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Volunteer Kinematics and Muscle Activity in Dynamic Events Representative of Pre-crash Scenarios

Evaluation Data for Human Body Models

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Abstract

Advanced integrated safety technologies in modern cars such as collision avoidance intervention and pre-crash activated restraint systems involve comprehensive research on how vehicle occupants respond to these systems in pre-crash situations. Human Body Models (HBMs) are mathematical tools developed to predict human responses and injury outcomes in different pre-crash and in-crash situations. In recent years, introducing muscular activation strategies into the HBMs has enhanced the accuracy of model responses in these situations. The development and validation of biofidelic HBMs intended for studies of pre-crash situations require information on kinematics and muscle activation of vehicle occupants in similar circumstances. This information can be obtained through volunteer experiments representative of pre-crash loading situations. To provide validation data for HBMs, this thesis investigates volunteer responses in evasive manoeuvres potentially occurring prior to a crash.

Kinematics and muscle responses of front-seat male passengers travelling at 73 km/h together with vehicle dynamics and boundary conditions were measured in the following scenarios: autonomous lane change and autonomous lane change combined with braking, each with two belt configurations; standard and reversible pre-pretensioner belts. The surface electromyography method was used to measure muscle activity and the data was then normalised using maximum voluntary contraction (MVC) values. Transformation of coordinates corresponding to several film targets attached to the head and torso was used to calculate head centre of gravity (CoG) and upper torso kinematics in 3-D. All data were presented in corridors comprising mean \pm one standard deviation. Muscle activity as well as head and torso motion were influenced by type of the manoeuvre and the belt configuration used. In addition to lateral motion observed in lane changes, forward displacement of the head and upper torso were also observed in lane changes with braking. Differences in activation time and amplitude between muscles in the right and left side of the body with respect to the vehicle's lateral motion were noted. Compared to the standard belt, pre-tensioning the seat belt prior to the manoeuvres reduced lateral and forward displacement of head and upper torso. Seat belt pre-tensioning was also associated with earlier muscle activation onset and significantly lower activation amplitude for specific muscles.

The data provided in this thesis can be used for further enhancement and validation of HBMs capable of simulating muscles activity in simulation of pre-crash situations, involving both sagittal and lateral loading. In addition to the volunteer data being suitable for directly assessing

the design of integrated safety systems, the HBMs validated against the volunteer data can facilitate the prediction of injury outcomes in crashes that may follow evasive manoeuvres. As such, the HBMs would be applicable in the optimisation of integrated safety technologies targeted at the reduction of injuries of vehicle occupants. Further studies identifying responses of other occupant categories based on seated position, gender, age, stature and BMI are needed for subject-specific optimisation of safety systems in modern cars. Furthermore, studies on volunteer responses in other types of omnidirectional loading scenarios as well as the effect of being unprepared compared to anticipatory or voluntary responses, can help understand human motor control strategies specific to pre-crash situations.

Keywords: boundary conditions, EMG, evasive manoeuvres, human body model, lane change, occupant kinematics, pre-pretensioner belt, validation data, volunteer.

No amount of experimentation can ever prove me right; a single experiment can prove me wrong.

- Albert Einstein

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Thesis

This thesis is based on the work presented in the following publications:

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.

Division of work: The experiment was planned by Brolin, Davidsson, Pipkorn and Jakobsson. Ghaffari and Davidsson performed the experiment with support from Bråse and Svanberg. Ghaffari analysed the data. The paper was written by Ghaffari and was reviewed by all authors.

Paper B

Ghaffari, G., Brolin, K., Pipkorn, B., Jakobsson, L. and Davidsson, J. 'Passenger Muscle Responses in Lane Change and Lane Change with Braking Manoeuvres using two belt configurations: standard and reversible pre-pretensioner', *Unpublished; Abstract submitted for publication*.

Division of work: The experiment was planned by Brolin, Davidsson, Pipkorn and Jakobsson. Ghaffari and Davidsson performed the experiment. Ghaffari analysed the data. The paper was written by Ghaffari.

