle falls result from such direct ground contact (Stigson et al., 2014).

Mountain biking presents a distinct injury profile compared to urban commuter cycling, however the shoulder girdle is one of the most frequently affected region, with clavicle fractures being the most common skeletal injury (Aitken et al., 2011; Bigdon et al., 2022; Saragaglia et al., 2022; Bonte et al., 2025). Bonte et al. (2025) linked these injuries to specific crash kinematics, showing that forward over-the-bars falls—the most frequent scenario (55%)—combined with tumbling upon ground contact are specifically associated with shoulder injuries. Despite the widespread use of upper body protective equipment among mountain bikers, shoulder injuries remain prevalent (Saragaglia et al., 2022).

In contrast, in vehicle–cyclist collisions, the injury mechanism varies. The contact with the vehicle bonnet or windscreen can generate various loading patterns associated with soft tissue injuries, e.g. dislocations, and clavicle or rib fractures (Schick et al., 2022).

2.4 Finite element human body models

Finite Element Human Body Models (FE-HBMs) are valuable tools in injury biomechanics, enabling prediction of how bones, organs, and connective tissues respond to external loading. By using medical imaging, human anatomy and tissue-level material properties can be represented in computational detail (Gayzik et al., 2011), allowing internal stresses and strains to be evaluated under simulated impact conditions.

A key advantage of FE-HBMs over anthropomorphic test devices is their capacity to incorporate both geometric and material variability (Larsson et al., 2022). In practice, however, state-of-the-art models are typically defined to represent a small population of individuals, such as an average male or female subject, a small female or a large male, characterized by global anthropometric parameters—age, stature, and Body Mass Index (BMI)—as well as detailed anatomical geometry of bone, muscle, and soft tissue structures. The geometries of widely used models such as the GHBMC and THUMS, for example, are derived from three-dimensional medical imaging of individuals whose body dimensions are representative of this small population of individuals (Shigeta et al., 2009; Gayzik et al., 2011). While a chosen subject is considered average by evaluations on global measurements (like stature and body mass), the tissue geometry might vary significantly from that of the true average (Brynskog et al., 2021; Robinson et al., 2024), highlighting the limitation of applying a single-subject model to a

diverse population. Efforts to incorporate more generalized geometric representations have been undertaken in different models. For example, in the SAFER HBM, targeted updates have addressed the ribcage and sternum (Iraeus et al., 2019), and the pelvis (Brynskog et al., 2021). These parametric and population-informed approaches represent a methodological step toward models capable of predicting injury risk across a broader range of body sizes and compositions (Iraeus et al., 2019; Larsson et al., 2019; Larsson et al., 2022; Larsson et al., 2023; Larsson et al., 2024; Brynskog et al., 2025).

SAFER HBM shoulder

In the SAFER HBM v.12, the FE models of the scapula, clavicle, and humerus were developed from an average-sized female geometry from Gayzik et al. (2011), scaled to match an average sized male. Cortical bone is represented by a single layer of solid elements, except for the humeral shaft, where the cortical wall is anatomically thicker (Iraeus et al., 2024).

The kinematics and kinetics of this model have previously been validated (Iraeus et al. 2024) for three-point bending and axial loading of the clavicle (Zhang et al., 2014), of the humerus (Kemper et al., 2005), of the complete upper arm (Kemper et al., 2005), and lateral compression of the upper arm.

VIVA+ HBM shoulder

The VIVA+ HBM is an open-source line-up of HBMs developed to enable sex-specific injury evaluation in vehicle safety (John et al., 2022). In the shoulder region, the FE models of the clavicle, scapula, and humerus were derived from Gayzik et al. (2011). Cortical bone is modelled using shell elements and trabecular bone using solid elements, both with isotropic elasto-plastic material properties. The shoulder joints are currently simplified and modelled as spherical joints. Shoulder kinematics and kinetics have been validated against lateral impact experiments by Compigne et al. (2004), where the VIVA+ v. 1.1.0 model showed a stiffer response compared to experimental data (John et al., 2022).

GHBMC shoulder

The Global Human Body Models Consortium (GHBMC M50) is a detailed 50th percentile male HBM developed from CT and MRI data of a living 26-year-old male subject (Gayzik et al., 2011). Geometrical and material updates on the clavicle were performed by Li et al. (2013). The bones of the upper extremity, e.g. the clavicle and humerus, are modelled using hexahedral solid elements for trabecular bone and quadrilateral shell elements for cortical bone (Gayzik et al., 2012). In its original configuration, the GHBMC M50 showed good bio-fidelity for shoulder impact force but under-predicted shoulder deflection in lateral impact when validated against Lessley et al. (2010). Park et al. (2016) introduced modifications to the muscle material properties, the acromioclavicular joint definition, and the pectoralis major attachment region, improving peak shoulder deflection predictions to within 10% of experimental PMHS data and achieving good correlation in three-dimensional scapula kinematics (Park et al., 2016).

