THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY
IN
MACHINE AND VEHICLE SYSTEMS

Postural and Muscular Responses of Car Occupants under Pre-Crash Conditions

The biomechanics of pre-crash: in-vehicle experiments, data analysis, and statistical modeling

GHAZALEH GHAFFARI

Department of Mechanics and Maritime Sciences

CHALMERS UNIVERSITY OF TECHNOLOGY

Gothenburg, Sweden 2021

Postural and Muscular Responses of Car Occupants under Pre-Crash Conditions
The biomechanics of pre-crash: in-vehicle experiments, data analysis, and statistical modeling
GHAZALEH GHAFFARI
ISBN 978-91-7905-535-6

Doktorsavhandlingar vid Chalmers tekniska högskola
Ny serie nr 5002
ISSN 0346-718X

Department of Mechanics and Maritime Sciences
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-772 1000

Cover:
A volunteer seated in the test vehicle as a front-row passenger during a lane change maneuver

Chalmers Reproservice
Gothenburg, Sweden 2021

Postural and Muscular Responses of Car Occupants under Pre-Crash Conditions
The biomechanics of pre-crash: in-vehicle experiments, data analysis, and statistical modeling
GHAZALEH GHAFFARI
Department of Mechanics and Maritime Sciences
Chalmers University of Technology

Abstract

Advanced integrated safety technologies in modern cars such as collision avoidance intervention and pre-crash activated restraint systems require comprehensive research on how vehicle occupants respond to these systems. The aim of this thesis is to provide insights into car passengers' body kinematics and muscle activations in representative pre-crash circumstances with respect to two belt configurations (i.e., standard versus pre-pretensioner). Another objective is to explore the influence of occupants' individual characteristics — namely age, stature, and sex — on their body kinematics. A complementary objective is to provide validation data for human body models (HBMs).

A set of in-vehicle experiments was carried out in which front-row passengers were traveling at 73 km/h and subjected to autonomous lane changes and lane changes combined with braking, each with two belt configurations: standard and reversible pre-pretensioner belts. Volunteer muscle activations were measured by the surface electromyography (EMG) technique. Transformation of coordinates corresponding to several film targets attached to the head and upper torso was used to calculate the kinematics in 3-D. The volunteers' EMG and kinematics were processed, and the quantified kinematics were statistically explored using principal component analysis and linear mixed model.

Compared to the standard belt, pre-tensioning the seat belt prior to the maneuvers reduced lateral and forward displacements of the head and upper torso significantly. Seat belt pre-tensioning was also associated with earlier muscle activation onset and significantly lower activation amplitude for specific muscles. The influence of sex, stature, and their interaction on the head and upper torso kinematics were found statistically significant but accounted for a small amount of variance. A statistical model was developed which can predict head and upper torso kinematics of occupants with different stature and sex.

The data provided in this thesis can be used for further enhancement and validation of HBMs. Consequently, the design of integrated safety systems in modern cars can benefit from more biofidelic models representing a wide range of population more accurately. Further statistical investigations for other types of omnidirectional loading scenarios and, preferably with a larger and more diverse sample space, are required to establish more accurate statistical models that can be generalized to the whole population.

Keywords: EMG, evasive maneuvers, human body model, lane change, linear mixed model, pre-crash, pre-pretensioner belt, principal component analysis, vehicle occupant kinematics.

to the sound of my life, Ava

Acknowledgment

I would like to acknowledge the efforts of my academic supervisors. Special thanks to Johan Davidsson, for his continued help and support throughout my PhD studies. I had a long journey together with you, with many valleys and hills, and I learned a lot from you! Many thanks to Mats Svensson, for believing in me. Your guidance, respect, and encouragement were invaluable. I would also like to admire my examiner, Robert Thomson, for his irreplaceable care and leadership. You were more than an examiner! Also, thanks to all my colleagues at the Vehicle Safety Division and SAFER for creating a friendly and inspiring atmosphere. I will never forget our small chats, especially when it was very late in the evening and we were still working! Thanks, Jóna, Alexander, Jordanka, Eleonora, Thomas, Giulio, Selpi, and Pinar.

Finally, to my dear family, I am grateful for their endless love, sacrifices, and support. My parents who are always here for me no matter they live far away. You taught me how to be patient to achieve my goals. Thank you, Mom! A constant cheer from you makes me feel that there is nothing impossible in this world. My brother who always has some nice words to calm me down. I am lucky to have you! And my dear husband, Amin, who makes my life full of joy and beauty. You taught and helped me to overcome the difficulties throughout these years. I would not come this far without you! And a great thank to my lovely daughter, Ava. You came into my life in the last years of my PhD studies. Thank you darling for coping with my hard-working days. Your love makes my life meaningful. You are the reason for me to complete this challenging and exciting tour.

Ghazaleh Ghaffari
Gothenburg, Aug 2021

Funding

The work presented in this thesis was funded by FFI-Strategic Vehicle Research and Innovation, by Vinnova, the Swedish Energy Agency, the Swedish Transport Administration, and the Swedish Vehicle Industry in the project Active human body models for virtual occupant response- step 3. The project has been carried out at SAFER- Vehicle and Traffic Safety Centre at Chalmers University of Technology, Sweden. Project partners were Chalmers, Autoliv Research AB, and Volvo Cars. A part of the work presented in this thesis was funded by the European Union Horizon 2020 Research and Innovation programme project, Future Occupant Safety for Crashes in Cars, OSCCAR, under Grant Agreement No 768947. They are all appreciated.

Thesis

This thesis is based on the work contained in the following papers, referred to by A, B, C and D in the text:

Paper A Ghaffari G, Brolin K, Bråse D, Pipkorn B, Svanberg B, Jakobsson L, and Davidsson J (2018) 'Passenger kinematics in Lane change and Lane change with Braking Manoeuvres using two belt configurations: standard and reversible pre-pretensioner', *Proceedings of IRCOBI Conference*, Athens, Greece, pp. 493-511.

Paper B Ghaffari G, Brolin K, Pipkorn B, Jakobsson L, and Davidsson J (2019) 'Passenger muscle responses in lane change and lane change with braking maneuvers using two belt configurations: Standard and reversible pre-pretensioner', *Traffic Injury Prevention*, 20:sup1, S43-S51.

Paper C Ghaffari G and Davidsson J (2021) 'Female kinematics and muscle responses in lane change and lane change with braking maneuvers', *Traffic Injury Prevention*, 22:3, 236-241.

Paper D Ghaffari G, Iraeus J, and Davidsson J (2021) 'The effect of age, stature, and sex on passenger kinematics in lane change maneuvers', *Unpublished, In preparation for journal submission.*

The appended papers were prepared in collaboration with the co-authors. The author of this thesis was responsible for the major progress of the work in conducting the experiments, analyzing the data, and writing the papers. Responsibility for the information and assessments stated in the papers lies totally with the authors.

Table of Contents

Definitions and Acronyms

ACh	Acetylcholine
ADELT	Anterior Deltoid
AEB	Autonomous Emergency Braking
AHBM3	project Active human body models for virtual occupant response- step 3
AP	Action Potential
ATD	Anthropometric Test Device, also known as crash test dummy
BIC	Biceps
BMI	Body-Mass Index
C1–C7	Cervical Vertebrae
CNS	Central Nervous System
CoG	Centre of Gravity
CPVM	Cervical Paravertebral Muscles
EMG	Electromyogram
ESC	Electronic Stability Control Systems
EU	European Union
Euro NCAP	European New Car Assessment Programme
EXOB	External Oblique
FARS	Fatality Analysis Reporting System
Finite Element	FE
GHBMC	Global Human Body Models Consortium
GMAX	Gluteus Maximus
HBM	Human Body Model
HIC	Head Injury Criterion
LBPT	Lane change with Braking and with Pre-pretensioner belt
LBSB	Lane change with Braking and with Standard Belt
LD	Latissimus Dorsi
LMM	Linear Mixed Model
LPT	Lane change with Pre-pretensioner belt
LPVM	Erector Spinae (longissimus), also known as Lumbar Paravertebral Muscle
LSB	Lane change with Standard Belt
LTRP	Lower Trapezius
MB	Multibody
MS	Middle Scalene
MU	Motor Unit
MUAP	Motor Unit Action Potential
MVC	Maximum Voluntary Contraction
NHTSA	National Highway Traffic Safety Administration
PC	Principal Component
PCA	Principal Component Analysis
PDELT	Posterior Deltoid
PID	Proportional-Integral-Derivative

PM	Pectoralis Major
PMHS	Post-Mortem Human Subject
RA	Rectus Abdominis
Ref	Reference Electrode
RF	Rectus Femoris
SCM	Sternocleidomastoid
SEMI	Semitendinosus
SERAN	Serratus Anterior
T1	First Thoracic Vertebra
THUMS	Total Human Body Model for Safety
TRIC	Triceps
USA	United States of America
UTRP	Upper Trapezius
VM	Vastus Medialis
VMT	Vehicle Miles Traveled
WHO	World Health Organization

Part I
Overview

1. INTRODUCTION

1.1. Epidemiology

According to the World Health Organization, road traffic accidents lead to the death of approximately 1.35 million people every year (WHO 2020). In addition to a high number of fatalities, between 20 and 50 million people have been reported as suffering from non-fatal injuries, including many disabilities, because of their injuries. It has also been reported that approximately half of the fatalities involve vehicle occupants and the other half vulnerable road users including pedestrians and cyclists (26% of all deaths), and two- and three-wheeler motorcyclists (28% of all deaths). Besides, more than half of the crashes are preceded by vehicle maneuvers such as braking or steering in order to avoid the crash (Ejima *et al.* 2009). Therefore, increasingly more research is being carried out on different approaches for enhancing the safety of both roads and vehicles with the aim of reducing road traffic mortality and morbidity.

According to the European Commission (2020), the estimated number of road crash fatalities in 2019 was 22800, which was around 7000 fewer than in 2010. This improvement is a reduction of 23% making Europe the safest region in the world with regard to road safety. However, all European Union (EU) countries have not progressed the same. As reported by the European Commission (2020), the road fatality rate in the worst-performing countries is four times higher than in the best-performing countries. In 2019, Sweden and Ireland reported that they have the safest roads (22 and 29 deaths/million inhabitants respectively) whereas Romania, Bulgaria, and Poland reported the highest fatality rate (96, 89 and 77 deaths/million inhabitants respectively). Therefore, the average fatality rate in the EU was 51/million. Moreover, it is estimated that for each road traffic fatality, another five people sustain serious injuries with life-changing consequences. The European Commission has adopted the Safe System which includes safer vehicles, safer infrastructure, enhanced protective equipment, and improved post-crash care to accomplish EU road safety policy.

According to National Highway Traffic Safety Administration (NHTSA), 36096 fatalities in motor vehicle traffic accidents were reported in United States of America (USA) in 2019 which indicated a decrease of 2% as compared to 2018 (NHTSA 2020). This was an improvement even though Vehicle Miles Traveled (VMT) increased by 0.8%. Based on an investigation by the US Department of Transportation's Fatality Analysis Reporting System (FARS 2021), passenger vehicle occupant deaths accounted for 62% of those 36096 deaths which was 27% less than in 1975. Around 16% of passenger vehicle occupant fatalities was reported for the front row passengers. In general, passenger vehicle occupant fatalities decreased by 2.8% compared to 2018 (NHTSA 2020). Consequently, the fatality rate in USA was 1.10 fatalities per 100 million VMT in 2019 which was the lowest rate since 2014. All these reports indicate that traffic safety is improving in the developed world. Although car occupant safety has been enormously improved, there is still a crucial need for a greater traffic safety.

1.2. Passive, Active, and Integrated Safety Systems

In the field of vehicle safety, there are different categories of safety systems. Passive safety systems, also denoted as in-crash or secondary systems such as seat belts and airbags, have been designed to protect occupants during a crash. For instance, seat belts have been shown to decrease the total number of casualties by about 40% (Thomas *et al.* 2006). Active safety systems, also denoted as pre-crash, or primary systems have been designed to avoid crashes by the means of sensors and automated programs issuing warnings or intervening in the pre-crash phase. Electronic stability control (ESC), forward collision warning and autonomous emergency braking (AEB) are examples of such systems. For instance, ESC which was presented in a mass market car model in 1998, has been shown to reduce the incidence of vehicle crashes significantly (Frampton and Thomas 2007). In Sweden, ESC systems were implemented in about 99% of all new cars, by 2010 (Lie *et al.* 2013). AEB systems perform wheel braking using similar hardware as used in ESC, with additional information from the radar sensors (Coelingh *et al.* 2007; Schittenhelm 2009). Post-crash systems, also denoted as tertiary systems, have been designed to be active after the crash has occurred.

In recent years, integrated safety technologies, combining active and passive safety systems, have been developed for the purpose of reducing fatalities and injuries by mitigating crashes and protecting vehicle occupants during a crash (Lemmen *et al.* 2012 and Aparicio 2005). Examples of these new technologies include evasive maneuvers such as autonomous steering and braking together with seat belts equipped with pre-pretensioners. A pre-pretensioner is a belt configuration in which the belt is tensed before an evasive maneuver during the pre-crash phase. In general, five possible functions for the current and the predicted future integrated safety systems have been defined: "*Alert the driver; Decrease vehicle speed; Prepare the vehicle for impact; Prepare occupants for impact; and Optimize impact angle*" (Aparicio 2005). Occupant-vehicle interactions are parts of these safety technologies. For the evaluation and development of these technologies, we must be able to predict human occupant responses in the total sequence from the pre-crash to the in-crash phase. As a result, computer modeling and simulation of human bodies are essential tools for the assessment and development of such integrated safety systems.

Standard three-point seat belt versus pre-pretensioner

The three-point seat belt was first introduced in 1957. In the beginning, an injury reduction of about 40–90% (Bohlin 1967), or more than 35% (Norin *et al.* 1984), was found in the studies. Accident data from 1986–1998 confirmed an estimation of 61% lower fatality risk for front seat occupants wearing a seat belt than for those unbelted (Cummings *et al.* 2003). The three-point seat belt is today the most commonly used passive safety system and is legally mandated in most countries.

The reversible pre-pretensioner seat belt was introduced as an active safety component together with autonomous braking by Schöneburg *et al.* (2011). It was developed to enhance restraint functionality and to prepare a vehicle occupant for the potential impact by tightening the occupant’s seat belt during autonomous braking. It was confirmed that using pre-pretensioner seat belts reduces the occupant’s forward motion (Antona *et al.* 2011). Others also studied pre-pretensioner seat belts in different loading scenarios such as in combination with driver emergency braking (Tobata *et al.* 2003), autonomous braking (Östh *et al.* 2013, Ólafsdóttir *et al.* 2013, and Woitsch and Sinz 2014), sled tests (Ito *et al.* 2013), stationary conditions (Good *et al.* 2008a; Good *et al.* 2008b; Develet *et al.* 2013) and lateral maneuvers (Mages *et al.* 2011, Holt *et al.* 2018). Either volunteers or crash test dummies have been used in these studies.

1.3. Active HBMs and their Validation

Human body models (HBMs), which are numerical anthropomorphic models with the details of human anatomy, have been developed to replicate human responses (Unselt *et al.* 2011, Iwamoto *et al.* 2012, Subit *et al.* 2016, Östh *et al.* 2012, Östh *et al.* 2015, Östh *et al.* 2017). As a result of increased computational power, enhanced model detail and fidelity provided by improved knowledge about mechanical properties of materials and boundary conditions, the development of these models has expanded in recent years. The ultimate goal of HBMs is to predict the level of injury risk at tissue level, i.e., different body regions and severity levels. HBMs have the potential to model different types of vehicle occupants in terms of gender and body size subjected to a variety of loading scenarios. In addition, various measurements related to injury causation can be performed using HBMs. Also, computer simulations are repeatable and can be faster and less costly than testing with crash test dummies or cadavers. Thus, HBMs are useful tools for the assessment of safety systems.

Historically, computational models of the human body have been introduced since the 1960s to investigate how the vehicle occupant responds in crashes (Yang 2015). In principle, two modeling approaches have been utilized: multibody (MB) and finite element (FE) methods. MB models are based on multiple rigid bodies with simplified geometry which are interconnected. FE models are based on smaller elements of the anatomical structures using the governing differential equations to describe the kinematics of deformation. FE models can potentially represent various body entities with fine details and therefore, can predict injuries at the tissue level. However, modeling high level of detail in FE methods requires substantial computational resources. Commercial explicit FE solvers such as Radioss (Altair), and LS-DYNA (LSTC) are used for FE model simulations in academia as well as automotive industry research. Nevertheless, there are many simplifications, even in the most advanced FE models, because of the high level of complexity in human anatomy and mechanical properties of the biological tissues.