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Definitions and Acronyms

Ach	Acetylcholine
AEB	Autonomous Emergency Braking
ATD	Anthropometric Test Device, also known as a crash test dummy
AP	Action Potential
BMI	Body-Mass Index
C1-C7	Cervical Vertebrae
CoG	Centre of Gravity
EMG	Electromyogram
ESC	Electronic Stability Control Systems
Euro	NCAP European New Car Assessment Programme
HBM	Human Body Model
MU	Motor Unit
MUAP	Motor Unit Action Potential
MVC	Maximum Voluntary Contraction
PMHS	Post Mortem Human Subject
T1	First Thoracic Vertebra
WHO	World Health Organization
SCM	Sternocleidomastoid
MS	Middle Scalene
CPVM	Cervical Paravertebral Muscles
PDELTA	Posterior Deltoid
LTRP	Lower Trapezius
LD	Latissimus Dorsi
LPVM	Erector Spinae (longissimus), also known as Lumbar Paravertebral
UTRP	Upper Trapezius
ADELTA	Anterior Deltoid
BIC	Biceps
TRIC	Triceps
EXOB	External Oblique
RA	Rectus Abdominis
SERAN	Serratus Anterior
PM	Pectoralis Major
GMAX	Gluteus Maximus
SEMI	Semitendinosus
RF	Rectus Femoris
VM	Vastus Medialis
Ref	Reference Electrode

Part I

Overview

1 Introduction

1.1 Epidemiology and Motivation

According to the World Health Organization (WHO), road traffic accidents lead to the loss of more than 1.25 million people every year [1]. 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, as a result 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, cyclists and motorcyclists. Therefore, increasingly research on different approaches for enhancing the safety of both roads and vehicles with the aim of reducing the number of road traffic fatalities and injuries is being carried out.

In the field of vehicle safety, passive safety systems such as seatbelts and airbags have been designed to protect occupants during a crash. For instance, seatbelts have been shown to decrease the total number of casualties by about 40% [2]. Active safety systems have been designed to avoid crashes by the means of sensors and automated programmes issuing warnings or interventions. Electronic stability control (ESC), forward collision warning and autonomous emergency braking (AEB) are examples of such systems. For instance, ESC systems have been shown to reduce the incidence of vehicle crashes significantly [3]. 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 any crashes [4, 5]. Examples of these new technologies include evasive manoeuvres such as autonomous steering and braking as well as seatbelts equipped with pretensioners that are tensed before an evasive manoeuvre during the pre-crash phase.

All these technologies need to be evaluated with regard to their performance in providing safety features for vehicle occupants. Anthropometric Test Devices (ATDs), also known as crash test dummies, i.e., mechanical models of humans, have been developed in a few different body sizes for the assessment of safety systems. 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 are still very simplified models of the human anatomy. Human body models (HBMs), i.e., numerical anthropomorphic models with the details of human anatomy, have been developed to replicate the responses of the humans [6-10]. 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 been increasing in recent years. The ultimate goal with regard to the HBMs is to predict the level of risk of injury with in terms of location at tissue level i.e., different body regions and severity levels. However, before the models can be applied for the assessment of safety systems, they must be validated. There are different sources of validation data, such as post mortem human subjects (PMHSs). 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 [11-13], 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.

Particularly, introducing integrated safety systems in vehicle safety development has created a 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 respond with human-like kinematics in pre-crash situations. By optimising the design requirements for integrated safety technologies and restraint systems based on how the HBMs behave in various pre-crash and crash scenarios, will consequently lead to a reduction in the injury risk of vehicle occupants.