THUMS HBM shoulder

The Total Human Model for Safety (THUMS) is a detailed HBM developed by Toyota and Toyota Central R&D Labs. The shoulder model, first described by Iwamoto et al. (2000), was based on anatomical geometry from Viewpoint Data Lab, with the shoulder complex modelled as four articulated joints—the glenohumeral, acromioclavicular, sternoclavicular, and scapulothoracic joints—including major ligaments and muscles. From Version 4 onward, body-part geometries were refined using high-precision CT scan data (Iwamoto et al., 2015). The shoulder model was validated against cadaver test data from (Bendjellal et al., 1984; Cavanaugh et al., 1993; Bolte et al., 2003; Compigne et al., 2004; Ono et al., 2005). The humerus was validated in three-point bending and soft tissue compression tests against Kemper et al. (2005).

2.5 Principal component analysis for morphometric modelling

Clavicle morphology and cortical bone thickness variability were analyzed using Principal Component Analysis (PCA). PCA was applied to a clavicle mesh—represented by Cartesian coordinates—and their respective cortical bone thickness values associate to each node. In this framework, each specimen was described by a p-vector containing the x-, y-, z-, and t-coordinates. The resulting data matrix $\mathbf{X} \in \mathbb{R}^{n \times p}$contained n specimens and p coordinate variables (Jolliffe, 2002). PCA was used to identify the dominant modes of geometric and cortical bone thickness variations across specimens and to reduce the dimensionality of the coordinate data while preserving the major variance structure.

PCA was then performed on the centered data matrix $\mathbf{X}^*$, either through the covariance matrix or, equivalently, through singular value decomposition (SVD). In the SVD formulation,

$$\mathbf{X}^* = \mathbf{ULA}^T \tag{1}$$

where $\mathbf{U}$ and $\mathbf{A}$ are orthonormal matrices and $\mathbf{L}$ is a diagonal matrix containing singular values in descending order (Jolliffe, 2002). The principal component directions were obtained from the columns of $\mathbf{A}$, and the variance explained by each principal component (PC) was proportional to the corresponding squared singular value.

The PCs define orthogonal directions in the coordinate space along which the sample variance is maximized. Each specimen was assigned a PC score by projection onto the PC directions. The first few PCs describe the dominant patterns of variability in the dataset, whereas higher-order PCs capture progressively smaller fractions of the total variance.

Dimensionality reduction was achieved by retaining only a subset of PCs that accounted for the total variance. Clavicle morphology changes associated with individual PCs were visualized by reconstructing mesh configurations at selected score levels relative to the mean shape. For PC k, a reconstructed configuration was computed as

$$\mathbf{x}_k(z) = \boldsymbol{\mu} + z\sigma_k\mathbf{a}_k \tag{2}$$

where $\boldsymbol{\mu}$ is the mean shape, $\sigma_k$is the Standard Deviation of the scores for PC k, $\mathbf{a}_k$is the corresponding loading vector, and z specifies the score level, e.g. ± 2 SD (Lundin et al., 2024).

PCA was selected since the method provides a compact description of global geometric variability in high-dimensional coordinate data and is well established in geometric morphometrics and statistical shape modelling (Heimann et al., 2009). A limitation of PCA is that each component is estimated from the covariance structure of the full dataset. As a result, spatially localized variation can be distributed across several PCs, which may complicate anatomical interpretation of the changes. In the present work, PCA was therefore used primarily to quantify and visualize the dominant global patterns of geometric and cortical bone thickness variation of the clavicle.

2.6 Multivariate linear regression

The relationship between the outcome variable and the predictor variables was investigated using multivariate linear regression. In particular, the response was identified in each individual PC score, and the predictors were sex, stature, age and BMI of the individuals.

In the present work, the method was formulated for one response variable and multiple predictors. Let y_i denote the response for observation i, and let $x_{i1}, x_{i2}, \dots, x_{ip}$denote the corresponding predictor values. The regression model was written as

$$y_i = \beta_0 + \sum_{j=1}^{p} \beta_j \, x_{ij} + \sum_{j=1}^{p} \gamma_j \, x_{kj} + \sum_{j=1}^{p} \delta_j \, x_{ij} x_{kj} + \varepsilon_i \tag{3}$$

where $\beta_0$is the intercept, β_j and $\gamma_j$are the regression coefficients associated with the predictors, δ_j their interaction effect, and ε_i is the residual error term. The coefficients were estimated by ordinary least squares, i.e., by minimizing the sum of squared residuals between the observed and predicted responses (Gareth et al., 2013).