Several HBMs have been developed to simulate human responses. The commercially available Total Human Body Model for Safety (THUMS) (Iwamoto *et al.* 2002; Iwamoto and Nakahira 2015) and Global Human Body Models Consortium (GHBMC) (Gayzik *et al.* 2011) series of models, which are the most common FE models, are available in three sizes: 50th percentile male (stature: 175 cm, weight: 77 kg), 95th percentile male (stature: 186 cm, weight: 102 kg), and 5th percentile female (stature: 151 cm, weight: 47 kg), based on Schneider *et al*. (1983). Initially, all these models were established to study vehicle occupant responses in crash situations and did not comprise active muscles.

The role of muscle activities

The influence of muscle activation on kinematic responses of occupants in pre-crash situations has been recognized (Beeman *et al.* 2011, Ejima *et al.* 2007, Stemper *et al.* 2006, Brolin *et al.* 2005, Siegmund *et al.* 2003, Wittek *et al.* 2000, van der Horst *et al.* 1997, Blouin *et al.* 2006, Kumar *et al.* 2002). Longer duration and lower loading levels in pre-crash than in-crash situations are the main reasons allowing active muscle responses to play an important role in the dynamic response of an occupant. Donlon *et al.* (2015) performed a study on cadavers and found a correlation between pre-impact posture and the injury outcome, although their data was insufficient for probabilistic analysis. If and how active muscles are involved in injury causation remains unknown but most likely, active muscles can indirectly affect the injury outcome during a crash. Injuries may occur due to the pre-impact posture, which might change because of the existence of active muscles, thereby initiating changes in initial body posture relative to the interior structure of the vehicle as well as to the restraint systems, immediately before impact. For instance, initial inboard-leaning in a frontal impact has been suggested to increase the risk and severity of the head hitting the vehicle interior because this pre-impact posture can affect the location and timing of interaction with the airbag (Donlon *et al.* 2020). Current vehicle safety assessment programs, such as the European New Car Assessment Program (Euro NCAP) are based on studies of crash test dummies of average body size and standardized seated posture. Therefore, among many other factors lacking in vehicle safety assessment programs of today, current safety assessments do not consider the occupant out of position when exposed to the crash. Since exposing volunteers to dangerous loading impacts to study both the pre-crash and in-crash phases together is prohibited due to ethical considerations, the need for computer simulations of the human body including active muscles facilitating studies of both pre-crash and in-crash situations, has arisen. The advanced HBMs with active musculature have been developed to provide improved biofidelity in pre-crash simulations lasting over a longer duration of time than in crashes (Iwamoto *et al.* 2012, Östh *et al.* 2015, Brolin *et al.* 2008, Dibb *et al.* 2014, Meijer *et al.* 2013). Recent approaches of including active muscles in the models via neuromuscular feedback control, regulates muscle activation in conjunction with the body posture and kinematics, (Östh *et al.* 2015, Meijer *et al.* 2013) as well as reinforcement learning techniques (Iwamoto *et al.* 2012).

Active muscle control in HBM

Active muscle forces have been commonly modeled in HBMs through Hill-type models in which the predicted force varies according to the muscle length, shortening velocity, and activation level (e.g., Östh *et al.* 2015). Generally, the methods for regulating muscle activity in HBMs can be divided into two main categories: open-loop control and closed-loop control. In the open-loop control, muscle activation functions are determined prior to the simulation; for instance, by using experimentally recorded muscle activities. In the closed-loop control, muscle activations are adapted based on sensory information about the present state of the model, such as the position of a limb, allowing the model to maintain its posture. The latter approach has recently been incorporated in the models to specifically represent car occupant muscle responses in pre-crash scenarios (Meijer *et al.* 2013, Östh *et al.* 2015, Martynenko *et al*. 2019).

Similar muscle control strategies have been implemented in the GHBMC (M50-OS v2 + Active) (Devane *et al*. 2019) and the THUMS v6 (Kato *et al*. 2017 and Kato *et al*. 2018) models. Both models have adopted several Proportional-Integral-Derivative (PID) controllers that control muscles to adjust for angle changes in body joints or between body parts. Another HBM, the SAFER HBM (v9) (Iraeus and Pipkorn 2019, Pipkorn *et al*. 2019), which is a modified THUMS v3, has the capability to control lumbar, neck, and arm muscles by responding to angle changes between body parts using PID controllers (Östh *et al.* 2014 and Ólafsdóttir *et al.* 2019). The models mentioned above can, to some extent, model passenger and driver in braking scenarios. The SAFER HBM is the only model that has applied recorded muscle activation data from volunteers to develop neck and lumbar controllers (Putra *et al.* 2021 and Ólafsdóttir *et al.* 2019).

Evaluating active HBMs

In order to evaluate the performance of the active HBMs and determine their ability to resemble human behavior in pre-crash situations they are required to be validated against volunteer data. It is important to be able to accurately predict the changes in body posture and active musculature in pre-crash situations, as they may affect occupant responses in the actual in-crash situation and therefore possibly the injury outcome. The validation procedure can be made by comparing normalized experimental muscle activations and well-quantified body motions to muscle activation levels and body motions predicted by the models respectively, having the same boundary conditions as in the experiments. Therefore, three types of data are required to validate active HBMs in pre-crash events: normalized electromyography data, kinematics, and boundary conditions. For instance, a previous version of the SAFER HBM has been validated against volunteer data in 1.1 g braking scenarios for driver and passenger positions (Östh *et al*. 2012, 2014 and 2015). Volunteer data including both body kinematics and muscle activations are also essential for model development and understanding human motor control strategies specific to pre-crash situations. Model tuning and model validation are two different processes and are required to be done using different sets of data in each loading condition. For instance, specific parameters in an HBM, such as the gain of PID controllers, can be tuned to reproduce a set of volunteer data in a specified loading condition, and then the model's responses can be validated using another set of volunteer data in the same loading condition.

Realistic test environment

A practical and ethical way to collect validation data is to perform volunteer experiments in replicated pre-crash scenarios comprising a controlled test environment where volunteers are subjected to non-injurious, but representative, loading conditions. Vehicle-based experiments, either on a test track or on public roads, can provide more representative situations close to daily driving conditions than experiments performed in the laboratories and thus, they are preferrable for HBM validation. Ideally, the tests should be performed in an environment identical to normal driving on the road with volunteers minimally aware when the tests start. However, the development of specific body parts of the HBMs might require volunteer kinematics and muscle activation of those body parts regardless of how realistic the test environment is. Moreover, measurements of boundary conditions such as the seat, floor plate or seat belt interaction forces in a test environment resembling the actual environment, are required for the purpose of HBM validation. Hence, the required level of details in volunteer data and boundary conditions differs depending on the intended purpose of the respective data set.

HBMs of different sex, age, and body size

Currently, most HBMs represent male occupants (Iwamoto *et al.* 2012; Östh *et al.* 2015; Subit *et al.* 2016). However, according to the field studies, females are at higher risk of traffic injuries compared to males. Whiplash Associated Disorders (WAD) are examples of cases in which females have averagely shown double or even higher risks than males, in comparable crash conditions (Morris and Thomas 1996; Temming and Zobel 1998; Krafft *et al.* 2003; Jakobsson *et al.* 2004; Carstensen *et al.* 2012; Carlsson *et al.* 2014). Likewise, the risk for more severe injuries has been reported higher in female than male occupants (Bose *et al.* 2011). In particular, muscle activations and body kinematics, under different loading conditions, might be influenced by the physiological differences between males and females. For example, the cervical spine flexion has been shown to vary significantly between males and females exposed to a maximum 1 g loading in the posterior–anterior direction, when they were asked to relax their neck (Seacrist *et al.* 2012). Therefore, biomechanical data from female volunteers in representative pre-crash loading situations are needed in order to further develop and specifically validate female HBMs. Moreover, the current HBMs are mostly established to represent the average body-size occupants. There is some ongoing research to include morphing capabilities in the models in order to represent occupants of different sex, age and body size (Hwang *et al.* 2016a and 2016b, Zhang *et al.* 2017, Larsson *et al.* 2019b). Therefore, it is crucial to obtain data to develop and validate such HBMs of different stature, age, and sex is crucial. An improved understanding of how occupant characteristics affect their responses to the safety systems can support this model development and facilitate achieving the ultimate goal of enhancing the effectiveness of the restraint systems for the entire population.

1.4. Physiology behind Muscle Activity

Generally, there are three kinds of muscle tissues in the human body which are skeletal muscles, heart muscles, and smooth muscles. The muscles that are responsible for the movement and maintenance of the body posture are skeletal muscles. They are attached to the skeletal structures by connective tissues (tendons) at the ends of the muscles and are controlled by the central nervous system (CNS).

The role of skeletal muscles in posture maintenance: Motor control

The combination of two types of motor acts generates human movements (Massion 1992). One, is maintaining a reference position, also denoted as postural control, in which the CNS applies stabilizing muscle activations without human awareness. The other type is the goal-directed movement, in which a limb is moved along a path in the direction of a pre-defined goal.

In postural control, information about the current state of the body, e.g., center of mass of the trunk in relation to the feet (Winter 1995), is used to produce stabilizing muscle activations. In other words, postural control acts as a closed-loop system in which the state of the body is given by the sensory part of the peripheral nervous system (PNS) and according to that information, the CNS generates compensating motor instructions relative to the deviation from the desired posture. Another important factor in postural control is muscle co-contraction. For example, activation of antagonistic muscles around a joint, increases the fundamental stiffness and damping of the joint while no net-moment is generated. It has been confirmed that the stability of the lumbar spine is increased by muscle co-contractions of the trunk flexors and extensors (Hodges 1999). Theses muscle co-contractions play an important role in postural control of the upper extremities (de Vlugt *et al.* 2002; de Vlugt *et al.* 2006). Also, studies in impact biomechanics demonstrated that muscle co-contractions in lower extremities significantly change the restraint interaction forces prior to the impact (Begeman *et al.* 1980).

Motor Unit Action Potential

The skeletal muscles are formed of multiple bundles of cells called muscle fibers. The muscle fibers consist of two overlapping types of contractile proteins, i.e., actin and myosin, which are attached to each other through cross-brides during the activation of the muscle fibers. Dozens to hundreds of muscle fibers in conjunction with a motor neuron which innervates them makes up a motor unit (MU). Each skeletal muscle is made up of a few to hundreds of MUs. As illustrated in Fig.1, the contact between a motor neuron and a muscle fiber forms a neuromuscular junction where an electrical signal in the form of an Action Potential (AP) is produced and transmitted, inducing muscle contraction. In particular, when an AP reaches the presynaptic terminal of a motor neuron, the voltage-dependent calcium channels are activated and calcium ions are allowed to enter the neuron, initiating the synaptic transmission. Subsequently, calcium ions bind to sensor proteins on synaptic vesicles. This triggers vesicle fusion with the cell membrane, and as seen in Fig.2 causes the release of a neurotransmitter such as acetylcholine (ACh) from the neuron into the synaptic cleft. Subsequently, the ACh diffuses across the synaptic cleft and binds to ACh receptors on the cell membrane of the muscle fiber. Binding ACh to receptors can depolarize the muscle fiber in a cascade which eventually leads to muscle contraction.

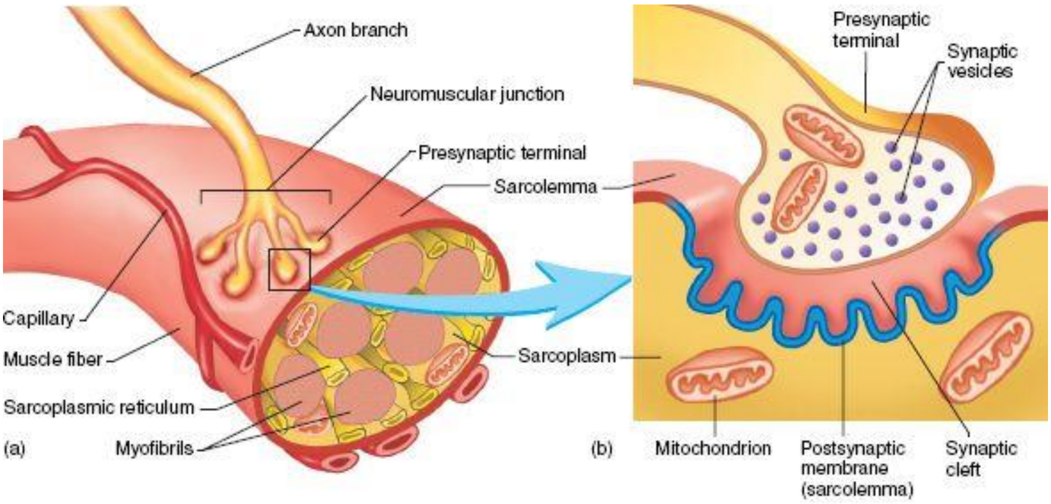

Fig. 1. *Neuromuscular junction. https://i.pinimg.com/originals/4b/3e/a4/4b3ea433552f1b24c904977f63f2aa5d.jpg (Accessed:25 July 2021).*

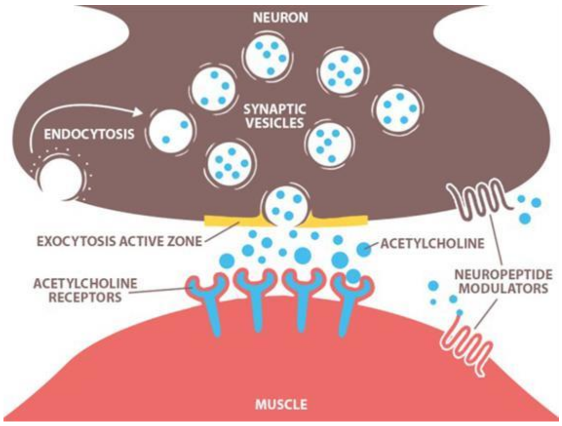

Fig. 2. *Mechanism of synaptic transmission. https://www.tankonyvtar.hu/hu/tartalom/tamop412A/2011-0094_neurologia_en/images/chapter09/c09f_pic003_eng.jpg (Accessed:25 July 2021).*

Electromyography

Surface electromyography is a technique for measuring muscle activation. Surface electrodes placed on the skin covering the skeletal muscles measure the AP propagation in the muscle fibers. The superposition of all APs recorded by the electrode forms an electrical signal (in volts) called electromyogram (EMG) (Winter 2009). The topography of this signal is depending on anatomical and physiological factors, such as the number of active MUs and the discharge rate of each one, the thickness of the subcutaneous tissue and the orientation of the MUs, as well as the detection factors such as the location, area and spacing of the detection electrodes (Barbero *et al*. 2012). Further information on the role of these parameters can be found in the literature (Farina *et al.* 2002a). Moreover, the surface EMG signal is preferably normalized to maximum voluntary contractions (MVC) under isometric conditions, in order to be expressed in terms of muscle activation level. In fact, normalization reduces the effect of extrinsic and intrinsic features influencing the EMG signal. For instance, the distance and conductivity of the tissues between the contracting muscle fibers and the skin may appear dissimilar in different individuals, which makes any subject comparison of non-normalized EMG levels inaccurate. There is also another technique for measuring muscle activation which is done through indwelling electrodes. This type of electrode is inserted inside the muscles by means of wires and thus, due to its invasive nature, its applications are limited for safety reasons.

Force-EMG relationship and the use of EMG for HBM validation

The goal of HBM validation is to assess how much the predicted muscle forces are consistent with experimental muscle data. Direct measurement of muscle forces in the experimental studies is a complex and invasive process. Therefore, EMG measurements are typically used to estimate the muscle forces. In isometric contractions, force-EMG relationship can be estimated by linear approximations (Staudenmann *et al.* 2010). While in dynamic contractions, this relationship is nonlinear and it is a function of muscle length, shortening velocity and the passive properties of the muscle. Another issue in dynamic contractions is the relative location of the electrode to the detectable and contracting muscle fibers which can be changed during the measurement (de Luca 1997 and Farina 2006). These issues make the model validation and subsequently the injury risk estimation problematic. Comparing the muscle activation levels predicted by active HBMs to the measured EMG levels is a more reasonable validation procedure (e.g., Iwamoto and Nakahira 2015 and Östh *et al.* 2014). Another validation method is to compare the produced moments in the model with the joint moments estimated by inverse dynamics (Staudenmann *et al.* 2010). This method is limited to only a comparison of the produced net moment and the influence of individual muscle forces cannot be compared.