1.2 Active HBMs and their Validation

The influence of muscle activation on kinematic responses of vehicle occupants in pre-crash situations has been recognised [14-28]. 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.* [11] performed a study on PMHSs 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 result 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. Current vehicle safety assessment programmes, such as the European New Car Assessment Programme (Euro NCAP) are based on studies of ATDs of average body size and standardised seated posture. Therefore, among many other factors lacking in vehicle safety assessment programmes 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 not allowed 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 increasingly developed to provide improved biofidelity in pre-crash simulations lasting over a longer duration of time than in crashes [7, 8, 18, 29, 30]. Recent approaches of including active muscles in the models via neuromuscular feedback control, regulates muscle activation in conjunction with the body posture and kinematics, [8, 30] as well as reinforcement learning techniques [7]. In order to evaluate the performance and determine their ability to resemble human behaviour in pre-crash situations the active HBMs 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 experimental

normalised muscle activation and well-quantified body motion to muscle activation levels with body motion predicted by the models respectively, having the same boundary conditions as in the experiments. Volunteer data including both body kinematics and muscle activation are also essential for model development and understanding human motor control strategies specific to pre-crash situations. A practical and ethical way to collect such 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.

1.3 Previous Volunteer Experiments

Volunteer data from experiments in sagittal plane loading are fairly available [15, 16, 31-34]; however, fewer studies have explored volunteer responses in lateral plane loading. Among these studies, Muggenthaler *et al.* [35] 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 manoeuvres, and therefore further volunteer studies are essential. Other studies have also confirmed that the occupant kinematics is dependent on muscle activity [36-38]. Ejima *et al.* [36] exposed three volunteers, seated in a sled and restrained with a lap belt, to lateral accelerations and found 20-40% reduction in head and T1 lateral flexion when the volunteers were requested to tense their muscles compared to when they were relaxed. Van Rooij *et al.* [37] studied occupant responses in relaxed and braced conditions, when restrained by a 4-point belt and exposed to simulated lane change manoeuvres in a laboratory test vehicle. They stated a significantly higher upper body sideways displacement and lower muscle activity for relaxed conditions. Huber *et al.* [38, 39] conducted a series of volunteer experiments with a modified passenger seat subjected to lane change manoeuvres to the right, and measured head and torso kinematics as well as activity bilaterally from three neck muscles and four trunk muscles without normalisation. Noticeably high activation of the right side muscles was shown in their result while an inter-subject variability of above 200% was found in kinematic responses for each manoeuvre. A detailed study of neck muscle activity was carried out by Ólafsdóttir *et al.* [40] 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.

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. 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, except a few studies such as Hubber *et al.* [39] 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, did not

explain in depth the strategies they used to estimate the head and torso kinematics. This information is not only needed to advance comparison between the results of different volunteer studies, it 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 some understanding of the occupant kinematics and the activity of a limited number of muscles when volunteers were subjected to lateral loading in a laboratory environment. Some of these studies were only on a low number of volunteers or conducted in a laboratory environment; in some, muscle activation data were not normalised or only a few muscles were studied. Nevertheless, for the purpose of model validation, none have provided comprehensive boundary conditions, occupant kinematics and normalised muscle data from volunteers seated in a regular car travelling in a realistic environment.

1.4 Physiology behind Muscle Activity

Motor Unit Action Potential

The skeletal muscles are formed of multiple bundles of cells called 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 [41], 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 [42] causes the release of a neurotransmitter such as acetylcholine (ACh) from the neuron into the synaptic cleft. Consequently, 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 depolarise the muscle fiber in a cascade which eventually leads to muscle contraction. Thus, in a similar fashion each muscle fiber contributes to a single AP. The APs produced by fibers belonging to the same MU join to build the motor unit action potential (MUAP). The rate at which each active MU discharges is 6-8 to 30-40 times per second. The discharging rate depends on the MU's central drive [43].