The fitted model was used to quantify the association between the predictors and the response and to identify predictors that contributed to the explained variation in the outcome. Statistical significance of the estimated regression coefficients was evaluated by hypothesis testing under the null hypothesis $H_0\colon \beta_j = 0$. For each coefficient, a t-statistic and corresponding p-value were computed. A predictor was considered to contribute significantly to the model when the corresponding p-value was below the predefined significance level of 0.05.

The validity of the linear regression model was assessed by evaluating the assumptions of linearity, homoscedasticity, and normality of residuals. If interaction terms were included and found to be significant, the regression model was extended accordingly and the main effect included.

To identify and select a set of predictors, best subset selection was used. In this procedure, regression models were fitted for all combinations of the available predictors, and the resulting models were compared using predefined selection criteria. The selection criteria were based on Akaike information criterion (AIC), and significant F-statistics. The selected model was therefore not only required to provide good fit to the data, but also to avoid inclusion of predictors that contributed limited additional information (Gareth et al., 2013).

Model performance was evaluated from the proportion of variance explained by the regression model, expressed as the coefficient of determination,

$$R^2 = 1 - \frac{SS_{\mathrm{res}}}{SS_{\mathrm{tot}}} \tag{4}$$

where SS_{res} is the residual sum of squares and $SS_{\mathrm{tot}}$is the total sum of squares.

In addition, the standard error of the regression was used to include and produce synthetic clavicle samples based on the statistical shape model of the typical deviation between observed and predicted values,

$$SE = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{n - p - 1}} \tag{5}$$

where n is the number of observations, p is the number of predictors, y_i is the observed response, and $\hat{y}_i$ is the model prediction.

CHAPTER 3

Methodology

This section outlines the methods employed to address the two study objectives and connects them to the theoretical background presented in the background section. The first part describes the Statistical Shape Model (SSM) framework used to characterize population-level variability in clavicle geometry and cortical bone thickness in Paper A (Objective 1). The second part describes the FE modelling and the validation strategy used to evaluate the mechanical response of the clavicle under impact-relevant loading conditions (Objective 2). Full methodological details are provided in Paper A (Objective 1) and Paper B (Objective 2).

3.1 Statistical shape modelling

Statistical shape modelling is a framework for representing and analyzing population-level variation in bone morphology using sets of anatomically corresponding geometric representations. The bone morphology is encoded as a 3D set of coordinates value, typically segmented from CT imaging data and represented through surface meshes.

The construction of the SSM followed several steps. The process began with a cohort of segmented bone geometries. A registration procedure was then applied to map landmarks across all specimens, ensuring that each shape was represented in a common coordinate system. A template geometry was selected, and mesh morphing was performed onto all subject-specific geometries through landmark correspondences, imposing a consistent mesh topology across the entire cohort. Procrustes analysis was used to align the geometries through rigid registration (i.e. rotation and translation).

In this thesis, because both geometry and cortical bone thickness were included in the model, normalization was necessary to prevent the larger-magnitude coordinate values from dominating the thickness values during the subsequent analysis. Each feature set—cortical bone thickness values and 3D surface coordinates—were normalized separately by mean-centering and scaling by the norm of the Standard Deviation (SD) of that feature.

Using PCA, the resulting model decomposes variability encoded in the geometry into a mean shape and a set of orthogonal modes of variation—the Principal Components—each mode describing an independent pattern of geometric change present in the population under study. The associated mode coefficients provide a compact parameterization of individual bone instances relative to the population mean.

Statistical shape models (SSM) are used to study anatomical variability and for instance to identify shape features associated with biological factors. In this study, multivariate linear

regression was used to identify trends and predict samples based between the variation and the anthropometric factors (sex, stature, BMI and age).

3.2 FE clavicle model

From the SSM and linear regression models, a morphable baseline clavicle FE model was developed. Meshing was performed using a hexa-block design in ANSA v24.1.2 (Cadence, San Jose, USA). The mesh was generated with a target shell element edge length of 2 mm and aimed at fulfilling the criteria by Burkhart et al. (2013).

The cortical bone was represented by fully integrated quadrilateral shell elements placed on the outer bone surface, with shell thickness projected inward. The trabecular bone was discretized using under-integrated hexahedral solid elements. An isotropic elasto-plastic constitutive model was assigned to both cortical and trabecular bone. Cortical bone properties were derived from wet humeral cortical bone data reported by Nahum et al. (2012), with a Young's modulus of 17.2 GPa and a yield stress of 123 MPa. Trabecular bone properties were based on indentation tests of the distal humerus by Dunham et al. (2005), with a Young's modulus of 0.31 GPa and a yield stress of 4.4 MPa. Humeral bone data were adopted as surrogate values given the lack of published material properties specific to clavicular bone tissue.