1.5. Test Subjects: ATD, PMHS, and Volunteer

New technologies need to be evaluated with regard to their performance in providing safety features for vehicle occupants. Anthropometric Test Devices (ATDs), i.e., mechanical models of humans, also known as crash test dummies, have been developed for the assessment of safety systems. ATDs typically represent adult vehicle occupants in a few different body sizes: a large male (stature: 186 cm, weight: 102 kg), a midsize male (stature: 175 cm, weight: 77 kg), and a small female (stature: 151 cm, weight: 47 kg), based on Schneider *et al*. (1983). To allow more parametric studies, mathematical models of ATDs have also been developed to replicate the response of the dummies. Although ATDs are valuable tools that can be subjected to physical crash impacts, they have severe limitations. They are still very simplified models of the human anatomy and are also too stiff to represent vehicle occupants in low loading situations such as pre-crash conditions (Beeman *et al.* 2012).

There are different sources of validation data, such as Post-Mortem Human Subjects (PMHSs), also known as cadavers. PMHSs can be used to validate HBMs in both pre-crash and in-crash situations. While there are previous studies on PMHSs subjected to in-crash impacts (Donlon *et al.* 2015, Beeman *et al.* 2012, White *et al.* 2009), few studies have investigated the response of PMHSs in pre-crash loading situations, which can provide validation data for HBMs with passive muscles, in pre-crash situations. In contrast to the ATDs, PMHSs are too soft to represent vehicle occupants in low loading situations (Beeman *et al.* 2012). Nevertheless, PMHSs cannot provide information on how the muscles are activated and how the alive humans' displacement would be in pre-crash situations. Therefore, PMHSs were traditionally used to provide validation data for HBMs capable of predicting occupant responses only in crash scenarios. In fact, PMHSs are useful sources of validation data in crash conditions since living humans cannot be exposed to the injurious crash loads.

Introducing integrated safety systems in vehicle safety development has created the need for studies on pre-crash situations in order to evaluate such systems. For instance, in studies of HBMs subjected to simulated integrated safety systems, models are required to include active musculature, and to respond with a human-like control strategy of the muscles and kinematics, in pre-crash situations. By optimizing the design requirements for integrated safety technologies and restraint systems based on how the HBMs behave in various pre-crash and in-crash scenarios, a reduction in the injury risk of vehicle occupants can be achieved. Hence, it is essential to acquire volunteer data including kinematics and muscle activations that can be applied for validation of HBMs in pre-crash scenarios.

1.6. Previous Volunteer Experiments

A brief review of studies to investigate the kinematics and muscle activation of volunteers in potential pre-crash situations is given here. The emphasis is on lateral loading conditions, typically below 1g and with durations of at least 0.2 s. Volunteers studied in these experiments are mostly around average body size. There are a few studies exploring the influence of body characteristics on volunteer kinematics in response to evasive maneuvers which are mainly addressed in the next section.

Volunteer data from experiments in sagittal plane loading are fairly available (Ejima *et al.* 2007, Ejima *et al.* 2008, Östh *et al.* 2013, Ólafsdóttir *et al.* 2013, Behr *et al.* 2010, Choi *et al.* 2005); however, fewer studies have explored volunteer responses in lateral plane loading. Among these studies, Muggenthaler *et al.* (2005) established torso kinematics and the activity of four muscles (sternocleidomastoideus, trapezius, obliquus externus abdominis and rectus femoris) for one helmeted volunteer seated in the passenger seat in a car that drove through a lane change test, and then compared these to the kinematic response of ATDs. They found that muscle activation is related to the applied lateral vehicle acceleration and that ATDs are unable to predict human occupant responses in this type of evasive maneuvers, and therefore further volunteer studies are essential. Other studies have also confirmed that the occupant kinematics is dependent on muscle activity (Ejima *et al.* 2012, Van Rooij *et al.* 2013, Huber *et al.* 2013). Ejima *et al.* (2012) exposed three volunteers, seated in a sled and restrained with a lap belt, to lateral accelerations and found 20–40% reduction in head and upper torso (T1) lateral flexion when the volunteers were requested to tense their muscles compared to when they were relaxed. Van Rooij *et al.* (2013) studied occupant responses in relaxed and braced conditions, when restrained by a 4-point belt and exposed to simulated lane change maneuvers in a laboratory test vehicle. They stated a significantly higher upper body sideway displacement and lower muscle activity for relaxed conditions. Huber *et al.* (2013) and Huber *et al.* (2015) conducted a series of volunteer experiments with a modified passenger seat subjected to lane change maneuvers to the right, and measured head and torso kinematics as well as activity bilaterally from three neck muscles and four trunk muscles without normalization. Noticeably, high activation of the right-side muscles was shown in their results while an inter-subject variability of above 200% was found in kinematic responses for each maneuver. A detailed study of neck muscle activity was carried out by Ólafsdóttir *et al.* (2015) on volunteers subjected to perturbation type loading in eight different directions. Their results indicate that the recruitment pattern and the neck muscle activity levels are dependent on the loading direction. Among the studies listed above, Huber *et al.* (2015) and Ólafsdóttir *et al.* (2015) collected data from a few females besides the males, and the others studied only male volunteers. A quantitative study on both male and female passengers exposed to braking and lane change events was led by Reed *et al.* (2018). They did not find any significant difference in head excursions of males versus females, after accounting for body size differences.

There are different ways to estimate linear excursion and rotation of a point approximately at the head Centre of Gravity (CoG) and a point close to the T1 vertebra body in the upper torso. For instance, the rotation angles can be estimated by the projected vectors on the horizontal and vertical planes using film targets coordinates. Previous volunteer studies on lateral plane loading scenarios with test vehicle did not explain in depth the strategies they used to estimate the head and torso kinematics, except a few studies such as Hubber *et al*. (2015) which used Vicon near-infrared motion tracking cameras and a set of retro-reflective markers to present centroid displacement and segment orientation at the ear and T5 level for the head and torso, respectively. A common estimate of head and torso kinematics is needed to compare the results of different volunteer studies but is also essential for validating HBMs when comparing the kinematic responses of the models and the volunteers.

To the best of the author’s knowledge, published volunteer studies have so far provided only some partial understanding of the occupant kinematics and the activity of a limited number of muscles when volunteers were subjected to lateral loading conditions. Some of these studies were only on a small number of volunteers or conducted in a laboratory environment; in some, muscle activation data were not normalized or only a few muscles were studied. Nevertheless, for the purpose of model validation, and more specifically female HBMs and male HBMs, none have provided comprehensive boundary conditions, occupant kinematics and normalized muscle data from volunteers seated in a regular car travelling in a realistic environment.

1.7. Effects of Body Characteristics on Occupant Kinematics

A large variability among the volunteer responses was observed in past volunteer studies which have quantified head and torso kinematics during potential pre-crash situations. This variability is likely due to differences in physical characteristics such as stature, age and sex or differences in sitting postures and behaviors in response to evasive maneuvers. The effects of age, sex, and body size on volunteer responses in pre-crash circumstances are explored in a few studies. Volunteer kinematics under driver-initiated and autonomous braking were investigated by Carlsson and Davidsson (2011) in real traffic scenarios. Larger head forward motion was found in the group of volunteers with higher stature than shorter and also, in females than males of the same sitting height comparing the average motions. However, they reported a quite large amount of variation among the volunteer responses (e.g., a mean forward head displacement of 96 mm, with a standard deviation of 47 mm). The influence of sex and stature on volunteer kinematics during braking and lane change events was studied by Kirschbichler *et al.* (2014). For the braking events, their analysis of variance (ANOVA) showed a significant effect of sex while omitting the factor of sex resulted in a significant effect of stature. In the lane change events, no significant effect of stature or sex was reported which was possibly due to their small sample size. Reed *et al.* (2018) studied volunteers with quite a wide range of age and body size and explored the effects of volunteer characteristics on their head excursions in abrupt braking and lane change maneuvers. Their linear regression analyses resulted in significant effects of body mass index (BMI) and age on head frontal excursions and, significant effects of stature and sitting height on head lateral excursions. In their study, passengers with higher stature had slightly larger lateral excursions. Nevertheless, their analyses contained only the head maximum and mean excursions and not the head kinematics over time. Besides, the significant effects they found accounted for only a small amount of total population variance.

This review of the previous studies reveals two main gaps in the existing knowledge of the effects of body characteristics on occupant kinematics in pre-crash circumstances. First, either maximum or mean excursions were investigated and none of the studies mentioned above have explored the potential effects of body characteristics on the kinematics timeseries. Nevertheless, the kinematics timeseries (i.e., shapes of the excursions as a function of time) can provide extra information about the amount and the timing of volunteer displacements beyond what maximum or mean excursions can provide. Second, the kinematic responses have not been statistically modeled as a function of possible predictors in any of those studies.

1.8. Predictions based on Population’s Anthropometric Data

Experimental data are always limited in including volunteers across all ranges of body characteristics. Despite the remarkable diversity in the population, experimental studies are mostly done on average sizes and thus, small sized females or large sized males are not regularly included in volunteer studies. Therefore, we need to predict occupant kinematics with respect to body characteristics from the available data in pre-crash situations. It is of great importance to statistically model the vehicle occupant kinematics over time as a function of influencing predictors. This allows for the development and validation of advanced morphed HBMs which incorporate the effects of age, sex, and body size, for representing a wide range of vehicle occupants in total sequence of pre-crash and in-crash situations.

There are some statistical approaches such as Principal Component Analysis (PCA) and linear regression, suggested by several studies in different fields addressing prediction problem based on the subject's anthropometric data. Parkinson and Reed (2010) and Brolin *et al*. (2017) have used PCA and linear regression analysis to transform a large set of variables into a data set with fewer parameters that still covers most of the variances in the large set or to predict unknown parameters from known parameters. Rasmussen *et al.* (2018) used similar techniques to generate a valid pseudo population based on anthropometric data. PCA has also been used to model running kinematics using motion capture and anthropometric data (Rasmussen *et al*. 2020). This method was applied on Fourier-transformed data to predict motion patterns of runners based on body size information. Holcombe *et al*. (2020) have used a shaped-based PCA to define cross-sectional geometry of the ribs of different length and to reproduce them for statistically average male and female rib geometry.

In the field of traffic safety, Samuels *et al.* (2016) have used PCA and linear regression analysis to predict trajectories of the head, spine, and pelvis in low-speed (<4 g) frontal impacts for occupants of specified seated heights corresponding to pediatric and adult ATDs. They first modeled trajectories as combinations of cubic basis splines with eight control points and then performed PCA on the control points. Their results indicated shorter and flatter trajectories with increasing seated heights. PCA and linear regression analysis have also been utilized to develop corridors of pelvic impact force data predicted for the subjects of specified anthropometric dimensions (Sun *et al.* 2016). The force data were collected in the lateral impact tests with nine seated PMHSs. PCA was applied on timeseries of force data and regression analysis was conducted on the resulted scores. Their results indicated that the predicted corridors could reasonably reflect the original data. To the best of the author's knowledge, no published study has statistically modeled occupant kinematics in pre-crash circumstances as a function of age, sex, and body size by conducting PCA on timeseries of volunteer kinematics.

1.9. Summary of Introduction

Road traffic accidents represent one of the main sources of injuries and fatalities worldwide. Vehicle occupants are involved in half of the accident-related fatalities. Evasive maneuvers such as braking, and steering occur prior to more than half of the crashes to avoid the crash. These evasive maneuvers affect the occupant posture in relation to the vehicle interior structure and the restraint systems. Several investigations dedicated to improving the safety systems in vehicles and reducing the number of injured and killed people in traffic accidents, have been carried out. Integrated safety systems combine active and passive systems for pre-crash and in-crash phases to avoid the crash as much as possible and to protect the occupant during the crash.

Computer simulations, i.e., human body models are developed to replicate human responses in the different phases of a crash with the final goal of predicting the injury risk and assessing the safety systems. Introducing muscular activation strategies into the HBMs has enhanced the accuracy of the model responses. Volunteer experiments are used to provide insights into the human responses including kinematics and muscle activities in situations representative of pre-crash phases. Volunteer responses have been studied mostly in sagittal plane loading and less in lateral plane loading scenarios. A large variability has been observed in volunteer responses. A few studies have investigated the effect of volunteer characteristics such as age, sex, and stature on their kinematics. Volunteer data can be applied to evaluate the restraint systems as well as to validate the HBMs.

2. OBJECTIVES, RESEARCH QUESTIONS, AND SUMMARY OF METHODS

2.1. Objectives

The first objective of this thesis was to provide insights into volunteer muscle activations and body kinematics in representative pre-crash circumstances with lateral plane loading conditions. This objective was chosen because there have been few volunteer kinematics studies in lateral loading conditions. These studies have typically included a small number of muscles and have been performed in a laboratory environment, not on volunteers traveling in a regular car. A complementary objective was to provide validation data for active HBMs. The second objective was to investigate the effects of two belt configurations (i.e., standard versus pre-pretensioner) on occupant kinematic and muscle responses in lateral loading scenarios. A complementary objective was to investigate the differential effect of pre-pretensioner belt on male versus female occupant responses. This objective was chosen because many new vehicle models are fitted with seat belts that can be pre-tensioned in the pre-crash phase. The third objective was to explore the influence of individual characteristics of occupants, namely age, stature, and sex, on their body kinematics. This objective was chosen because large statistical variabilities have been observed in the kinematics of occupants, hence it is important to better understand the underlying individual factors influencing the kinematic outcomes of pre-crash scenarios.

2.2. Research Questions

To achieve the thesis objectives, the following research questions were addressed:

Research Question 1:

- Are muscles activated in pre-crash? How much?

Research Question 2:

- Does the pre-pretensioner belt affect muscle activation? How much?
- Does the pre-pretensioner belt help maintain sitting posture in pre-crash? How much?

Research Question 3:

- Do factors such as sex, age, and stature influence volunteer kinematic outcomes? Are their influences statistically significant? How differently do males and females respond in pre-crash?

2.3. Summary of Methods

To answer the research questions mentioned above, a new and comprehensive set of experiments was carried out involving volunteers traveling in a regular car, in a realistic environment, being subjected to repeatable and typical low-g interventions representative of pre-crash situations. Volunteers' muscle activations were measured by surface EMG technique to answer Research Question 1. Vehicle maneuvers were performed while volunteers seated in the front-row passenger seat were restrained using two belt configurations, i.e., standard and pre-pretensioner. The volunteers' EMG and kinematics were then processed and statistically analyzed to answer Research Question 2. The quantified kinematics of male and female volunteers of different ages and statures were statistically explored to answer Research Question 3. In addition to providing answers for these research questions, the aforementioned set of experiments was conducted in order to provide the necessary post-processed data for validation and further improvement of active HBMs specifically designed to represent male and female occupants at the whole-body level.

Volunteers and inclusion criteria

The set of experiments studied in this thesis was part of a larger study, the Active human body models for virtual occupant response - Step 3 (AHBM3) project, covering several different loading conditions that can potentially occur in pre-crash situations for vehicle passengers and drivers. On average, conducting the experiments for each single volunteer required about nine hours, including all preparations and instrumentations. Finding volunteers was difficult as most of these experiments were carried out in the summer holidays, and each experiment session was rather time consuming. Twenty-five volunteers (13 males and 12 females) were recruited in total. The recruitment process was intended to be unbiased and was based on announcements in university, industry, and social networks. The data from the first volunteer (a male) served as a pilot to better learn the measurement process. The data from two other males had to be excluded as they were physically too active during the experiments, hence the collected data from them could not be compared with data of other volunteers. The experiments with another male volunteer could not be completed because of technical failure with the measurement equipment. Two female volunteers were obese and because of technical issues with measuring their muscle activations, were excluded from the study. The data from one more female was also excluded because of poor visibility in the recorded videos. Finally, the data from 9 males and 9 females remained suitable for the study presented in this thesis.

Volunteers included in this study, had no history of poor general health or other medical conditions potentially presenting an increased risk of injury. Their BMI was from 18 to 23, mostly within normal range while age and stature covered 23–71 years and 174–192 cm for males, and 25–65 years and 160–180 cm for females, respectively. To create a realistic atmosphere, they were not strictly instructed to sit still and look forward (i.e., neutral posture), just before the beginning of the maneuvers. Parts of the data in which volunteers were not in neutral posture at the beginning of the events, were hence excluded to fulfil the requirement for data with the purpose of model validation. Other inclusion criteria were the proper functionality of the driving robot and the pre-pretensioner seat belt. In addition, for the study of muscle activations all individual EMG data were examined. Both experimental documents and the recorded videos were investigated and if a clear reason, such as a loose EMG electrode attachment or a voluntary body motion could be observed, those test results were not shown in any graphs. In total, 92 tests involving nine male and 69 tests involving nine female passengers were included in this thesis.