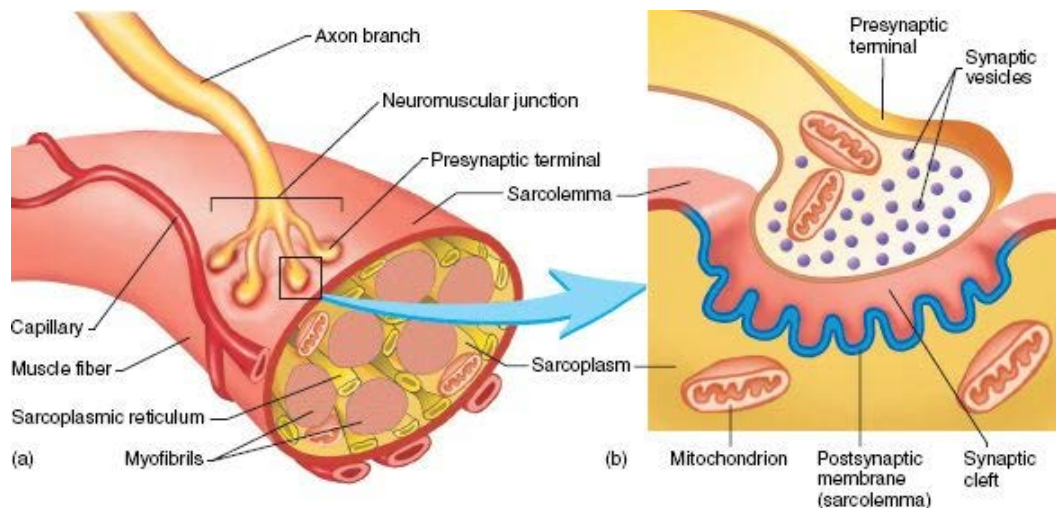


Fig. 1. Neuromuscular junction [41].

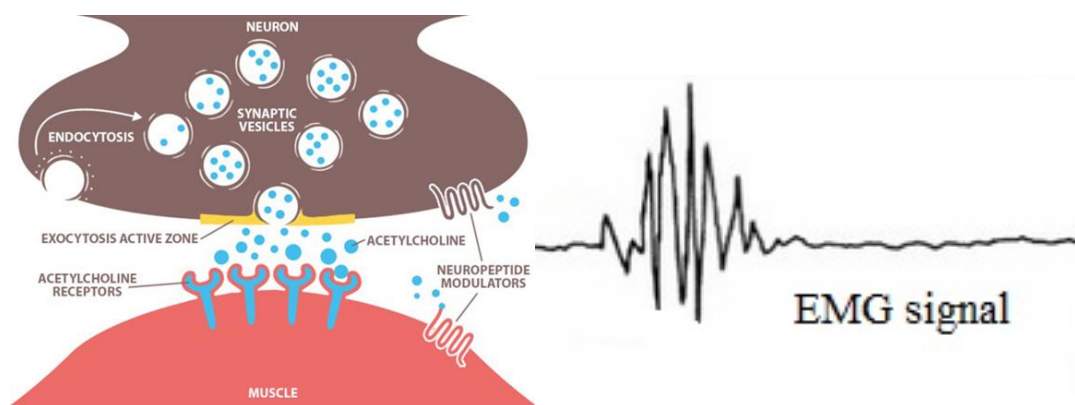


Fig. 2. Mechanism of synaptic transmission [42].

Electromyography

Surface electromyography is a technique for measuring muscle activity. Surface electrodes placed on the skin covering the skeletal muscles measure the AP propagation in the muscle fibres. The superposition of all APs recorded by the electrode forms an electrical signal in volt called electromyogram (EMG) [44]. 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 [43]. Further information on the role of these parameters can be found in the literature [45]. Another technique for recording EMG uses indwelling electrodes which are 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 due to surface

electrodes recording any superficial activation which has 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. However, because of the safety aspects, application of indwelling electrodes in vehicle occupant studies is particularly limited. Furthermore, the surface EMG signal is usually normalised in order to be expressed in terms of muscle activation level. In fact, normalisation 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 fibres and the skin may appear dissimilar in different individuals, which renders any subject comparison of non-normalised EMG levels inaccurate.