Two clavicle models were generated by morphing the baseline to the predicted geometries and cortical bone thickness distributions for a 50F (45 years, 162 cm, 24 kg/m²) and a 50M (45 years, 175 cm, 25 kg/m²); shown in Figure 3. These anthropometric targets were selected because they represent the reference population most commonly used in the injury biomechanics field (Schneider, 1983), providing a basis for contextualizing the validation results.

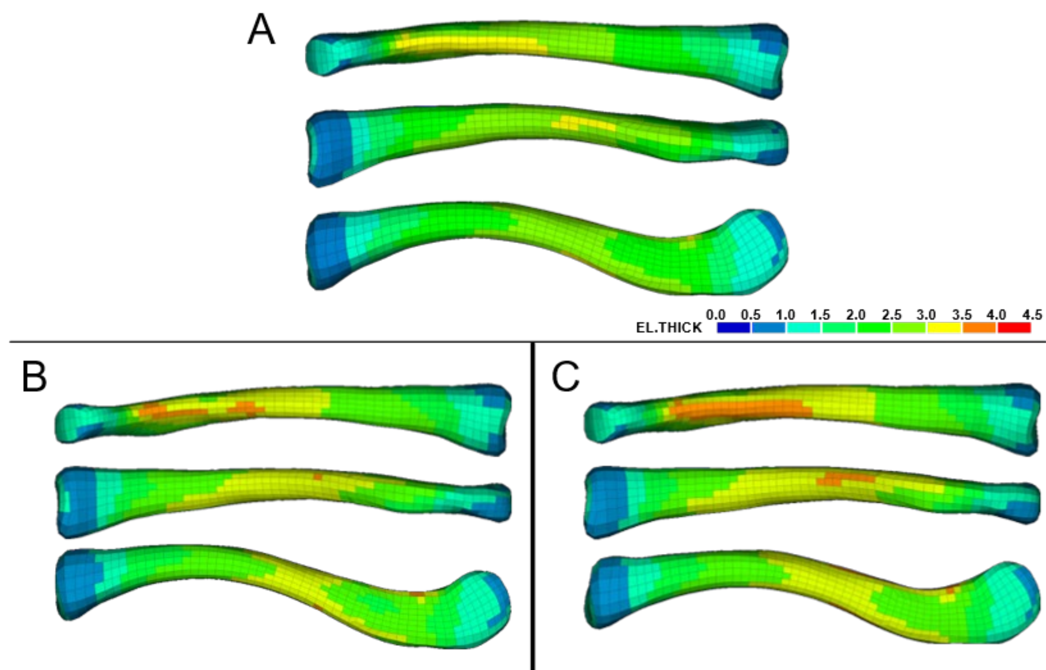

Figure 3: Right clavicle geometry and cortical bone thickness distribution (colormap, mm) for (A) the average model, (B) the 50F model, and (C) the 50M model. For visualization purposes, size differences between models are not preserved. Views are shown from top to bottom: posterior, anterior and superior.

3.3 FE clavicle validation

For the FE clavicle validation, experimental test series were selected from the literature based on their relevance to clavicle loading under impact. Two loading conditions were identified as relevant: bending (Kemper et al., 2009; Spiegl et al., 2014; Zhang et al., 2014) and axial compression (Zhang et al., 2014).

The response of the two clavicles (50F and 50M) was compared to the experiment responses corridor developed using ARCGen (Hartlen et al., 2022).

Next, the full geometrical and cortical bone thickness variability included in the SSM was evaluated with the same loading conditions. The cortical bone thickness and geometry were sampled from the residual distribution of the statistical shape model to generate synthetic clavicles. This variability was evaluated by comparing the corridor width between the synthetic sample and the experimental corridor at a determined relevant point in the curve (e.g. max peak force or deflection).

CHAPTER 4

Summary of papers

4.1 Paper A

Chiara R. Fichera, Samyuktha Neeluru, Johan Davidsson, Jonas Östh, Jingwen Hu, Johan Iraeus
Investigating Clavicle Morphology: A Statistical Model of Clavicular Cortical Bone Thickness and Geometry
Under review after conditional acceptance.

The aim of Paper A was to quantify inter-individual variability in clavicle geometry and cortical bone thickness and to investigate how the observed anatomical variation was associated with sex, age, stature, and Body Mass Index (BMI).