Tests and procedures

There were four loading scenarios studied in this thesis (as listed below) and three trials were performed per volunteer and type of loading scenario in a randomized order.

- lane change with standard belt (LSB)
- lane change with pre-pretensioner belt (LPT)
- lane change with braking and with standard belt (LBSB)
- lane change with braking and with pre-pretensioner belt (LBPT)

Surface EMG electrodes were attached to the corresponding muscles of each volunteer to record muscle activities during the tests. Film markers were also mounted on the head and upper body of each volunteer to track the excursions of the volunteer during the maneuvers. Fig.3 shows the lateral and longitudinal vehicle accelerations (a and b) and the coordinate system used in the analysis (c).

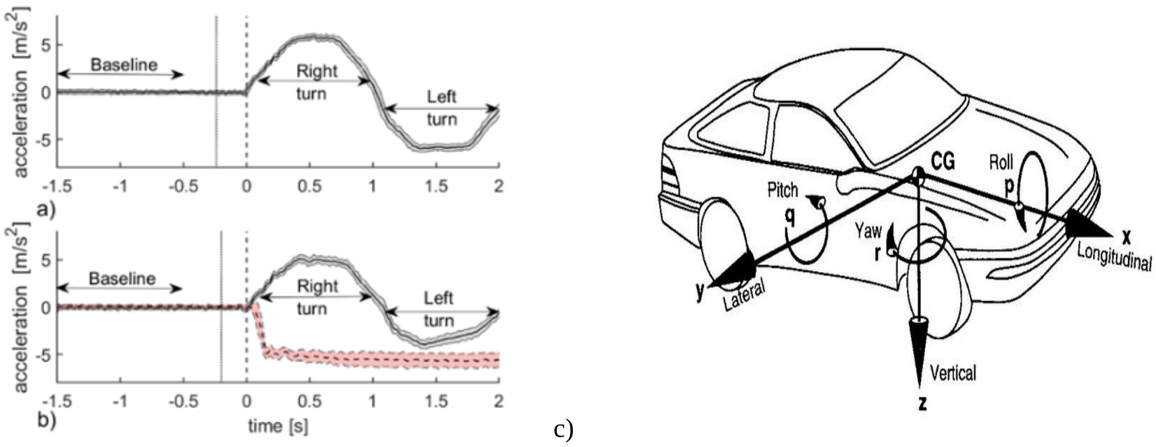

Fig. 3. *Lateral vehicle acceleration (solid gray) in LSB & LPT (a) and lateral and longitudinal vehicle acceleration (solid gray and dashed pink, respectively) in LBSB & LBPT (b). Vertical dashed lines present time zero and vertical dotted lines present the onset time of the pre-tensioned belt. The coordinate system in the test vehicle (c).*

Data analysis

The major parts of the data analysis consisted of EMG analysis and kinematics analysis to quantify volunteers' muscular and postural responses to evasive maneuvers, respectively. The quantified volunteer kinematics were subjected to further numerical and statistical analyses to identify the significant influencing factors. The following list summarizes the analytical methods used in this study. These methods are justified and presented in depth in the appended papers.

- **EMG analysis:** Surface EMG mesurements were performed on 38 muscles during isometric MVC tests and vehicle manuevers. The EMG data were filtered, rectified, normalized against MVCs, and analyzed to assess muscle activation levels and onset times. Muscle activations were presented in corridors containing mean and mean ± 1 standard deviation (SD). The EMG corridor was scanned per muscle for the existence of two distinctly different levels of muscle activation, and for a few muscles, two separate response corridors were established. The Shapiro-Wilk test of normality was conducted on EMG data. Muscle activation levels and onset times were compared for the two belt configurations (i.e., standard versus pre-pretensioner) using nonparametric Wilcoxon signed ranks tests.

- **Kinematics analysis:** Three-dimensional target tracking and motion analysis were performed on the recorded videos of volunteer movements during vehicle maneuvers. The Euler angle technique was used to obtain the rotation matrix using coordinates of the three best trackable markers attached to the presumed corresponding rigid body. The coordinates of film markers attached to the head and upper torso were transformed to estimate linear and rotational excursions at head CoG and T1 vertebra body, with respect to the vehicle coordinate system in 3D space. The rotation angles were quantified using the Tait-Bryan convention and projected rotation angles. Quantified kinematics were presented in corridors (mean ± SD). Maximum displacements (head CoG and T1 forward and lateral linear excursions) were compared for the two belt configurations (i.e., standard versus pre-pretensioner) using nonparametric Wilcoxon signed ranks tests.

- **Statistical analysis: the influence of age, stature, and sex on kinematic outcomes:** PCA was applied to head and upper torso forward and lateral displacement data in the time domain. Timeseries of displacements were re-parameterized to the principal components (PCs) and each PC represented a specific shape of data (i.e., the body motion over time during the lane change maneuver). The scores of the first three PCs as well as maximum lateral displacements were separately fitted into a Linear Mixed Model (LMM) with potential predictors (fixed effects) age, stature, and sex. Individual-specific effect (i.e., random effect) was also included in the model. In addition, the model took into account all 2-way interactions of the predictors and the residuals, which represented the variabilities within volunteers. The influence of these fixed and random effects on the kinematic outcomes was assessed and the statistical significance of the results were reported. Also, to specify the percentage of the variance explained by the entire model, a type of R-squared coefficient, conditional R^2_{LMM}, was estimated. Another type of R-squared coefficient, marginal R^2_{LMM}, was estimated to specify the percentage of the variance explained only by the fixed effects.

3. SUMMARY OF APPENDED PAPERS

The objectives in this thesis were planned to be fulfilled in the following four papers. The aim of Paper A was to investigate the kinematic response of male car occupants during low-g evasive maneuvers representing pre-crash events. The aim of Paper B was to investigate muscle activation of the male occupants during these maneuvers. Both Paper A and Paper B provide data sets that could be applicable for validating HBMs capable of controlling muscles in simulation of evasive maneuvers. Furthermore, considering the introduction of new vehicles fitted with pre-pretensioner seat belts, both papers include comparisons of occupant responses with respect to a standard versus reversible pre-pretensioner belt. The aim of Paper C was to study female responses under the same loading scenarios as presented in two previous papers, in order to provide validation data for female HBMs and also to compare the effect of belt configuration on female kinematics and muscle activation. As described in the previous chapters of this thesis, the need for validation data and further development of female HBMs are particularly important since most of the current HBMs are exclusively parameterized for male occupants. The aim of Paper D was to investigate potential influencing factors such as sex and body characteristics on occupant kinematics and to develop a statistical model that can be used to predict kinematics of occupants with different characteristics. As mentioned before, traffic safety research has revealed a large variability among volunteer kinematics, in response to evasive maneuvers representative of pre-crash situations. The intent of this paper was to support developing HBMs for a wide range of population with different sex, age, and stature. In summary, Research Question 1 is answered by Paper B and C, Research Question 2 is answered by Paper A, B and C, and Research Question 3 is answered by Paper C and D.

Paper A

The focus of Paper A was to quantify occupant kinematics for the head CoG and the upper torso using the coordinates of the film targets attached to each volunteer's body as well as to analyze belt characteristics and vehicle dynamics. The test subjects included nine front-seat male passengers. The seat belt was either in standard or pre-tensed configuration activated around 200 ms prior to the autonomous maneuver, with a target force of a minimum 170 N. The maneuvers were composed of multiple repeatable lane change, and lane change with braking, at 73 km/h. The maximum lateral acceleration in lane changes was 5.8 m/s^2 while in lane changes with braking, it was 5 m/s^2 and the longitudinal acceleration was -5.6 m/s^2. The maneuver duration was approximately 2 seconds, steering to the right during the first second and steering to the left during the last second. Time shifting was done based on the onset of vehicle lateral acceleration and in addition to accelerations, vehicle roll, pitch, and yaw angles, were also measured, as well as shoulder belt, lap belt force, and belt payout. Fig.4 shows a volunteer prepared for the test with the attached film targets (a) and the passenger seat position (b).

The motion of the volunteers during the maneuvers was captured by means of three DS-CAM 600 cameras mounted inside the vehicle; one camera in front of the volunteer, one to the rear and one to the side, to record videos from three directions. Film targets, white and lightweight spheres, were attached to each volunteer's head, skin covering the T1 process, sternum, and acromion, to provide 3D information required for kinematics post-processing. TEMA Automotive was used as a tool for 3D film analysis in order to obtain coordinates of the markers attached to the body with respect to the vehicle coordinate system. The methodology used for kinematics post-processing is provided in this paper. The Euler angle technique was used to obtain the rotation matrix using coordinates of the three best trackable markers attached to the corresponding body segment (typically, one marker on the forehead and two markers on the right and left sides of the head, and single markers on the left acromion, T1 process and sternum for the upper torso). Subsequently, the 3D linear displacements and the rotation angles of the head were estimated by transforming coordinates of the film markers to the head CoG. Likewise, the linear excursions of the upper torso at the T1 vertebra level were calculated in 3D.

All post-processed data were presented in corridors containing mean ± one standard deviation intended as validation data for active HBMs. The resultant volunteer kinematics corridors indicated certain variability in the responses, especially for head kinematics, resulting in wider corridors than for upper torso kinematics. The results also showed lower lateral and forward displacements for the head CoG and upper torso when the volunteers were restrained by the pre-pretensioner belt than by the standard belt. Similar upper torso and head lateral excursion were found for lane change and lane change with braking maneuvers, however the longitudinal excursion was found to be highly influenced by the existence of longitudinal acceleration.

a b

Fig. 4. *A volunteer prepared for the test with attached film targets (a), passenger seat position (b).*

Paper B

The focus of Paper B was to analyze the muscle response data for the same set of volunteer tests presented in Paper A. Hence, the experimental setup including the measurement systems, the maneuvers, and the vehicle instrumentation, were identical to those in Paper A. The EMG technique was used to measure muscle activation. Surface EMG Ag/AgCl electrodes were placed bilaterally on 19 muscles, as illustrated in Fig.5.

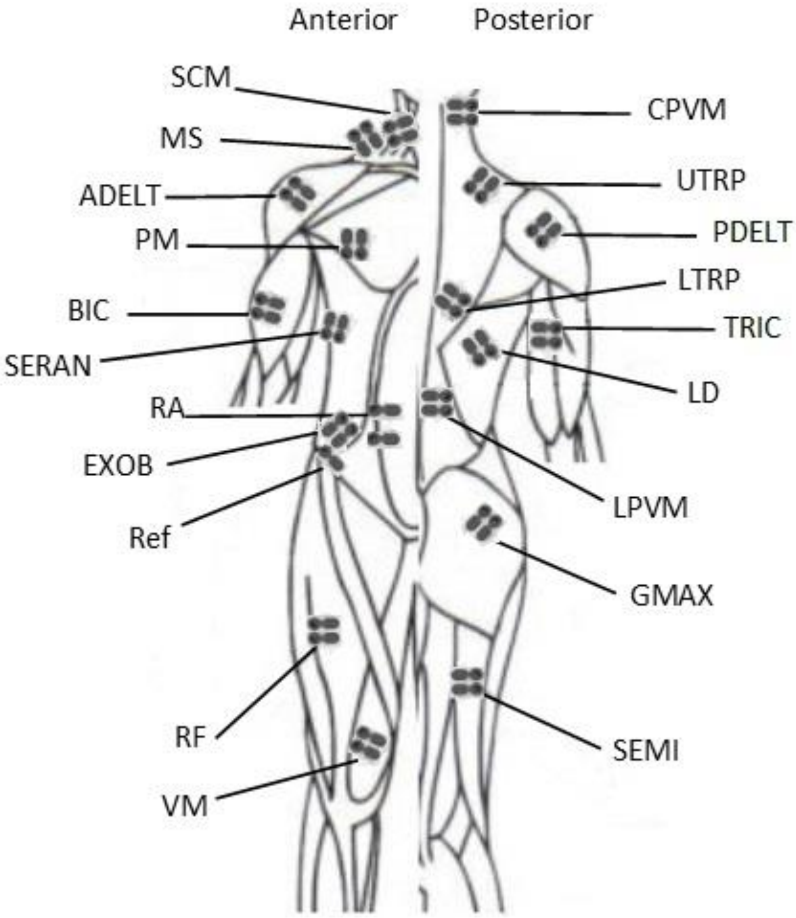

Fig. 5. *Electrode placement on the anterior and posterior side of the body shown to the left and right, respectively. Muscle acronyms according to Definitions and Acronyms section of this thesis.*

EMG data were acquired from 38 muscles in the neck, upper extremities, torso, and lower extremities. The complete definition of each muscle can be found in the Definitions and Acronyms section of this thesis, and further information such as position of the electrodes are provided in Paper B. Subsequently, the recorded EMG data were post-processed according to Fig.6.

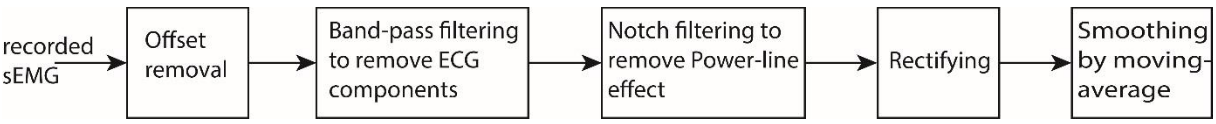

Fig. 6. *A diagram of the sEMG signal processing.*

The post-processed EMG data were normalized to maximum voluntary contractions (MVC) under isometric and posture-specific conditions. In the MVC tests conducted separately prior to the vehicle tests, the volunteers were seated in a custom-made test rig to resemble the posture of a car occupant (Fig.7) and were asked to contract specific muscles.

Fig. 7. EMG electrodes on a volunteer's upper body (a) MVC test rig with a volunteer (b).

Corridors of mean ± one standard deviation were established for each muscle in four different loading scenarios, i.e., LSB, LPT, LBSB and LBPT.

The established muscle activation corridors can be applied for active HBM validation. The results showed that the muscle activation levels collected in normal driving conditions, prior to any evasive maneuver, were low (<2 %MVC) in all muscles except the lumbar extensors (3–5.5%). Selective muscles were found to be activated during the lane change maneuver which restricted the body lateral motion caused by inertial loading. Soon after the vehicle accelerated in the lateral direction, increased muscle activation up to 24% of MVC was observed predominantly in the neck, lumbar extensor, and abdominal muscles. The results also indicated that with respect to the vehicle's lateral motion, muscles in the right and left side of the body were activated at different times and amplitude. Comparing the muscle responses in two belt configurations revealed earlier activation onsets and significantly ($p<0.05$) smaller activation amplitudes for specific muscles in lane changes, when the volunteers were restrained by the pre-pretensioner belt than by the standard belt.

Paper C

The focus of Paper C was to quantify linear and rotational displacements of head center of gravity and T1 vertebra body and analyze the muscle response data collected from female passengers exposed to the same loading scenarios as male passengers presented in Paper A and B. The kinematics post processing and the EMG data analysis were similar to methods described in Paper A and B. To study the effect of belt configuration on female responses, separate Wilcoxon signed ranks tests were applied on EMG onset and amplitude as well as peak displacements of head and T1. Lateral and forward displacements of the head and T1 were significantly ($p<0.05$) smaller using the pre-pretensioner belt than the standard belt (e.g., Fig.8). The neck, lumbar extensor and abdominal muscles activated up to 16% MVC following vehicle acceleration in the lateral direction (Fig.9). In addition, the pre-pretensioner belt decreased specific muscle activation onsets and amplitudes compared to the standard belt, which confirmed previously published results for male passengers. The volunteer response data together with the boundary conditions such as seat belt forces and position as well as vehicle dynamics provided in this paper can be used as validation data for female HBMs.