2 Objectives

The main objective of this thesis was to provide required post-processed data for active HBM validation as well as further improvement at the whole body level. The objectives were achieved by performing a new and comprehensive set of experiments, comprising volunteers travelling in a regular car, in a realistic environment, being subjected to repeatable and typical low g intervention representative of pre-crash situations. Another objective was to investigate the effect of two belt configurations on volunteer responses in lateral loading scenarios. This objective was chosen for more comprehensive study because new vehicle models are fitted with seat belts that can be pre-tensioned in the pre-crash phase which are known to affect the volunteer response in braking events [31, 32].

Therefore, this thesis comprises kinematics and muscle activation of male passengers in autonomous lane change, as well as autonomous lane change with braking vehicle manoeuvres, using a 3-point seat belt in either activated, henceforth referred to as pre-pretensioner, or non-activated configuration, henceforth referred to as standard.

3 Summary of Appended Papers

The objectives in this thesis were planned to be fulfilled in the following two papers. The aim of Paper A was to investigate occupant kinematics and the aim of Paper B was to investigate occupant muscle activation, both with the intent of being applicable for validating HBMs capable of controlling muscles in simulation of evasive manoeuvres which potentially occur prior to a crash. Furthermore, both papers include comparison of occupant responses with respect to standard and reversible pre-pretensioner belt.

Paper A

The focus of Paper A was to quantify the occupant kinematics for the head CoG and the upper torso using coordinates of the film targets attached to each volunteer's body as well as analyse 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 manoeuvre, with a target force of minimum 170 N. The manoeuvres were composed of multiple repeatable lane change, and lane change with braking, at 73 km/h. Hence, four different randomized loading scenarios and three trials per loading scenario were tested. 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 manoeuvre duration was approximately 2 seconds with steering during the first second was to the right and in the second second, steering was to the left. Time scaling was done based on the onset of vehicle lateral acceleration and in addition to accelerations, vehicle roll, pitch and yaw angles, were also measured. Furthermore, shoulder belt, lap belt force and belt payout, were also measured.

The motion of the volunteers during the manoeuvres 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 achieve coordinates of the markers attached to the body with respect to the vehicle coordinate system. The methodology used for kinematics post-processing has been explained in detail. The Euler angle technique was used to obtain the rotation matrix using coordinates of the three best trackable markers attached to the corresponding presumably rigid body (typically, one marker on forehead and two markers on right and left sides of head, and single markers on left acromion, T1 process and sternum for the upper torso). This technique was chosen, since it is a straight forward method applicable for rigid bodies, applying a small number of film markers to the volunteers. 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 excursion of the upper torso at T1 vertebra level were calculated in 3D.

All post-processed data were presented in corridors containing mean \pm one standard deviation intended as validation data for active HBMs. The resultant volunteer kinematics corridors indicate certain variability in the responses, especially for head kinematics, resulting in wider corridors than for upper torso kinematics. The results also show 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 manoeuvres, but the longitudinal excursion was found to be highly influenced by the existence of longitudinal acceleration.

Paper B

The focus of Paper B was to analyse the muscle response data for the same set of volunteer tests presented in Paper A. Hence, the experimental setup including the measurement systems, the manoeuvres and the vehicle instrumentation, were identical to those in Paper A. The electromyography (EMG) technique was used to measure muscle activation. Surface EMG Ag/AgCl electrodes were placed bilaterally on 19 muscles, as illustrated in Fig. 3.