Right clavicles were segmented from 99 clinical CT scans, of which two were excluded due to atypical morphology, yielding a final sample of 97 clavicles (42 males and 55 females). Cortical bone mapping was performed to estimate subject-specific cortical thickness. The clavicles were pre-aligned using a rigid transformation based on four landmarks, followed by placement of 110 pseudo-landmarks to describe shaft curvature and the medial and lateral ends. Generalized Procrustes analysis was then applied to align all specimens to a common reference frame. A high-resolution template mesh comprising 18,134 nodes was morphed to each subject geometry using thin-plate spline radial basis function interpolation, after which subject-specific cortical bone thickness values were mapped onto the morphed meshes. PCA was performed on the combined matrix of nodal coordinates and cortical thickness values to construct the SSM. The resulting PC scores were related to sex, age, stature, BMI, and first-order interaction terms using multivariate linear regression. For each PC, model selection was performed via best subset selection with 10-fold cross-validation, using the Akaike Information Criterion (AIC) as the selection criterion.

The first three PCs explained 23.0%, 19.7%, and 3.9% of the total variance, respectively, accounting for 46.6% cumulatively. In total, 23 PCs were required to capture 80% of the variance. PC1 primarily described variation from a short and thin clavicle to a long and thick clavicle, PC2 described variation from a long and thin clavicle to a short and thick clavicle, and PC3 mainly represented variation in shaft curvature in the frontal and horizontal planes. Eleven of the 23 retained PCs showed significant associations with one or more demographic predictors. Sex and stature were the strongest contributors, with the highest coefficient of determination observed for PC1 (R^2 = 0.50). The overall morphometric regression model explained 25% of the total clavicle variation represented by the SSM (R^2 = 0.25). Regression-based predictions indicated that sex and stature were primarily associated with differences in

clavicle size and cross-sectional area, with males and taller individuals having, on average, longer and bigger clavicles. Stature was additionally associated with localized increases in cortical thickness, particularly in the region of the conoid tubercle and the deltoid attachment site. Age and BMI were associated with comparatively small differences in geometry and cortical thickness distribution.

Conclusions from this study were:

- Clavicle morphology exhibits substantial inter-individual variability in both geometry and cortical bone thickness.
- The first three principal components primarily described differences in clavicle size, cortical thickness distribution, and shaft curvature.
- Sex and stature explained part of the observed variation, but the investigated demographic variables account for only a limited proportion of the total variability.
- Sampling the full principal component space may therefore be more suitable than only considering the variability represented by the regression for generating representative clavicle morphologies in future biomechanical and clinical applications.

4.2 Paper B

Chiara R. Fichera, Johan Davidsson, Jonas Östh, Johan Iraeus
Population Variance in Clavicle Response to Bending and Axial Compressive Loading
Draft Manuscript

Building on the statistical shape model developed in Paper A, Paper B aimed to develop and evaluate a morphable clavicle FE framework. The framework incorporates inter-individual variability in geometry and cortical thickness and quantifies its effect on mechanical response under bending and axial compression loading.

A population-based FE template model of the right clavicle was developed using the SSM from Paper A as its geometric and morphological basis. The morphable template mesh was morphed to generate two models targeting a 50F and a 50M anthropometry, which were then validated against experimental test data.

Model validation was performed by reproducing published clavicle test series under axial compression and bending. The reproduced load cases were based on experiments reported by Zhang et al. (2014) (axial compression and three-point bending), Kemper et al. (2009) (three-point bending at 0° and 45° degrees), and Spiegl et al. (2014) (bending of the distal end). Simulated force–displacement responses were compared against the published experimental data and response corridors generated using ARCGen. The baselines differed in size and stiffness, with the male baseline producing higher peak loads than the female baseline across configurations. The model seemed to capture the peak force in three out of four set up. In addition, the baseline geometries were compared with published morphometric data, including clavicle length, diameters, and cortical area.

To assess population variability, a synthetic clavicle population was generated by sampling residual variability SSM of Paper A. Across all test series, the synthetic population generated a measurable spread in force–displacement response, demonstrating that variation in geometry and cortical bone thickness alone can reproduce a substantial portion of the inter-specimen variability observed in the published experimental data. Specifically, the synthetic sample captured 60% of the variability in Zhang et al. (2014) test series and more than 100% of the variability in Kemper et al. (2009) and Spiegl et al. (2014).

Conclusions from this study were:

- A SSM-informed morphable FE clavicle model was developed to study population-level response in bending and compression.
- Sampling geometric and cortical-thickness variability generated response corridors that captured the majority of the experimental spread in several configurations.
- Main limitations were uncertainty in reconstruction of published boundary conditions (limited specimen metadata) and constant material-property.