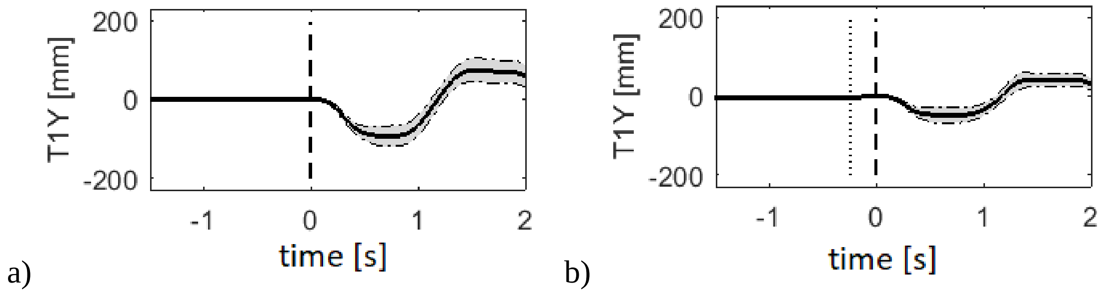

Fig. 8. *Corridors (i.e., mean ± SD) of female volunteers' T1 lateral displacements in LSB and LPT (a and b respectively). Vertical dashed lines present time zero and vertical dotted line presents the onset time of the pre-pretensioner belt.*

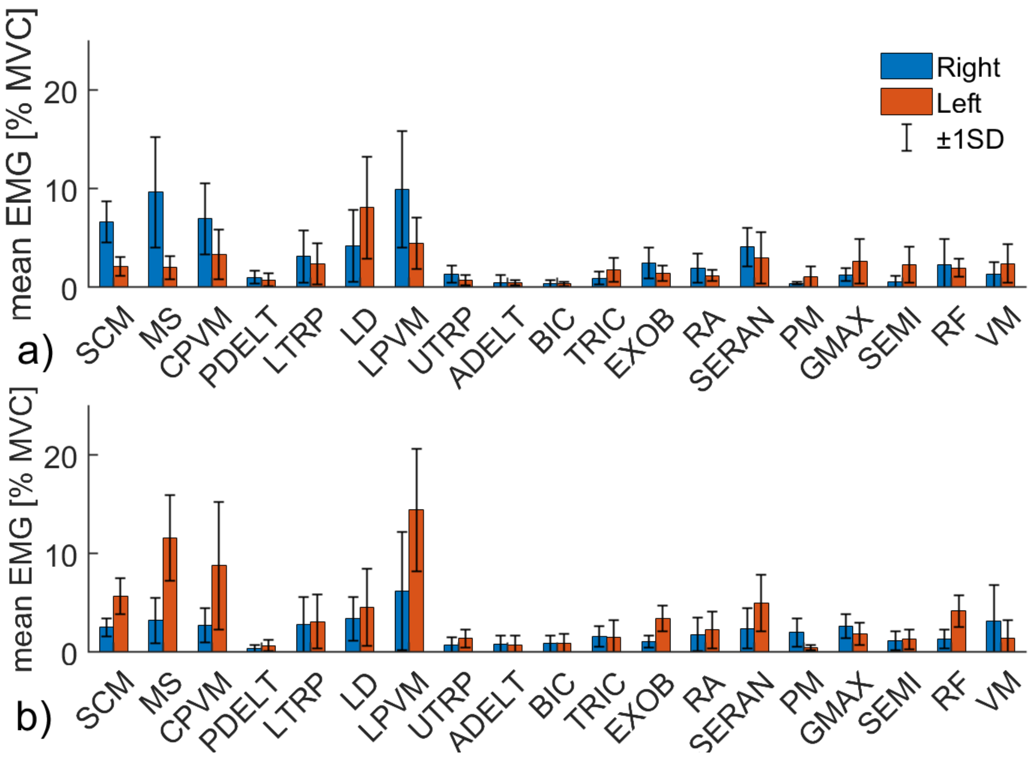

Fig. 9. *Grand average and standard deviation of EMG for the LSB maneuver, during the right turn phase and left turn phase (a and b respectively) for all muscles on the right (blue bars) and the left (red bars) sides of body. Muscle acronyms according to Definitions and Acronyms section of this thesis.*

Paper D

The focus of Paper D was to explore the variabilities in the volunteer kinematic responses to the lane change events with a standard seat belt. The kinematic data used in this paper included the head and T1 forward and lateral displacements which were previously quantified and presented for male and female passengers (Paper A and Paper C, respectively). The data set was collected from nine male and nine female adult passengers with a BMI from 18 to 23, mostly within normal range, and different age and stature. The possible influencing predictors, i.e., age, stature, and sex on the principal features of volunteers' lateral and forward displacements were investigated. PCA was performed on timeseries of quantified body kinematics. The first three PCs of the head and T1 forward and lateral displacements were found as the most important features of the examined kinematics which could explain most of the existing variances among the volunteer responses. LMM analyses were then performed on the scores of the first three PCs of the head and T1 displacements as well as their maximum lateral displacements to study the effects of age, stature, and sex on these data. The three mentioned predictors were set as fixed effects, while individual-specific effect, which was variability between volunteers, was set as a random effect in the statistical multilevel models. The models comprised all 2-way interactions of the predictors and the residuals, which were variabilities within volunteers. To specify the percentage of the variance that could be explained by the entire model with both fixed and random effects, a type of R-squared coefficient specifically generalized for LMMs, i.e., conditional R^2_{LMM}, was estimated for each metric of interest. Also, to specify the percentage of the variance that could be explained only by the fixed effects, another type of R-squared coefficient, i.e., marginal R^2_{LMM}, was estimated for each metric of interest.

About 94–98% of the variance in volunteer responses was explained by the first three PCs for each of the body kinematics. The LMM analyses resulted in statistically significant ($p < 0.05$) predictors including sex, stature, and their interaction effect found for all first PCs and maximum displacements. The individual-specific effects were also statistically significant ($p < 0.05$) whereas age was not a significant effect. For the second and third PCs, no predictors were found statistically significant. The metrics of interest were statistically modeled as a function of resultant significant predictors. According to the conditional R^2_{LMM} calculated for each model, more than 80% of the variance could be explained by both fixed and random effects whereas according to the marginal R^2_{LMM}, not more than 6% of the variance could be explained only by the fixed effects. Examples of predicted kinematic corridors for different categories of sex and stature (e.g., Fig.10) suitable for validation of HBMs that incorporate these body characteristics were also presented. As can be seen in Fig.10, the model predicted almost the same curves based on the effect of PC1s for 50th percentile and 5th percentile females (stature:

162 cm and stature:151 cm respectively, Schneider *et al*. 1983). This was due to the volunteer displacements did not differ greatly as a function of stature in the female group. In contrast, the volunteer displacements differed significantly as a function of stature in the male group. The information provided in this paper can be used in the assessment of HBMs of different age, stature, and sex to improve the advanced safety systems.

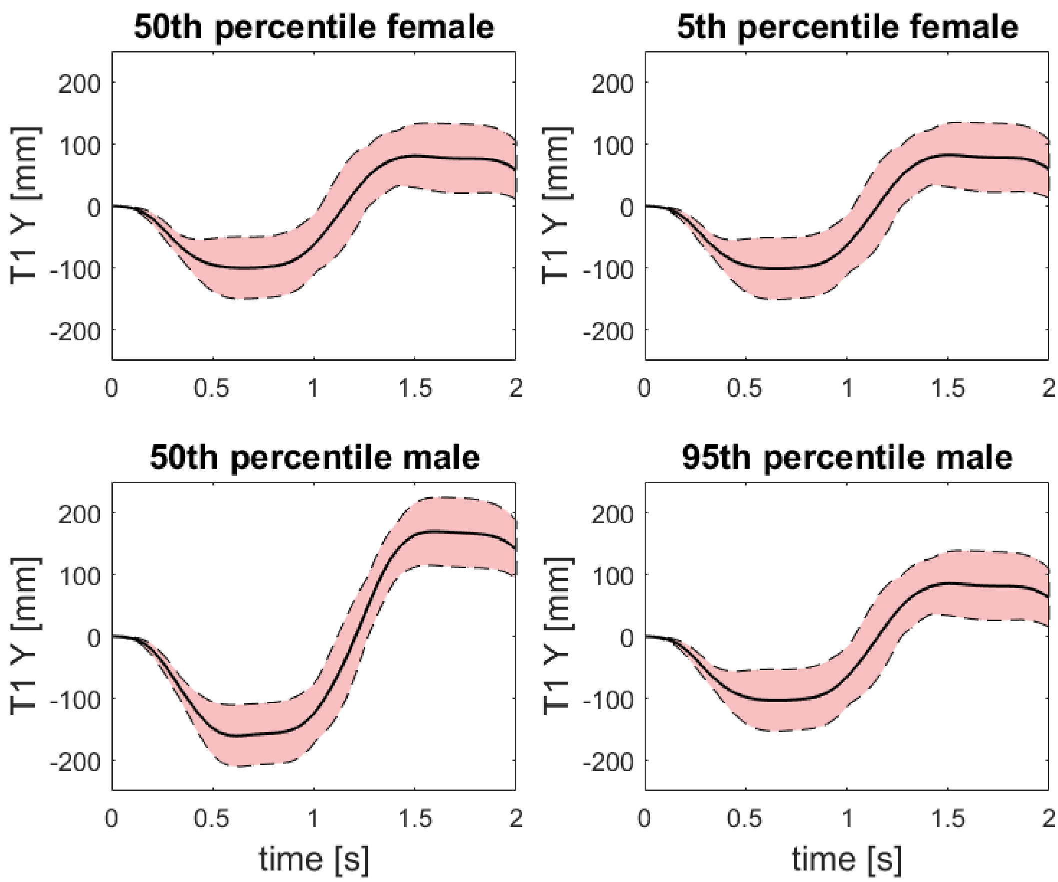

Fig. 10. *Corridors of T1 lateral displacement in lane change events with a standard seat belt. The effect of PC1 (solid black) is predicted for 50th percentile female (stature: 162 cm), 5th percentile female (stature: 151 cm), 50th percentile male (stature: 175 cm) and 95th percentile male (stature: 186 cm), and ±SD (dashed black) is the estimated standard deviation. Percentile values are based on Schneider et al. (1983).*

4. DISCUSSION

4.1. Volunteer Kinematics and Muscle Responses

The vehicle-based experiments as used in this thesis have advantages and disadvantages compared to sled tests, the most common method applied in vehicle occupant studies (Beeman *et al.* 2011, Ejima *et al.* 2007, Ejima *et al.* 2008, Choi *et al.* 2005, Ejima *et al.* 2012, van Rooij *et al.* 2013, Ólafsdóttir *et al.* 2015, Dehner *et al.* 2013). The use of a test vehicle outdoors provided more realistic data than a sled setup conducted in a laboratory indoors. On the other hand, some factors such as weather conditions and limited space inside the test vehicle restricted recording the kinematics. For instance, the pelvis and lower extremities were obscured by the vehicle interior structures and hence could not be captured by the cameras.

Although the volunteer responses presented in this thesis cannot be compared with previous studies due to the boundary conditions in those studies not matching this study, all studies comprising lateral loading are reasonably consistent with regard to upper torso lateral motion (Ejima *et al.* 2012, van Rooij *et al.* 2013, Huber *et al.* 2013, Huber *et al.* 2015). To a certain extent, biomechanical studies have confirmed that muscle activation can affect body posture and kinematics in a crash event (Hendler *et al.* 1974, Begeman *et al.* 1980), as well as pre-crash events to a greater degree. This thesis covered both kinematics and normalized muscle activity in response to different loading scenarios.

Surface versus indwelling electrodes

In this work, muscle activities were recorded using surface electrodes. Another technique for recording EMG, uses indwelling electrodes inserted inside the muscles through wires. The indwelling electrodes provide more accurate measurements of any electrical activity produced by individual muscles than the surface electrodes. This is because surface electrodes record muscle activations which have been attenuated by electrical resistance of the internal tissues and the skin. Such superficial activation can also be influenced and overlapped by the surrounding muscles or any muscles located deeper than the target muscle. The indwelling electrodes have been used in a volunteer study performed in the laboratory to record neck muscle activities in omnidirectional loading cases (Ólafsdóttir *et al*. 2015). Using such EMG data enabled them to determine activation patterns and spatial distribution of the activated muscles, and to implement this information for the development of spatial tuning patterns in the active HBM (Ólafsdóttir *et al*. 2015 and Ólafsdóttir *et al*. 2019). However, because of the safety aspects, application of indwelling electrodes for studies of volunteers travelling in vehicles is particularly restricted.

Choice of muscles for recording surface EMG

As stated in the summary of Appended Papers, surface EMG data derived from 19 muscles located all over the body were measured bilaterally. Only some of those muscles, i.e., Sternocleidomastoid (SCM), Cervical Paravertebral Muscles (CPVM), Upper Trapezius

(UTRP), Anterior Deltoid (ADELT), Lumbar Paravertebral Muscles (LPVM), Latissimus Dorsi (LD), Rectus Abdominis (RA), External Oblique (EXOB), and Rectus Femoris (RF), have previously been investigated in volunteer studies (Muggenthaler *et al.* 2005, Ejima *et al.* 2012, van Rooij *et al.* 2013, Huber *et al.* 2013). Although, with regard to future model development and validation, it would have been preferable to collect data from as many skeletal muscles potentially involved in evasive maneuvers as possible. However, several factors had to be taken into consideration in order to prioritize a number of muscles. Issues for some muscles, such as the Deltoid, include lack of space to place surface electrodes. Hence, the selection process for inclusion of certain muscles in this study involved considering the functionality of each muscle and its potential role in maintaining the vehicle occupant's seated posture and body motion during evasive maneuvers. For instance, the lateral Deltoid muscle was not prioritized since it is involved in shoulder abduction angles to a higher degree than becoming activated when vehicle occupants are exposed to evasive maneuvers. Seat contact and possible pressure artifacts were other factors considered in the muscle selection process. Some muscles such as Infraspinatus were excluded from this study because they are located below the upper Trapezius and lateral to the middle Trapezius, and to some extent, hidden by other muscles. Therefore, these muscles are difficult to distinguish by palpation and their surface EMG signals can be severely affected by other muscles.

MVC normalized EMG data

The normalization method applied for muscle activities in this work was through MVC values. Despite the fact that measuring MVCs require time-demanding contraction tests for each muscle, and is thus often avoided, normalization makes it possible to objectively compare normalized muscle activation levels between individuals in different maneuvers (Östh *et al.* 2013, Ólafsdóttir *et al.* 2013, Behr *et al.* 2010, Choi *et al.* 2005, Ólafsdóttir *et al.* 2015). The MVC-normalized EMG data are also appropriate for HBM validation purpose. The MVC tests performed in this thesis included a total of 31 different isometric contractions designed to cover almost all isometric contraction possibilities in an occupant's seated posture for muscles on the right and left side of the neck, torso, upper and lower extremities. The order in which isometric contractions were performed is stated in the appendix of Paper B. Another normalization method often used in vehicle occupant studies is normalization to maximum EMG levels recorded during the experimental task (Ejima *et al*. 2012). This approach is event-dependent and therefore is not suggested for comparing maneuvers. Normalization to the maximum EMG values recorded in all maneuvers (van Rooij *et al.* 2013) is still posture-dependent and therefore not as precise as isometric MVC.

As addressed in this work, it is also important to know about the body posture and muscle activity of the volunteers during normal driving before the maneuvers begin. With regard to muscle activity, this information provides a background level to compare with the muscle activity during the maneuvers. Furthermore, they can serve as input for the initial states of active HBMs. With regard to body posture, any voluntary motion that displaces the volunteers from their neutral (i.e., sitting still and looking forward) seated posture immediately prior to the maneuvers, should be avoided in order to provide data suitable for model validation. The results indicate that the activity was below 2.5% MVC during normal driving in all instrumented muscles except for the lumbar extensor muscles (LPVM). The LPVMs play a role in maintaining the seated posture which may be the reason for the activity being higher during normal driving, although the activity may partially be due to the pressure artifacts from the backrest contact.

The low muscle activity observed in the upper extremities was expected since the test subjects were passengers who rested their arms on their lap and did not hold on to any interior vehicle structures. The neck muscles (SCM, MS, and CPVM), lumbar extensor muscles (LPVM) and abdomen muscles (EXOB) had noticeable activation levels (3–24% MVC) on both sides of the body. All these neck muscles play important roles in head rotation, while lateral flexion, i.e., head rotation around the x-axis, was found to be the main head rotation. The linear displacement for the head was found slightly longer than T1 in all types of loading scenarios. High activation levels in the neck muscles can be to restrict the head relative to T1 motions. High activation levels in the LPVM and EXOB muscles may be due to the fact that these muscles are involved in lumbar rotation and lateral flexion, although any data of lumbar kinematics is not available. Furthermore, the muscles on the right-hand side of the body had high activation levels when the vehicle accelerated to the right (right turn), which was found for the left sided muscles when the vehicle accelerated to the left (left turn). Excursion of the head and T1 in the y-axis were the main linear displacements towards the left in right turns and towards right in left turns.