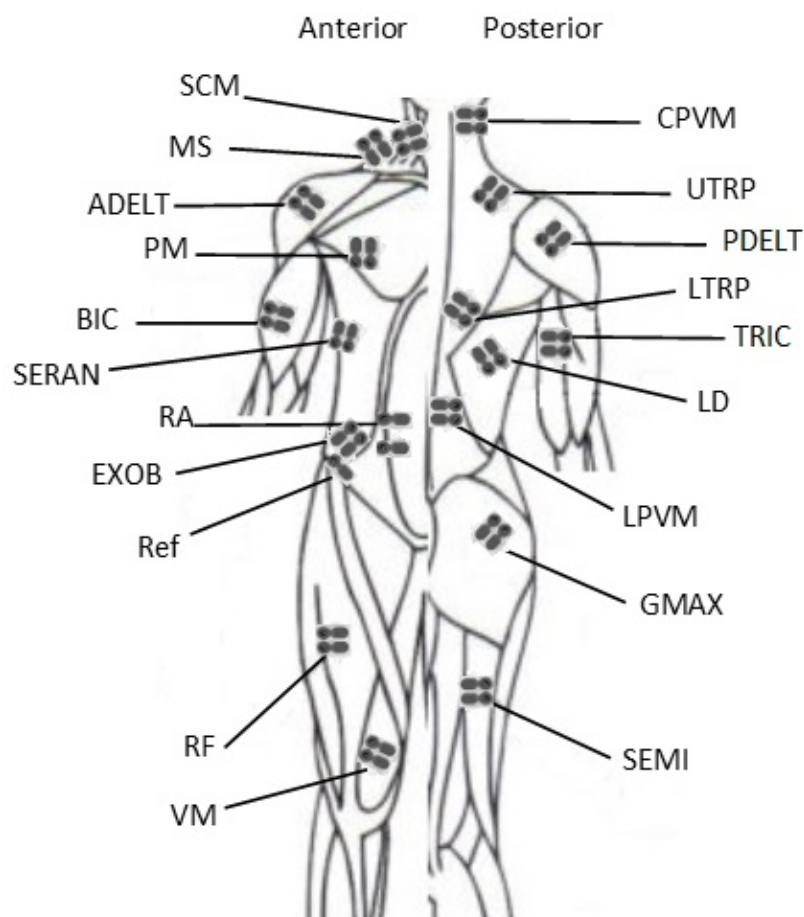


Fig. 3. Electrode placement on the anterior and posterior side of the body shown to the left and right, respectively. Muscle abbreviations according to Definitions and Acronyms section of this thesis.

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. 4.

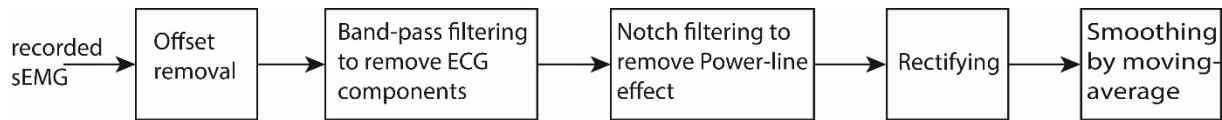


Fig. 4. A diagram of the sEMG signal processing.

The post-processed EMG data were normalised 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. 5) and were asked to contract specific muscles.



Fig. 5. MVC test rig with volunteer.

Corridors of mean \pm one standard deviation were established for each muscle in four different loading scenarios, i.e., lane change and combined lane change with braking, each either with a standard belt or with a pre-pretensioner belt. The muscle response data were compared to the results revealed in Paper A; head and torso kinematics; belt force and payout; and vehicles dynamics.

The established muscle activation corridors can be applied for active HBM validation. The results show that the muscle activation levels collected in normal driving conditions, prior to any evasive manoeuvre, were low ($<2\%$ MVC) in all muscles except the lumbar extensors (3-5.5%). Selective muscles were found activated during the lane change manoeuvre 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 indicate 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 smaller activation amplitudes for specific muscles in lane changes when the volunteers were restrained by the pre-tensioner belt than by the standard belt.

4 Discussion

4.1 Volunteer Kinematics and Muscle Responses

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 correlated with regard to upper torso lateral motion [36-39]. To a certain degree, biomechanical studies have confirmed that muscle activation can affect body posture and kinematics in a crash event [46, 47], as well as pre-crash events to a greater degree. This thesis covered both kinematics and normalised muscle activity in response to different loading scenarios.