CHAPTER 5

Discussion

In this Licentiate thesis, steps were taken toward incorporating clavicle population variability and evaluating its influence on mechanical response, with the goal of enabling injury risk evaluation in simulated bicycle crash scenarios. The two objectives fulfilled in this Licentiate thesis are in line with the main objective of my Ph.D. project, which is to develop methods/tools enabling shoulder-related injury risk evaluation. In Paper A, clavicle shape and cortical bone thickness were analyzed through PCA, and a SSM capable of predicting clavicle morphology and cortical bone thickness was developed. The SSM was then linked to the anthropometric variables through multivariate linear regression. In Paper B, a generic morphable FE-model of the clavicle was developed, and synthetic clavicles based on shape and cortical bone thickness variations, were validated for axial compression and bending.

5.1 Population variance in clavicle shape and cortical bone thickness

Previous studies have characterized aspects of clavicle geometry variation (Andermahr et al., 2007; Daruwalla et al., 2010b; Daruwalla et al., 2010a; van Tongel et al., 2012; Bernat et al., 2014; Lambert et al., 2016; Vancleef et al., 2019). One study has mapped the endocortical and periosteal surfaces of the clavicle (Lu et al., 2013), but the sample was rather small with only 19 subjects. The present work extends these efforts by developing a combined geometry and cortical bone thickness SSM from a cohort of 97 specimens, enabling simultaneous characterization of both sources of morphological variability.

A methodological consideration inherent to the developed combined model is that surface coordinates and cortical thickness values differ substantially in magnitude, which could bias the PCA toward the geometrically larger feature set. This was addressed through normalization, ensuring that both geometry and thickness contributed with comparable weight. The validity of this choice was supported empirically by the finding that the first five PCs each captured variation in both geometry and cortical thickness simultaneously.

An inherent limitation of PCA is that it defines orthogonal modes of variation defined globally across the entire bone surface, which limits its sensitivity to spatially localized morphological differences. This is, for example, why it is difficult to explain and describe what each mode encodes, as variation may be distributed across several components. For the purposes of injury biomechanics, the primary objective is not anatomical interpretation of individual modes, but rather the generation of realistic morphological instances that span the population distribution.

While a causal relationship between geometry and cortical thickness distribution was not formally tested in Paper A, the observed co-variation provides a biomechanically plausible basis for treating them within a unified model, and their joint influence on the mechanical response is of interest (Morgan et al., 2021). In bone mechanics, it has been proven that mechanical adaptations interact with bone cells promoting bone modelling and remodeling processes, that bone grows or adapts where the stresses are the highest. Thus, bone shape is linked to mechanical loading (Robling et al., 2006).

The regression results indicated that demographic variables—sex, stature, BMI, and age—collectively explained only 25% of the total morphological variability captured by the SSM, with sex and stature as the major contributors. This finding has an important implication: gross anthropometric descriptors are weak surrogates for clavicle morphology. This is consistent with the broader understanding that bone geometry and cortical bone thickness are influenced by mechanical loading histories, hormones, genetic factors, and bone remodeling dynamics that operate throughout the lifespan at rates that vary between individuals (Santos et al., 2017). These intrinsic biological factors cannot be captured by population-level demographic descriptors in the way that directly measurable variables such as sex and stature can. Thus, the rationale for using the residuals from the regression models—rather than regression-predicted values alone—and to sample the full morphological variability of the population in Paper B.

The CT dataset used in Paper A comprised 97 right clavicles from a US clinical cohort. A comparison of clavicle length and cortical bone area with literature (Andermahr et al., 2007; Lu et al., 2013) confirmed that the sample is comparative to other populations. However, the dataset has limited coverage at the extremes of the demographic distributions, i.e. very young or very old, severely obese, or underweight individuals are underrepresented, which constrains the reliability of regression-based predictions for those sub-populations. This is particularly relevant when comparing predictions against Post-Mortem Human Subject (PMHS) datasets, which are typically skewed toward older individuals. The SSM was not designed to extrapolate beyond the range of the training data, and predictions for older subjects—where age-related changes such as osteoporosis can alter cortical bone distribution—should be interpreted with caution, since the model is unlikely to capture these patterns reliably.

5.2 Clavicle response in different loading configurations

Paper B demonstrated that variability in clavicle geometry—encoded in differences in curvature, length, cross-sectional dimensions—and cortical bone thickness alters both the stiffness and load-carrying capacity of the bone. This finding indicates that clavicle mechanical response varies considerably across individuals and cannot be treated as a single deterministic outcome. An important related question is how much of the inter-specimen variability observed in published experiments reflects true anatomical differences, as opposed to variability introduced by the experimental setup, boundary condition uncertainty, or measurement noise. This distinction matters for validation: a model that reproduces only the mean experimental response may serve as a plausible reference case, but it is not sufficient for population-level injury tolerance assessment. For fracture-related applications, models must capture both the average response and its dispersion, as injury risk assessment based on a single representative geometry will fail to account for the variability relevant to predicting fracture across individuals.