Pre-pretensioner versus standard seat belt

A substantial part of this work is dedicated to the comparison of volunteer responses when restrained by the pre-pretensioner versus when using a standard belt. Significantly ($p<0.05$) lower lateral and forward displacements of the head and T1 were observed for the pre-pretensioner than standard belt. Activation levels in specific muscles all over the body, such as the CPVM muscles in lane change and RF muscles in combined lane change with braking, were significantly reduced when wearing the pre-pretensioner belt compared to the standard belt. This suggests that the use of the pre-pretensioner belt reduces the motion of the volunteer during the pre-crash situation, whereas wearing the standard belt allows the body to move more freely and thus muscles are required to be more activated to restrict the movement. Also, earlier activation onset was found for some muscles in the upper body when wearing pre-pretensioner versus the standard belt. Examples of muscles with earlier activation levels include MS and CPVM muscles which originate in the cervical vertebra, the LTRP muscles which are attached to the clavicle, and EXOB abdominal muscles which are attached to the iliac crest.

Implementing PCA and LMM statistical analyses

To re-parameterize the volunteer data, principal component analysis was applied on timeseries of kinematic responses from volunteers exposed to lane change with standard belt. Around 62%–86% of the variations among head and T1 displacements were explained by PC1s. Around 6%–27% of the variations and around 4%–8% were explained by PC2s and PC3s, respectively. Less than about 6% were explained by the remaining PCs (i.e., PC4s, PC5s, etc.) in total.

Therefore, it was reasonable to include only the first three PCs in kinematics analyses as these three PCs together accounted for 94% to 98% of the variance in the data.

Furthermore, as mentioned previously, HBMs have been mostly developed for average body-size male occupants practically ignoring differences in age, stature, and sex. Experimental studies also most often include volunteers of average sizes. Considering that, the statistical multilevel analysis presented in this thesis, i.e., linear mixed model, provided valuable information on the influence of age, stature, and sex on occupant kinematic responses. This preliminary work presented statistical models as functions of the significant fixed effects, i.e., sex, stature, their interaction effect as well as the random effect, i.e., individual-specific effect. The logic behind choosing LMM as an optimum statistical method applicable for the data set studied in this work was the correlated nature of the data which contained repeated measurements per volunteer (individual). The variability both between and within individuals can be assessed by this method using fixed and random effects. Another major benefit of this method which made it suitable to our data set was that it tolerates for missing data, uneven number and uneven spacing of repeated measurements (Seltman 2018). The individual-specific effect was found quite large and statistically significant ($p<0.05$) for all metrics of interest. An interpretation for the existence of significant individual-specific effect was that there might be important unmeasured explanatory variables for each volunteer that produced this variability between individuals. The random effect, together with the fixed effects, accounted for more than 80% of the variance in the data set (based on conditional R^2_{LMM}) while the fixed effects alone could not explain more than 6% of the variance (based on marginal R^2_{LMM}). The reason for fixed effects explaining only a small amount of variance was the large random effect and the large residual in the estimated models compared to the fixed effects.

Using PCA and LMM, a statistical model was developed which enabled prediction of occupant kinematics in lane change events with respect to specified stature and sex. Another approach was to normalize kinematic responses in order to account for the effects of body size. This approach is limited because it assumes that human geometry can be linearly scaled with body size and the human response can be described by simple mechanical models. Currently, there is not a proper normalization method applicable to volunteer responses. Therefore, in this thesis, volunteer kinematics were not normalized against body size and instead they were subjected to LMM analysis to model the relationship between PC features of kinematics and volunteer's sex and stature.

4.2. Population Heterogeneity

A limited range of occupant characteristics was considered in the studies included in this thesis. The selected experimental data used for Paper A, B, C, and D comprised nine male and nine female volunteers of nearly normal BMI ranging from 18 to 23 and different age and stature. They were all sitting in the neutral posture just before the beginning of the evasive maneuvers. In the real world, there are male and female occupants with a wider range of body size and with different siting postures subjected to evasive maneuvers and exposed to traffic accidents.

Several studies have confirmed that specific factors related to these characteristics can increase the risk of injury (e.g., Kent *et al.* 2009, Bose *et al.* 2011, Ridella *et al.* 2012 and Rupp *et al.* 2013). Therefore, the variability in occupant characteristics should be considered in the design and evaluation of safety systems in order to protect the wide range of population. As explained previously, HBM as an assessment tool needs to represent this variability among vehicle occupants by means of advanced parametric modeling and morphing techniques. Subsequently, the models need to be validated against volunteer data. Although the statistical methods developed in this thesis to specify some significant predictors and to model the occupant kinematics as functions of those predictors are applied in pilot studies, they can pave the way toward further statistical analyses on volunteer data to determine more potential significant influencing factors. The general framework of the techniques used in this thesis is applicable to other volunteer data sets comprising repeated measurements. Future studies could contain a larger sample size to cover a wider range of age, body size and sitting postures. Potential associations between occupant characteristics and their responses can be more effectively examined through a diverse and large sample space.

4.3. Application in Traffic Safety

The volunteer responses to the restraint system in pre-crash scenarios, such as autonomous collision avoidance steering and braking studied in this thesis, can be directly applied for evaluating integrated safety systems. For instance, wearing a pre-pretensioner produced less body motion (as observed in the volunteer tests) and can lead to reduced contact with interior vehicle structures and consequently the lower risk of injuries compared to when wearing a standard belt. Maintaining sitting posture with less muscle activation levels as another result of using pre-pretensioner can be also beneficial for aged, less muscular people or females.

Furthermore, the provided volunteer responses are suitable for validating HBMs against the experimental data in case they both have common definitions of body motion, muscle activity, and boundary conditions. These data sets can also be used for tuning the parameters of the models to reproduce the volunteer responses. Consequently, tuned and validated models allow for parametric and sensitivity studies to investigate the effect on human body postures and muscle activities by varying the belt pre-pretensioner onset and its force level in conjunction with the applied accelerations. For instance, sagittal plane simulation studies of frontal crashes have indicated that in comparison to a nominal body posture in pre-crash situations, increased forward motion can result in early contact with the airbag leading to higher Head Injury Criterion (HIC) values (Bose *et al.* 2010) and increased belt loads (Antona *et al.* 2011). Injury prediction in other types of crashes with complex pre-crash scenarios, such as lane change with braking, by means of validated omnidirectional active HBMs will facilitate the improvement of the design of integrated safety systems. Hence, enhanced integrated safety systems would potentially optimize them to contribute to reducing the risk of injury for different vehicle occupant categories, such as passengers, drivers, males, females, young, old, obese, etc., which would, for instance, be achieved by designing occupant-specific adaptive restraint systems.

In the set of experiments which this thesis is based on, passengers were subjected to autonomous maneuvers for which they were unprepared. The maneuvers were randomized to a certain extent, and volunteers were not aware what type of maneuver they would be exposed to, or when it would begin. Data collected in this thesis are of particular importance with regard to current technology trends moving toward fully automated vehicles. The repeatability feature of the autonomous interventions used in this thesis, which enhances the experimental methodology and the reliability of results, provide insight into how occupants interact with autonomous systems in pre-crash scenarios.

Example of data application

The kinematics and muscle activation data presented in this thesis have already been applied in some traffic safety research such as a study by Larsson *et al.* (2019a). They have compared the occupant kinematic and muscle activation level predicted by the SAFER HBM v9 (Fig.11), which was enhanced with active neck and lumbar muscle controllers, to the data from male passengers in lane change and lane change with braking maneuvers using two belt configurations provided in Paper A and B of this thesis. The comparison between HBM predictions with different model modifications and the volunteer data was done using cross-correlation analysis (CORA) and then averaging the CORA scores. They concluded that for some loading scenarios, the HBM predictions were improved using active muscles compared to using the model in a passive mode, whereas for other loading scenarios, these differences were small. For lane change with braking and with standard belt, these differences were the largest (Fig.12). In lane change with braking and with pre-pretensioner belt scenario, the active model showed the best correlation to the volunteer data.

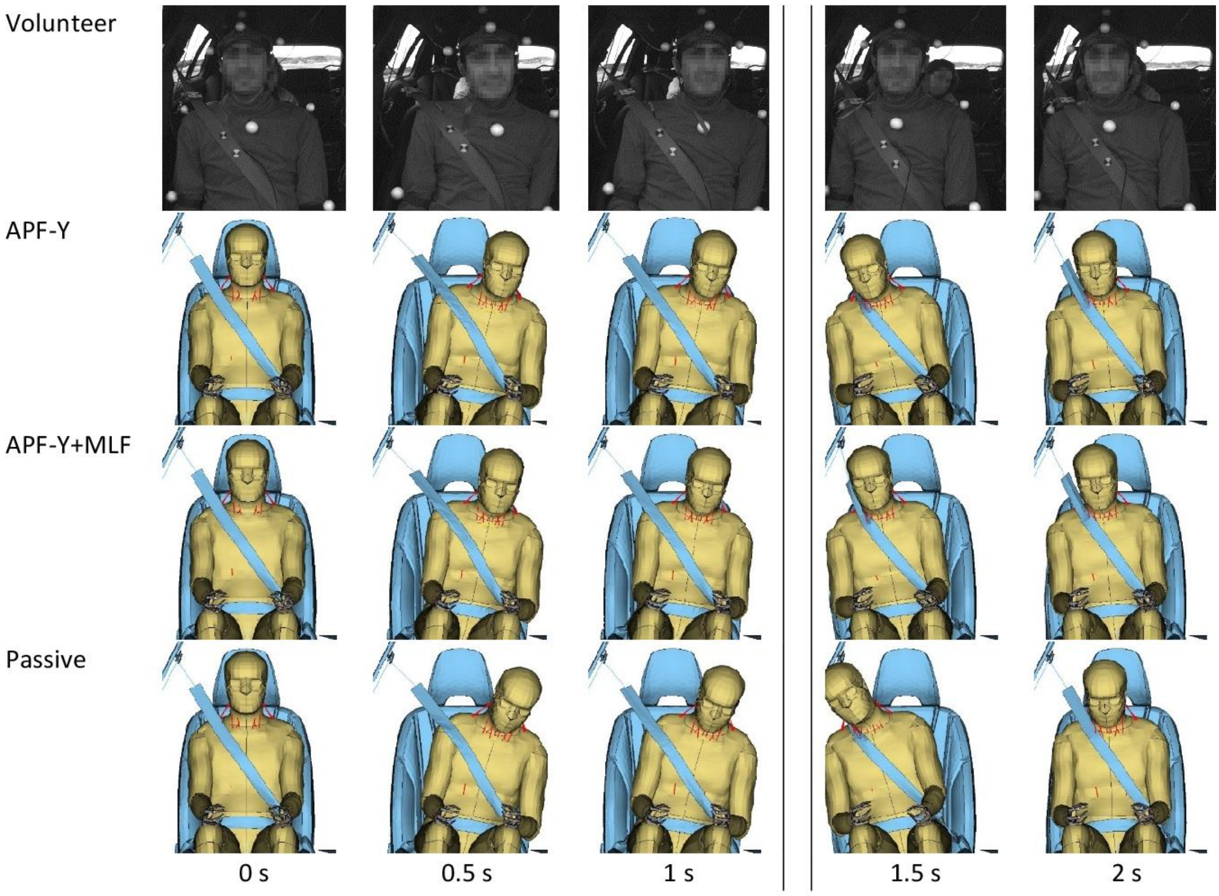

Fig. 11. *Snapshots of a volunteer compared to the HBM in the lane change with braking event, the upper row shows a volunteer, and the three lower rows show the simulation results using different modifications in the HBM, the vertical lines denote end of CORA evaluation (Larsson et al. 2019a).*

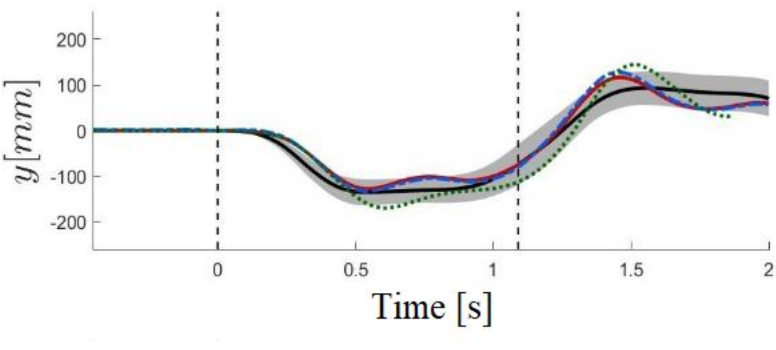

Fig. 12. *T1 lateral displacement in lane change with braking and with a standard belt. Gray curve shows corridor (i.e., mean ± SD) of volunteer data, colored curves show predictions of different modifications in HBM (Larsson et al. 2019a).*

4.4. Limitations

The experimental part of this thesis was intended to resemble actual pre-crash scenarios as closely as possible to real-world conditions. However, there were some limitations. For instance, despite using a regular test vehicle riding on a test track instead of the sled tests, surrounding traffic was still lacking. The test vehicle was not representative of all vehicle types, however, since a FE model including all boundary condition measurements of the used test vehicle already exists, it would still fulfill the requirements of boundary conditions for the purpose of reproducibility in the models, and hence HBM validation. Moreover, as the kinematics and muscle activation of volunteers can be affected by awareness of an upcoming maneuver, it is important to eliminate any signs of imminent maneuvers when investigating unprepared volunteers. In this study, volunteers were not completely unprepared, for example, they could be alerted by the sound produced within the driving robot unit mounted on the driver-side floor pan. The analytical part of this thesis was also associated with some limitations. For instance, the filtering process applied to EMG data to remove undesirable components could affect the actual recorded data. Also, the technique used to estimate body part kinematics was not fully precise. For example, an underlying assumption for calculation of Tait-Bryan rotation angles was that this method is applied to a rigid body whereas the upper torso is not truly a rigid body. Nonetheless, the method used here based on average coordinate of the markers attached to the T1 level and the Sternum provided a more accurate estimation of T1 linear excursion than using only one marker attached to the T1 level. Furthermore, some statistical limitations were imposed by the small and rather homogeneous data set in general and by the small number of volunteers for each age, stature, and sex, in particular. Nevertheless, the statistical results are still valid for the studied data set because only three covariates (i.e., sex, stature, and age) were investigated in the LMMs to ensure having the minimum number of samples per covariate in the analyses (Field, 2009). Ideally, for the experiments related to the traffic safety, a large number of volunteers, coming from different places in the world that covers a wide range of anatomical and behavioral differences, should be recruited in a complete random way. Otherwise, considering the aforementioned limitations, it might be problematic to generalize the results.

5. CONCLUSIONS AND FUTURE WORK

5.1. Conclusions

In this thesis, a set of experiments was conducted which was new and comprehensive since it involved volunteers being exposed to repeatable and typical low-g lateral loading representative of pre-crash situations while traveling in a regular car and in a realistic environment. This set of experiments was used to answer the research questions stated in section 2.2. The answer to Research Question 1 (i.e., *Are muscles activated in pre-crash? How much?*) was that several muscles predominantly in the neck, lumbar extensor and abdominal muscles are activated up to about 24% MVC, in the studied vehicle maneuvers that can potentially occur in pre-crash. Paper B and C provided surface EMG corridors for 38 instrumented muscles, from males and females respectively, all obtained either during normal driving before any extra loading conditions were applied or during replicated pre-crash lane change and combined lane change with braking maneuvers.

The answer to Research Question 2 (i.e., *Does the pre-pretensioner belt affect muscle activation? how much? Does the pre-pretensioner belt help maintain sitting posture in pre-crash? How much?*) was that the pre-pretensioner affects muscle activation. Earlier activation onset times and smaller activation amplitudes were observed for several muscles using pre-pretensioner compared to the standard belt, in both male and female groups. Also, a pre-pretensioner helps maintain sitting posture. Lower lateral and forward displacements for the head and upper torso were observed for both males and females, with the use of pre-pretensioner versus the standard belt. Paper A and C provided corridors of the head CoG and upper torso kinematics, as well as boundary conditions, such as belt interaction forces and vehicle dynamics, from males and females respectively.

The answer to Research Question 3 (i.e., *Do factors such as sex, age, and stature influence volunteer kinematic outcomes? Are their influences statistically significant? How differently do males and females respond in pre-crash?*) was that two variables, i.e., sex and stature, and their interaction significantly ($p<0.05$) influence the volunteers' kinematic outcomes. A small amount of variance in the studied data set was related to these variables. The influence of age was not significant. A statistical model was developed which can predict head and upper torso kinematics of occupants with different stature and sex. Paper D provided statistical investigations of variances among the volunteer kinematic data and presented them as a function of body characteristics. In general, males and females responded differently in the studied pre-crash situations. Females showed less lateral and forward displacement of the head and upper torso than males.