As stated in the summary of Appended Papers, surface EMG data derived from 19 muscles located all over the body were measured bilaterally. A few of those muscles, i.e., SCM, CPVM, UTRA, ADELTA, LPVM, LD, RA, EXOB and RF, have previously been investigated in volunteer studies [35-38]. Although, it would have been preferable, with regard to future model development and validation, to collect data from as many skeletal muscles, potentially involved in evasive manoeuvres, as possible, several factors had to be taken into consideration in order to prioritise a number of muscles. Issues for some muscles, such as the Deltoid, include lack of space to place all electrodes on all of them. Hence, the selection process for inclusion of certain muscles in this study involved considering the functionality of each muscle and its potential of maintaining the vehicle occupant's seated posture and body motion during evasive manoeuvres. For instance, the lateral Deltoid muscle was not prioritised since it is involved to a higher degree in shoulder abduction angles than is predicted to occur in vehicle occupants in evasive manoeuvres. Seat contact and possible pressure artifacts were other factors considered in the muscle selection process. Some muscles, such as Infraspinatus located below the upper Trapezius and lateral to middle Trapezius, and to some extent hidden by other muscles and therefore difficult to distinguish by palpation, were excluded from this study.

The normalisation 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, normalisation makes it possible to objectively compare normalised muscle activation levels between individuals in different manoeuvres [31-34, 40]. 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 normalisation method often used in vehicle occupant studies is normalisation to maximum EMG levels recorded during the experimental task [36]. This approach is event-dependent and therefore not suggested for comparing purposes between manoeuvres. Normalisation to the maximum EMG values recorded in all manoeuvres [37] 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 manoeuvres begin. With regard to muscle activity, this information provides a background level to compare with the muscle activity during the manoeuvres. 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 position immediately prior to the manoeuvres, should be avoided. The results indicate that the activity was below 2.5% the MVC during normal driving, in all instrumented muscles except for the lumbar extensor muscles (LPVM). This is in agreement with previous studies on muscle activity prior to the onset of events [31, 32, 40]. 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.

Muscles in the upper extremities (ADELT, PDELT, BIC and TRIC) showed the lowest activation among the instrumented muscles (below 2% of MVC) for all phases in all types of loading scenarios. The low activity 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, CPVM), lumbar erector 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 (averagely around 10° towards the left). 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. Previous studies on evasive manoeuvres also found a similar muscle activation pattern opposing the torso movement [36, 38]. Additionally, in manoeuvres including combined lane changing and braking, two muscles on the back of the torso (LTRP, LD) and four muscles of the lower extremities (GMAX, SEMI, RF and VM) had activity above 3% MVC, which may be due to larger forward displacement of the torso found in the manoeuvres involving braking events than without. Hence, in order to restrict the body's forward motion these muscles might need to be activated more. During the first second of the manoeuvres, i.e., right turn, volunteers had small elevation of the right acromion up to 27 mm in LSB, 20 mm in LPT, 28 mm in LBSB and 16 mm in LBPT which correlates with no noticeable activation (below 2% MVC) found in the UTRP muscles.

Another part of this work includes the comparison between volunteer responses when restrained by the pre-pretensioner and the standard belt. Lower lateral and forward displacement for the head and T1 were observed for the pre-pretensioner 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. Particularly, in the pre-pretensioner configuration, the tension was applied to the diagonal belt at around 200 ms before the onset of manoeuvres until reaching the target tension (170 N) at approximately time zero when the manoeuvres began. These muscles were activated before the onset of manoeuvres, therefore they could not be invoked by the loading due to acceleration. In fact, they became activated around 120 ms after the belt activation. Thus, earlier activation onset in the mentioned muscles can be related to somatosensory reflexes from the diagonal belt pulling back the upper body of the volunteer. The exact location of the load applied by the pre-pretensioner belt spreading on the body remains unknown, whether the load spread mainly to the clavicle or the majority of the torso, however, these muscles were most probably triggered by tactile stimuli as suggested in [31, 32].