Within this context, the 50th-percentile male and female models serve primarily as reference cases—useful for establishing whether simulated response levels are plausible, and for comparison with experimental corridors. The population-based sampling framework in Paper B extends beyond these reference cases by quantifying how anatomically realistic variation influences force–displacement response, thereby enabling the assessment of injury tolerance distributions across individuals.

The interpretation of the population results in this work is limited to changes in geometry and cortical bone thickness. Material properties were held constant, so the present framework therefore cannot determine additional variability arising from inter-individual differences in bone material behavior, age-related changes in bone quality, or other specimen-specific material factors. The current results support the conclusion that anatomy explains a substantial lower-bound component of clavicle response variability, but not the full variability relevant to mechanical response. The main contribution of the study is therefore the quantification of anatomical variability as one source of mechanical variation, while the relative contribution of material factors remains unresolved.

Finally, these findings point toward a broader methodological consideration for the field. Experimental clavicle test series are typically designed and reported without explicit documentation of specimen morphology, typically reporting only information such as sex, age or clavicle length. Given the demonstrated sensitivity of the mechanical response to geometry and cortical thickness, there is a case for calling for more detailed specimen morphology when reporting PMHS test series. The combination of morphological documentation with simulation-based variability analysis would provide a broader and more general overview of the mechanical response, ultimately improving the quality of the experimental data used to develop and validate injury criteria.

5.3 Broader considerations

Current state-of-the-art HBMs—including GHBMC, THUMS, VIVA+, and SAFER HBM—are typically developed around a small number of representative geometries defined by global anthropometric parameters such as sex, stature, and BMI. The present results suggest that this percentile-based approach inherently leaves a large proportion of anatomically relevant variability unrepresented. Similar observations have been reported for other body regions—e.g. the ribcage (Larsson et al., 2023), pelvis (Brynskog et al., 2021), femur (Klein et al., 2015), head (Wei et al., 2022)—suggesting that this limitation is not specific to the clavicle bone but may reflect a more general characteristic of skeletal structures. These findings collectively support a shift toward population-based probabilistic frameworks, in which injury risk is evaluated not for a single representative geometry but across a distribution of anatomically realistic morphologies sampled from statistical shape models (Larsson et al., 2023; Hu et al., 2026).

The validation presented in this thesis was performed at the component level, with the clavicle loaded in isolation under controlled boundary conditions. In a real bicycle fall, however, the clavicle is not loaded directly—forces are transmitted through the shoulder complex and mediated by the scapula, the acromioclavicular and sternoclavicular joints, ligaments, muscles, and surrounding soft tissues. The path from component-level response to whole-body injury

prediction therefore introduces additional sources of variability and uncertainty that are not captured in the present work.

The absence of shoulder-protective equipment for commuter cyclists represents a gap in current Personal Protective Equipment (PPE) for cyclists. The large inter-individual variability in clavicle mechanical response demonstrated in this thesis indicates that protective devices cannot be assessed against a single representative loading threshold. Current certification practices—e.g. for head protection—such as helmet testing using standardized headforms (Bland et al., 2018; Halldin et al., 2024)—illustrate both the value and the limitation of physical evaluations. These test methods provide repeatable and independently verifiable results, but used fixed geometry. The findings of this thesis suggest that coupling physical certification testing with simulation-based parametric studies across morphologically diverse HBMs would enable a more comprehensive evaluation of how well a given countermeasure protects the users.

It is important, however, to place the role of PPE within the broader landscape of cycling safety. Unlike motor vehicle occupants, cyclists have no vehicle structure, deformation zones, or restraint systems to absorb and distribute crash energy. Passive safety in the form of wearable PPE is effectively the only crashworthiness countermeasure available at the point of impact. This makes the development and evaluation of such equipment a necessary component of any comprehensive strategy towards cycling safety. Infrastructure measures—such as improved surface maintenance, removal of curbstone hazards, and better drainage to reduce slippery conditions—directly address the causes of the single-bicycle crashes that account for the majority of cyclist injuries (Rizzi et al., 2013; Eriksson et al., 2022). Similarly, emerging vehicle-integrated technologies, such as anti-lock braking systems or improved tire designs may reduce loss-of-control events before a fall occurs (Corno et al., 2018; Jannah et al., 2025). From a public health perspective, crash prevention will always be more efficient than injury mitigation, and the hierarchy of controls would place elimination of the hazard above personal protection. The methods and tools developed in this thesis are therefore best contextualized as one layer in a multi-layered approach to cycling safety: they enable the evidence-based evaluation of protective equipment for crashes that do occur, while recognizing that reducing the frequency and severity of those crashes through infrastructure, vehicle technology, and policy remains the most effective long-term strategy for reducing the overall burden of cycling injuries.