Moreover, this thesis provided a detailed set of data for HBM validation and improvement. The novel data set provided herein can be useful for improving the omnidirectional response of active HBMs. Consequently, the design of integrated safety systems in modern cars can benefit from developing more biofidelic models representing a wide range of population more accurately.

5.2. Future Work

This thesis was focused on passenger responses. Kinematic and muscle responses of male and female volunteers subjected to different evasive maneuvers, such as autonomous lane change and a combination of lane change and braking, were investigated. However, data from drivers subjected to the same evasive maneuvers were also collected as a part of the AHBM3 project and are now available for future studies. Identifying differences in the responses between drivers and passengers are of great importance in order to develop occupant-specific modelling strategies for HBMs.

The corridors presenting volunteer kinematics in Paper A and C showed that there are certain variabilities in their responses. The variations among volunteer kinematics obtained in one type of loading scenario (i.e., lane change with standard belt) were statistically studied in Paper D and resulted in preliminary statistical models of kinematics as a function of body characteristics. Further statistical investigations, using the same methods as presented in Paper D, for other types of loading scenarios and preferably with larger and more diverse sample spaces, are required in order to determine if occupant characteristics affect the responses differently for different pre-crash situations and to establish more accurate statistical models that can be generalized to the whole population. The spread in EMG corridors presented in Paper B and C demonstrated that muscle recruitment differs among different volunteers and different tests. This type of variation can generally be affected by body characteristics including sex and age but also behavioral aspects such as learning and awareness level (Siegmund *et al.* 2003a, Stenlund *et al.* 2015). Paper D investigated the statistical influence of body characteristics on head and upper torso displacements. However, for future studies, the muscle activation is also of interest to be subjected to similar statistical analyses to assess the role of these influencing factors on muscle responses as well. Volunteers included in this thesis were mostly within the normal BMI range while data from volunteers with higher BMI than normal were also collected. Future studies of those volunteers' responses to evasive maneuvers are required to recognize potential differences in vehicle occupant responses due to BMI variances. The influence of several other factors on volunteer responses such as non-optimal seat belt fit due to bulky clothing and out-of-position conditions would also be interesting to explore in future studies.

Furthermore, as a part of a larger study (the AHBM3 project), this set of experiments also included records of data from passengers and drivers in manual lane changes. This unique data set can be used in future studies on anticipatory responses in manual lane changes compared to responses from unprepared volunteers in autonomous lane changes. This is important because it has been confirmed that driver kinematics were substantially affected in anticipatory manual braking events versus autonomous braking events wherein the volunteer was unprepared for the upcoming events (Östh *et al.* 2013). To address this issue, some HBMs have incorporated specific anticipatory control modules (Östh et al. 2014). This experimental data set can potentially facilitate the development of anticipatory control modules in active HBMs that simulate events such as evasive steering.

REFERENCES

Antona J, Ejima S, and Zama Y (2011) 'Influence of the driver conditions on the injury outcome in front impact collisions', *International journal of automotive engineering,* 2(2): 33–38.

Aparicio F (2005) EEVC WG19 Activities on Primary and Secondary Safety Interaction. Paper presented at: 19th International Technical Conference on the Enhanced Safety of Vehicles, June 6–9, Washington (DC).

Beeman S M, Kemper A R, Madigan M L, Franck C T, and Loftus S C (2012) 'Occupant kinematics in low-speed frontal sled tests: Human volunteers, Hybrid III ATD, and PMHS', *Accident Analysis and Prevention,* 47: 128–139.

Behr M, Poumarat G, Serre T, Arnoux P J, Thollon L, and Brunet C (2010) 'Posture and muscular behaviour in emergency braking: An experimental approach', *Accident Analysis and Prevention,* 42(3): 797–801.

Barbero M, Merletti R, and Rainoldi A (2012) 'Features of the Single-Channel sEMG Signal', *Atlas of Muscle Innervation Zones,* Italia: Springer, pp. 49–59.

Begeman P C, King A I, Levine R S, and Viano D C (1980) 'Biodynamic response of the musculoskeletal system to impact acceleration', Paper presented at Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA, pp. 479–509.

Beeman S M, Kemper A R, Madigan M L and Duma S M (2011) 'Effects of bracing on human kinematics in low-speed frontal sled tests', *Annals of biomedical engineering,* 39(12): 2998–3010.

Blouin J S, Inglis J T and Siegmund G P (2006) 'Startle responses elicited by whiplash perturbations' *The Journal of physiology,* 573(3): 857–867.

Bohlin N (1967) 'A Statistical Analysis of 28,000 Accident Cases with Emphasis on Occupant Restraint Value', Paper presented at the 11th Stapp Car Crash Conference, Anaheim, CA, USA.

Bose D, Crandall J R, Untaroiu C D, and Maslen E H (2010) 'Influence of pre-collision occupant parameters on injury outcome in a frontal collision', *Accident Analysis and Prevention,* 42(4): 1398–1407.

Bose D, Segui-Gomez M, and Crandall J R (2011) 'Vulnerability of Female Drivers Involved in Motor Vehicle Crashes: An Analysis of US Population at Risk', *American Journal of Public Health*, 101(12): 2368–73.

Brolin E, Högberg D, Hanson L, and Örtengren R (2017) ‘Adaptive regression model for synthesizing anthropometric population data’, *International Journal of Industrial Ergonomics*, 59: 46–53.

Brolin K, Halldin P, and Leijonhufvud I (2005) ‘The effect of muscle activation on neck response’, *Traffic injury prevention*, 6(1): 67–76.

Brolin K, Hedenstierna S, Halldin P, Bass C, and Alem N (2008) ‘The importance of muscle tension on the outcome of impacts with a major vertical component’, *International Journal of Crashworthiness*, 13(5): 487–498.

Carlsson A, Chang F, Lemmen P, Kullgren A, Schmitt K U, Linder A, and Svensson M Y (2014) ‘Anthropometric Specifications, Development, and Evaluation of EvaRID – A 50th Percentile Female Rear Impact Finite Element Dummy Model’, *Traffic Injury Prevention*, 15(8): 855–65.

Carlsson S and Davidsson J (2011) ‘Volunteer occupant kinematics during driver initiated and autonomous braking when driving in real traffic environments’, Paper presented at: International Research Council on Biomechanics of Injury, September 14–16, Krakow, Poland.

Carstensen T, Frostholm L, Oernboel E, Kongsted A, Kasch H, Jensen T, and Fink P (2012) ‘Are there Gender Differences in Coping with Neck Pain Following Acute Whiplash Trauma? A 12-Month Follow-up Study’, *European Journal of Pain*, 16(1): 49–60.

Choi H, Sah S, Lee B, Cho H, Kang S, Mun M, Lee I, and Lee J (2005) ‘Experimental and numerical studies of muscular activations of bracing occupant’, Paper presented at: 19th International Technical Conference on the Enhanced Safety of Vehicles, Washington, DC, paper no. 05-0139.

Coelingh E, Jakobsson L, Lind H, and Lindman M (2007) ‘Collision Warning with Auto Brake – A Real-life Safety Perspective’, Paper presented at: 20th International Technical Conference on the Enhanced Safety of Vehicles, Lyon, France.

Cummings P, Wells J D, and Rivara F P (2003) ‘Estimating Seat Belt Effectiveness using Matched-pair Cohort Methods’, *Accident Analysis and Prevention*, 35:143–149.

de Luca C (1997) ‘The use of surface electromyography in biomechanics’, *Journal of Applied Biomechanics*, 13: 135–163.

de Vlugt E, Schouten A C, and van der Helm FCT (2002) ‘Adaptation of Reflexive Feedback during Arm Posture to Different Environments’, *Biological Cybernetics*, 87: 10–26.

de Vlugt E, Schouten A C, and van der Helm FCT (2006) ‘Quantification of Intrinsic and Reflexive Properties during Multijoint Arm Posture’, *Journal of Neuroscience Methods*, 155: 328–349.

Dehner C, Schick S, Kraus M, Hell W, and Kramer M (2013) ‘Muscle activity influence on the kinematics of the cervical spine in rear-end sled tests in female volunteers’, *Traffic Injury Prevention*, 14(4): 369–377.

Devane K, Johnson D, and Gayzik F S (2019) ‘Validation of a simplified human body model in relaxed and braced conditions in low-speed frontal sled tests’, *Traffic Injury Prevention*, 20(8): 832–837.

Develet J-A, Carlsson A, Svensson M, Fredriksson R, Bråse D, and Holcombe S (2013) ‘Evaluation of the Biofidelity of the BioRID-II and THOR-NT Anthropometric Test Devices under Seatbelt Pre-Pretensioner Loading in Stationary Conditions’, Paper presented at: Ohio State University Injury Biomechanics Seminar, Columbus, OH, USA.

Dibb A T, Cutcliffe H C, Luck J F, Cox C A, Myers B S, Bass C R, Arbogast K B, Seacrist T, and Nightingale R W (2014) ‘Pediatric Head and Neck Dynamics in Frontal Impact: Analysis of Important Mechanical Factors and Proposed Neck Performance Corridors for 6- and 10-Year-Old ATDs’, *Traffic Injury Prevention*, 15(4): 386–394.

Donlon J, Poulard D, Lessley D, Riley P, and Subit D (2015) ‘Understanding how pre-impact posture can affect injury outcome in side impact sled tests using a new tool for visualization of cadaver kinematics’, *Journal of Biomechanics*, 48(3): 529–533.

Donlon J, Richardson R, Jayathirtha M, Forman J, Kerrigan J, Kent R, Arbogast K, Maripudi V, and Scavnicky M (2020) ‘Kinematics of inboard-leaning occupants in frontal impacts’, *Traffic Injury Prevention*, 21(4): 272–277.

Ejima S, Ito D, Satou F, Mikami K, Ono K, Kaneoka K, and Shiina I (2012) ‘Effects of pre-impact swerving / steering on physical motion of the volunteer in the low-speed side-impact sled test’, Paper presented at: International Research Council on Biomechanics of Injury, Dublin, Ireland, pp. 352–366.

Ejima S, Ono K, Holcombe S, Kaneoka K, and Fukushima M (2007) ‘A study on occupant kinematics behaviour and muscle activities during pre-impact braking based on volunteer tests’, Paper presented at: International Research Council on Biomechanics of Injury, Maastricht, Netherlands, pp. 31–45.

Ejima S, Zama Y, Ono K, Kaneoka K, Shiina I, and Asada H (2009) ‘Prediction of pre-impact occupant kinematic behavior based on the muscle activity during frontal collision’, Paper presented at: International Technical Conference on the Enhanced Safety of Vehicles, Stuttgart, Germany, June 15–18.

Ejima S, Zama Y, Satou F, and Holcombe S (2008) 'Prediction of the physical motion of the human body based on muscle activity during pre-impact braking', Paper presented at: International Research Council on Biomechanics of Injury, Bern, Switzerland, pp. 163–175.

European Commission 2020, Available at: https://ec.europa.eu/commission/presscorner/detail/en/IP_20_1003, Accessed: 25 July 2021.

Farina D (2006) 'Interpretation of the surface electromyogram in dynamic contractions', *Exercise and Sport Sciences Reviews,* 34(3): 121–127.

Farina D, Cescon C, and Merletti R (2002a) 'Influence of anatomical, physical, and detection-system parameters on surface EMG', *Biological Cybernetics,* 86(6): 445–456.

Fatality Analysis Reporting System (FARS) 2021, Available at: https://www.iihs.org/topics/fatality-statistics/detail/passenger-vehicle-occupants, Accessed: 25 July 2021.

Field A (2009) Discovering Statistics Using IBM SPSS STATISTICS, Chapter 20, SAGE Publications Ltd, 3rd edition.

Frampton R and Thomas P (2007) 'Effectiveness of Electronic Stability Control Systems in Great Britain', Report prepared for the Department for Transport, VSRC, Loughborough, UK.

Gadd C (1966) 'Use of a Weighted-Impulse Criterion for Estimating Injury Hazard', SAE Technical Paper 660793.

Gayzik F S G, Oreno D P M, Eer C P G, Uertzer S D W, Artin R S M, and Titzel J D S (2011) 'Development of a Full Body CAD Dataset for Computational Modeling: A Multi-modality Approach', *Annals of Biomedical Engineering, 39*(10): 2568–2583.

Good C A, Viano D C, and Ronsky J L (2008a) 'Biomechanics of Volunteers Subject to Loading by a Motorized Shoulder Belt Tensioner', *Spine* 33: E225–E235.

Good C A, Viano D C, and Ronsky J L (2008b) 'The Hybrid III Dummy Family Subject to Loading by a Motorized Shoulder Belt Tensioner', *SAE International Journal of Passenger Cars Mechanical Systems,* 1(1): 383–395.

Happee R, Morsink P, Lange R D, Bours R, Ridella S, Nayef A, and Hoof J V (2000) 'Mathematical human body models representing a mid size male and a small female for frontal, lateral and rearward impact loading', Paper presented at: International Research Council on Biomechanics of Injury, September 20-22, Montpellier, France, pp.1–18.

Hendler E, O'Rourke J, Schulman M, Katzeff M, Domzalski L, and Rodgers S (1974) 'Effect of head and body position and muscular tensing on response to impact', Paper presented at: Stapp Car Crash Conference, Society of Automotive Engineers, Warrendale, PA, pp. 303–337.

Hodges PW (1999) 'Is there a Role for Transversus Abdominis in Lumbo-Pelvic Stability?', *Manual Therapy,* 4(2): 74–86.

Holcombe S A, Brown E, Agnew A M, and Wang S C (2020) 'Average male and female rib cross-sectional shapes via PCA', Paper presented at: International Research Council on Biomechanics of Injury, Asia Conference, pp 56–59.

Holt C, Douglas E, Graci V, Seacrist T, Kerrigan J, Kent R, Balasubramanian S, and Arbogast K (2018) 'Effect of Countermeasures on Adult Kinematics during Pre-Crash Evasive Swerving', Paper presented at: International Research Council on Biomechanics of Injury, September 12–14, Athens, Greece.

Huber P, Christova M, D'Addetta G A, Gallasch E, Kirschbichler S, Mayer C, Prüggler A, Rieser A, Sinz W, and Wallner D (2013) 'Muscle Activation Onset Latencies and Amplitudes during Lane Change in a Full Vehicle Test', Paper presented at: International Research Council on Biomechanics of Injury, Gothenburg, Sweden, pp. 628–640.

Huber P, Kirschbichler S, Pruggler A, Steidl T. (2015) 'Passenger kinematics in braking, lane change and oblique driving maneuvers', Paper presented at: International Research Council on Biomechanics of Injury, September 9-11, Lyon, France, pp: 783–802.

Hwang E, Hallman J, Klein K, Rupp J, Reed M, and Hu J (2016 a) 'Rapid Development of Diverse Human Body Models for Crash Simulations through Mesh Morphing', SAE Technical Paper 2016-01-1491, doi 10.4271/2016-01-1491.

Hwang E, Hu J, Chen C, Klein K, Miller C, Reed M, Rupp J, and Hallman J (2016 b) 'Development, Evaluation, and Sensitivity Analysis of Parametric Finite Element Whole-Body Human Models in Side Impacts', *Stapp Car Crash Journal*, 60: 473–508.

Iraeus J and Pipkorn B (2019) 'Development and validation of a generic finite element ribcage to be used for strain-based fracture prediction', Paper presented at: International Research Council on Biomechanics of Injury, September 11–13, Florence, Italy, pp: 193–210.

Ito D, Ejima S, Kitajima S, Katoh R, Ito H, Sakane M, Nishino T, Nakayama K, Ato T, and Kimura T (2013) 'Occupant Kinematic Behavior and Effects of a Motorized Seatbelt on Occupant Restraint of Human Volunteers during Low Speed Frontal Impact: Mini-sled Tests with Mass Production Car Seat', Paper presented at: International Research Council on Biomechanics of Injury, Gothenburg, Sweden.

Iwamoto M, Kisanuki Y, Watanabe I, Furusu K, Miki K, and Hasegawa J (2002) 'Development of a finite element model of the total human model for safety (THUMS) and application to injury reconstruction', Paper presented at: International Research Council on Biomechanics of Injury, Munich, Germany.

Iwamoto M and Nakahira Y (2015) 'Development and Validation of the Total HUman Model for Safety (THUMS) Version 5 Containing Multiple 1D Muscles for Estimating Occupant Motions with Muscle Activation During Side Impacts', *Stapp Car Crash Journal*, *59*: 53–90.

Iwamoto M, Nakahira Y, Kimpara H, Sugiyama T, and Min K (2012) 'Development of a human body finite element model with multiple muscles and their controller for estimating occupant motions and impact responses in frontal crash situations', *Stapp Car Crash Journal,* 56: 231–268.

Jakobsson L, Norin H, and Svensson M Y (2004) 'Parameters Influencing AIS 1 Neck Injury Outcome in Frontal Impacts', *Traffic Injury Prevention,* 5(2):156–63.

Kato D, Nakahira Y, and Iwamoto M (2017) 'A study of muscle control with two feedback controls for posture and reaction force for more accurate prediction of occupant kinematics in low-speed frontal impacts', Paper presented at: 25th International Technical Conference on the Enhanced Safety of Vehicles, June 5–8, Detroit, USA.

Kato D, Nakahira Y, Tsumi N, and Iwamoto M (2018) 'Development of human body model THUMS version 6 containing muscle controllers and application to injury analysis in frontal collision after brake deceleration', Paper presented at: International Research Council on Biomechanics of Injury, September 12–14, Athens, Greece.

Kent R, Trowbridge M, Lopez-Valdes F J, Ordoyo R H, and Segui-Gomez M (2009) 'How many people are injured and killed as a result of aging? Frailty, Fragility, and the elderly risk-exposure tradeoff assessed via a risk saturation model', *Annals of Advances in Automotive Medicine*, 53: 41–50.

Kirschbichler S, Huber P, Pruggler A, Steidl T, Sinz W, Mayer C, and D`Addetta G A (2014) 'Factors influencing occupant kinematics during braking and lane change maneuvers in a passenger vehicle', Paper presented at: International Research Council on Biomechanics of Injury, September 10–12, Berlin, Germany.

Krafft M, Kullgren A, Lie A, and Tingvall C (2003) 'The Risk of Whiplash Injury in the Rear Seat Compared to the Front Seat in Rear Impacts'. *Traffic Injury Prevention,* 4(2): 136–40.

Kumar S, Narayan Y, and Amell T (2002) ‘An electromyographic study of low-velocity rear-end impacts’, *Spine,* 27(10): 1044–1055.

Larsson E, Iraeus J, Fice J, Pipkorn B, Jakobsson L, Brynskog E, Brolin K, and Davidsson J (2019a) ‘Active Human Body Model Predictions Compared to Volunteer Response in Experiments with Braking, Lane Change, and Combined Manoeuvres’, Paper presented at: International Research Council on Biomechanics of Injury, September 11–13, Florence, Italy.

Larsson K J, Pipkorn B, Iraeus J, Bolte IV JH, Agnew A M, Hu J, Reed M P, and Sunnevång C (2019b) ‘Evaluation of the Benefits of Parametric Human Body Model Morphing for Prediction of Injury to Elderly Occupants in Side Impact’, Paper presented at: International Research Council on Biomechanics of Injury, September 11–13, Florence, Italy.

Lemmen P, Fagerlind H, Unselt T, Rodarius C, Infantes E, and Zweep C (2012) ‘Assessment of Integrated Vehicle Safety Systems for Improved Vehicle Safety’, *Procedia - Social and Behavioral Sciences,* 48: 1632–1641.

Lie A, Strandroth J, and Tingvall C (2013) Government Status Report, Sweden, Presented at: 23rd International Technical Conference on the Enhanced Safety of Vehicles, Seoul, South Korea.

Mages M, Seyffert M, and Class U (2011) ‘Analysis of the Pre-Crash Benefit of Reversible Belt Pre-pretensioning in Different Accident Scenarios’, Paper presented at: 22nd International Technical Conference on the Enhanced Safety of Vehicles, Washington, D.C., USA.

Martynenko O V, Neininger F T, and Schmitt S (2019) ‘Development of a Hybrid Muscle Controller for an Active Finite Element Human Body Model in LS-DYNA Capable of Occupant Kinematics Prediction in Frontal and Lateral Maneuvers’, Paper presented at: 26th International Technical Conference on the Enhanced Safety of Vehicles, Eindhoven, Netherlands.

Massion J (1992) ‘Movement, Posture and Equilibrium: Interaction and Coordination’, *Progress in Neurobiology,* 38: 35–56.

Meijer R, Broos J, Elrofai H, de Bruijn E, Forbes P, and Happee R (2013) ‘Modelling of bracing in a multi-body active human model’, Paper presented at International Research Council on Biomechanics of Injury, Gothenburg, Sweden, pp. 576–587.

Morris A P and Thomas P D. (1996) ‘Neck Injuries in the UK Co-operative Crash Injury Study’, Paper presented at Stapp Car Crash Conference, Warrendale, PA: Society of Automotive Engineers, pp. 317–29.

Muggenthaler H, Adamec J, Praxl N, and Schönpflug M (2005) ‘The influence of muscle activity on occupant kinematics’, Paper presented at: International Research Council on Biomechanics of Injury, September 21–23, Prague, Czech Republic, pp. 313–323.

National Highway Traffic Safety Administration (NHTSA) 2020, Available at: https://www.nhtsa.gov/press-releases/nhtsa-releases-2019-crash-fatality-data, Accessed: 25 July 2021.

Norin H, Carlsson G, and Korner J (1984) ‘Seat Belt Usage in Sweden and Its Injury Reducing Effect’, SAE Technical Paper 840194, Society of Automotive Engineers, Warrendale, PA.

Ólafsdóttir J M, Brolin K, Blouin J S, and Siegmund G P (2015) ‘Dynamic Spatial Tuning of Cervical Muscle Reflexes to Multidirectional Seated Perturbations’, *SPINE*, 40(4): E211–E219.

Ólafsdóttir J M, Östh J, and Brolin K (2019) ‘Modelling Reflex Recruitment of Neck Muscles in a Finite Element Human Body Model for Simulating Omnidirectional Head Kinematics’, Paper presented at: International Research Council on Biomechanics of Injury, September 11–13, Florence, Italy.

Ólafsdóttir J M, Östh J, Davidsson J, and Brolin K (2013) ‘Passenger kinematics and muscle responses in autonomous braking events with standard and reversible pre-tensioned restraints’, Paper presented at: International Research Council on Biomechanics of Injury, Gothenburg, Sweden, pp. 602–617.

Östh J, Brolin K, and Bråse D (2015) ‘A Human Body Model With Active Muscles for Simulation of Pretensioned Restraints in Autonomous Braking Interventions’, *Traffic Injury Prevention*, 16(3): 304–313.

Östh J, Brolin K, Carlsson S, Wismans J, and Davidsson J (2012) ‘The occupant response to autonomous braking: A modeling approach that accounts for active musculature’, *Traffic Injury Prevention*, 13(3): 265–277.

Östh J, Eliasson E, Happee R, and Brolin K (2014) ‘A method to model anticipatory postural control in driver braking events’, *Gait & Posture*, 40(4): 664–669.

Östh J, Mendoza-Vazquez M, Sato F, Svensson M Y, Linder A, and Brolin K (2017) ‘A female head–neck model for rear impact simulations’, *Journal of Biomechanics*, 51: 49–56.

Östh J, Olafsdóttir J M, Davidsson J and Brolin K (2013) ‘Driver kinematic and muscle responses in braking events with standard and reversible pre-tensioned restraints: validation data for human models’, *Stapp Car Crash Journal*, 57: 1–41.

Parkinson M B and Reed M P (2010) ‘Creating virtual user populations by analysis of anthropometric data’, *International Journal of Industrial Ergonomics*, 40(1): 106–111.

Pipkorn B, Iraeus J, Björklund M, Bunketorp O, and Jakobsson L (2019) ‘Multi-scale validation of a rib fracture prediction method for human body models’, Paper presented at: International Research Council on Biomechanics of Injury, September 11–13, Florence, Italy, pp: 175–192.

Putra I P A, Iraeus J, Sato F, Svensson M Y, Linder A, and Thomson R (2021) ‘Optimization of Female Head-Neck Model with Active Reflexive Cervical Muscles in Low Severity Rear Impact Collisions’, *Annals Biomedical Engineering*, 49(1): 115–128.

Rasmussen J, Waagepetersen R P, and Rasmussen K P (2018) ‘Projection of anthropometric correlation for virtual population modelling’, *International Journal of Human Factors Modelling and Simulation,* 6(1): 16–30.

Rasmussen J, Lund M E, and Waagepetersen R P (2020) ‘Data-based parametric biomechanical models for cyclic motions’, In L. Hanson, D. Hogberg, & E. Brolin (Eds.), DHM 2020, Paper presented at: 6th International Digital Human Modeling Symposium, pp. 372–379. IOS Press. Advances in Transdisciplinary Engineering Vol. 11.

Reed M P, Ebert S M, Jones M L H, Park B K D, Hallman J J, and Sherony R (2018) ‘Passenger head kinematics in abrupt braking and lane change events’, *Traffic Injury Prevention*, 19(S2): 70–77.

Ridella S, Rupp J D, and Poland K (2012) ‘Age-Related Differences in AIS 3+ Crash Injury Risk, Types, Causation and Mechanisms’, Paper presented at: International Research Council on Biomechanics of Injury, Dublin, Ireland, pp. 43–60.

Ruan J, El-Jawahri R, Chai L, Barbat S, and Prasad P (2003) ‘Prediction and analysis of human thoracic impact responses and injuries in cadaver impacts using a full human body finite element model’, *Stapp Car Crash Journal*, 47: 299–321.

Rupp J D, Carol C A, Leslie A J, Hoff C N, Reed M P, and Cunningham R M (2013) ‘Effects of BMI on the risk and frequency of AIS 3+ injuries in motor-vehicle crashes’, *Obesity*, 21(1): 88–97.

Samuels M A, Reed M P, Arbogast K B, and Seacrist T (2016) ‘Modeling spatial trajectories in dynamics testing using basis splines: application to tracking human volunteers in low-speed frontal impacts’, *Computer Methods in Biomechanics and Biomedical Engineering*, 19(10): 1046–1052.

Schittenhelm H (2009) ‘The Vision of Accident Free Driving – How Efficient are We Actually in Avoiding or Mitigating Longitudinal Real World Accidents’, Paper presented at: 21st International Technical Conference on the Enhanced Safety of Vehicles, Stuttgart, Germany.

Schneider L W, Robbins D H, Pflüg M A, and Snyder R G (1983) ‘Development of Anthropometrically Based Design Specifications for an Advanced Adult Anthropomorphic Dummy Family, Volume 1’, Washington, DC: US Department of Transportation, National Highway Traffic Safety Administration. Final report DOT-HS-806-715.

Schöneburg R, Baumann K-H, and Fehring M (2011) ‘The Efficiency of PRE-SAFE® Systems in Pre-braked Frontal Collision Situations’, Paper presented at: 22nd International Technical Conference on the Enhanced Safety of Vehicles, Washington, D.C., USA.

Seacrist T, Saffioti J, Balasubramanian S, Kadlowec J, Sterner R, García-España J, Arbogast K, and Maltese M (2012) ‘Passive cervical spine flexion: the effect of age and gender’, *Clinical Biomechanics,* 27(4): 326–333.

Seltman H J (2018) ‘Experimental Design and Analysis’, Chapter 15, Available at: http://www.stat.cmu.edu/~hseltman/309/Book/Book.pdf, Accessed: 25 July 2021.

Shah C S, Yang K H, and Hardy W N (2001) ‘Development of a computer model to predict aortic rupture due to impact loading’, *Stapp Car Crash Journal,* 45: 161–182.

Siegmund G P, Sanderson D J, Myers B S, and Inglis J T (2003) ‘Rapid neck muscle adaptation alters the head kinematics of aware and unaware subjects undergoing multiple whiplash-like perturbations’, *Journal of Biomechanics,* 36(4): 473–482.

Staudenmann D, Roeleveld K, Stegeman D F, and van Dieën J H (2010) ‘Methodological aspects of SEMG recordings for force estimation–a tutorial and review’, *Journal of Electromyography and Kinesiology*, 20(3): 375–87.

Stemper B D, Yoganandan N, Cusick J F, and Pintar F A (2006) ‘Stabilizing effect of precontracted neck musculature in whiplash’, *Spine,* 31(20): E733–E738.

Stenlund T, Lundström R, Lindroos O, Häger C, Burström L, Neely G, and Rehn B (2015) ‘Seated postural neck and trunk reactions to sideways perturbations with or without a cognitive task’, *Journal of Electromyography and Kinesiology*, *25*(13): 548–556.

Subit D, Möhler F, Wass J, and Pipkorn B (2016) ‘Robustness of Principal and Longitudinal Strains as Fracture Predictors in Side Impact’, Paper presented at: International Research Council on Biomechanics of Injury, September 14–16, Malaga, Spain, pp. 556–569.

Sun W, Jin J H, Reed M P, Gayzik F S, Danelson K A, Bass C R, Zhang J Y, and Rupp J D (2016) 'A method for developing biomechanical response corridors based on principal component analysis', *Journal of Biomechanics*, 49(14): 3208–3215.

Temming J and Zobel R (1998) 'Frequency and Risk of Cervical Spine Distortion Injuries in Passenger Car Accidents: Significance of Human Factors Data', Paper presented at: International Research Council on Biomechanics of Injury, September 16–18, Gothenburg, Sweden.

Thomas P, Wozdin E, Mackay M, Cesari D, Crandall C, Gennarelli T, Langwieder K, Lovesund P, Mclean A, Mellander H, Mohan D, Ono K, Otte D, Walz F, and Wismans J (2006) 'Future research directions in injury biomechanics and passive safety research', Paper presented at: International Research Council on Biomechanics of Injury, September 20–22, Madrid, Spain.

Tobata H, Takagi H, Pal C, and Fukuda S (2003) 'Development of Pre-Crash Active Seatbelt System for Real World Safety', Paper presented at: 18th International Technical Conference on the Enhanced Safety of Vehicles, Nagoya, Japan.

Unselt T, Mayer C, Chin E, Aparicio A, Muñoz O, Ranovona M, Tsuchida J, and Winkler B (2011) 'Assessment of behavioural aspects in integrated safety systems (EU FP7 project ASSESS)', Paper presented at: International Technical Conference on the Enhanced Safety of Vehicles, Washington, USA, paper no. 11-0284.

van der Horst M J, Thunnissen J G M, Happee R, van Haaster R M H P, and Wismans J S H M (1997) 'The influence of muscle activity on head-neck response during impact', Paper presented at: Stapp Car Crash Conference, Orlando, Florida, pp. 487–507.

van Rooij L, Elrofai H, Philippens M M G M, and Daanen H A M (2013) 'Volunteer Kinematics and Reaction in Lateral Emergency Maneuver Tests', *Stapp Car Crash Journal*, 11(57): 313–342.

Versace J (1971) 'A Review of the Severity Index', SAE Technical Paper 710881.

Vezin P, and Verriest J P (2005) 'Development of a set of numerical human models for safety', Paper presented at: International Technical Conference on the Enhanced Safety of Vehicles, Washington D.C., USA.

White N A, Begeman P C, Hardy W N, Yang K H, Ono K, Sato F, Kamiji K, Yasuki T, and Bey M J (2009) 'Investigation of Upper Body and Cervical Spine Kinematics of Post Mortem Human Subjects (PMHS) during Low-Speed, Rear-End Impacts', SAE Technical Paper 2009-01-0387.

Winter DA (1995) ‘Human Balance and Posture Control during Standing and Walking’, *Gait and Posture,* 3: 193–214.

Winter D A (2009) ‘Biomechanics and Motor Control of Human Movements’, NJ, USA: John Wiley & Sons.

Wittek A, Kajzer J, and Haug E (2000) ‘Hill-type muscle model for analysis of mechanical effect of muscle tension on the human body response in a car collision using an explicit finite element code’, *JSME International Journal,* 43(1): 8–18.

Woitsch G and Sinz W (2014) ‘Influences of Pre-Crash Braking Induced Dummy Forward Displacements on Dummy Behaviour during EuroNCAP Frontal Crashtest’, *Accident Analysis and Prevention,* 62: 268–275.

World Health Organization (WHO) 2020, Available at: http://www.who.int/news-room/fact-sheets/detail/road-traffic-injuries, Accessed: 25 July 2021.

Yang K and Chou C (2015) ‘Mathematical models, computer aided design, and occupant safety’, In book: Accidental injury. biomechanics and prevention, Yoganandan N, Nahum A M, and Melvin J W (Eds.), pp.143–182. Springer.

Zhang K, Cao L, Fanta A, Reed M P, Neal M, Wang J T, Lin C H, and Hu J (2017) ‘An automated method to morph finite element whole-body human models with a wide range of stature and body shape for both men and women’, *Journal of Biomechanics,* 60: 253–60.

Part II
Appended Papers A–D