CHAPTER 6

Conclusions

The overarching objective of the Ph.D. project is to develop methods and tools that enable shoulder-related injury risk evaluation for a population of bicyclists. The work presented in this licentiate thesis has advanced this goal through three contributions. The steps include:

- A statistical shape model capable of describing clavicle shape and cortical bone thickness based on anthropometric variables (sex, age, stature, BMI).
- A new generic morphable clavicle FE-model that facilitates evaluation based on population shape and cortical bone thickness.
- Validation of the clavicle models and quantification of population variability in simulated mechanical response under bending and axial compression.

Based on the results from both appended papers, it can be concluded that variability in clavicle morphology and cortical bone thickness is high, and that such variation measurably affects the simulated mechanical response. Furthermore, anthropometric variables (sex, age, stature, BMI) were found to capture only a limited proportion of the total cohort variability. Ultimately, integrating knowledge of population variability into safety evaluations has the potential to contribute to more robust protective systems and a reduced risk of shoulder injuries in real-world bicycle accidents.

CHAPTER 7

Future work

Beyond the scope of this licentiate thesis, the following objective of the Ph.D. project is the development of injury risk functions for shoulder injuries in bicycle crashes. Future research will focus on establishing an IRF for clavicle fractures (Objective 4).

Epidemiological evidence indicates that clavicle fractures are not only shoulder injuries associated with permanent medical impairment in cyclists; ligament damage—frequently leading to joint dislocations—constitute also a substantial share of the injury burden (Chillemi et al., 2013; Rizzi et al., 2013; Stigson et al., 2014). Future work will address explicit modelling of capsular structures, ligaments, and articular cartilage of the shoulder joints within the SAFER HBM (Objective 3), with the aim of developing strain-based injury risk functions for shoulder soft tissues (Objective 4). Finally, from a modelling perspective, the representation of stabilizing musculature in the shoulder girdle, needed to achieve physiologically realistic loading, constitutes an important direction for future development of the SAFER HBM shoulder model.

Extending the component-level validation presented here to full-scale bicycle crash simulations represents the next step toward population-level shoulder injury prediction and evaluation of injury risk curves. Full-body validation in bicyclist accident settings has proven challenging due to the numerous uncertainties affecting kinematics and injury outcomes (Klug et al., 2017; Trube et al., 2023). Several studies have used HBMs as vulnerable road user for accident reconstruction, demonstrating the potential of HBMs to reproduce injury patterns observed in real crashes (Paas et al., 2012; Lindgren, 2025; Lindgren et al., 2025). While demonstrating great potential in replicating event dynamics and reproducing observed injury patterns, these reconstructions are typically based on a small number of accidents, which limits the generalizability of their findings. The loading conditions and event dynamics arising during typical single-bicycle falls are currently not yet well characterized. Future work will need to combine real-world accident data, video-based fall reconstruction, and simulation to define representative shoulder-impact boundary conditions for cyclist falls. A complementary approach would be to use simulation-based parameter studies to investigate shoulder injury mechanisms—including the influence of impact orientation, fall velocity, and contact surface conditions—across a range of accident configurations, as was done for other body regions by (Larsson et al., 2023; Leledakis et al., 2023; Brynskog et al., 2024; Brynskog et al., 2025). This would enable identification of the loading modes most critical to shoulder injury and provide input conditions for population-level injury risk assessment and protection evaluation.

Current evaluation practices lack standardized methods or test protocols for assessing shoulder protection in bicyclists. Although previous studies (Koh et al., 2005; Fredriksson et al., 2014; Stigson et al., 2016; Carroll et al., 2025a; Carroll et al., 2025b; Fenini, 2025) have explored

concepts such as shoulder pads or wearable airbags, no standards exist to determine their effectiveness in a repeatable and comparable manner. This gap underscores the need for harmonized test methods and clearly defined performance criteria, based on boundary conditions and loading scenarios most representative of cyclist shoulder impacts. The final phase of the Ph.D. will therefore focus on developing physical test protocols for assessing PPE and countermeasures for shoulder injuries. This work will aim to translate simulation results and experimental data into repeatable procedures with defined boundary conditions and injury metrics suitable for standardization or consumer information testing.

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