4.2 Applications in Traffic Safety

As explained in the Epidemiology and Motivation Section, the predominant reason for the work in this thesis, including conducting a set of volunteer experiments through full-scale vehicle tests and analysis of the recorded data, was to provide validation data for active Human Body Models (HBMs). 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, can lead to reduced contact with interior vehicle structures and consequently lower the risk of injuries compared to when wearing a standard belt. Furthermore, the observed volunteer responses would also be suitable for validating HBMs against the experimental data while they both have common definitions of body motions and muscle activity. Consequently, validated HBMs 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 criteria (HIC) values [48] and increased belt loads [49]. 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 optimise 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 manoeuvres for which they were unprepared. The manoeuvres were randomised to a certain extent, and volunteers were not aware what type of manoeuvre 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.

4.3 Limitations

This experimental work was intended to resemble actual pre-crash scenarios as closely as possible. However, there were some limitations. For instance, despite using a regular test vehicle instead of the most common method applied in vehicle occupant studies [14-16, 34, 36, 37, 40, 50], sled tests conducted in a laboratory environment, 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 test vehicle used already exists, it would still fulfill the requirements of boundary conditions for the purpose of reproducibility in the models, and hence HBM validation. It is important to be able to implement realistic boundary conditions when validating HMBs against experimental data, which has not been considered in the majority of previous volunteer studies. Furthermore, as the kinematics and muscle activation of volunteers can be affected by awareness of an upcoming manoeuvre, it is important to eliminate any signs of imminent manoeuvres when investigating unprepared volunteers. In this study, volunteers were not completely unprepared, for example, they could potentially be aware of imminent manoeuvres by being alerted by the sound produced by the clutch.

5 Conclusions

This thesis provides a detailed set of data for validation and improvement of active HBMs. Corridors of head CoG and upper torso displacement and head rotation around three axes, as well as boundary conditions, such as belt interaction forces and vehicle dynamics are presented in Paper A. Paper B provides surface EMG corridors for 38 instrumented muscles, 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 manoeuvres. Comparing the two belt configurations studied in this thesis revealed earlier activation onset time and smaller amplitude for several muscles, as well as lower sideways and forward displacement for the head and upper torso, with the use of pre-pretensioner seat belt versus the standard belt. This novel dataset can be useful for improving the omnidirectional response of active HBMs. Accordingly, the future validated and improved HBMs with active musculature will enhance the possibility of predicting human behaviour in pre-crash scenarios. Consequently, the design of integrated safety systems in modern cars can benefit from developing more biofidelic models representing human behaviour more accurately.

6 Future Directions

Kinematic and muscle responses of only male volunteers were investigated in this thesis. In order to validate and improve female HBM models, future studies on collected data from female volunteers and any gender differences in volunteer responses are also required. In fact, physiological differences between males and females might make gender a factor influencing muscle responses, body kinematics and the behaviour of volunteers in various loading conditions.

The corridors presenting the kinematics and muscle activation of volunteers with regard to applied loading scenarios showed that there are certain variability in the responses of volunteers. These variations might originate from different muscle recruitment strategies based on age, stature or some other physiological features. Volunteers included in this thesis were aged between 23-71 with a stature of 174-192 cm. Their body-mass index (BMI) was 18-23, which is essentially within normal weight range, and data from volunteers with higher and lower BMI than normal were also collected. Studies on population heterogeneity and regression analysis are required to recognise differences in vehicle occupant responses due to age, stature and BMI variances.

This thesis is focused on passenger responses. However, data from drivers subjected to different evasive manoeuvres, such as autonomous lane change and a combination of lane change and braking, were also collected 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.

Furthermore, as a part of a larger study, this set of experiments also includes records of data from passengers and drivers in manual lane changes. This unique dataset can be used in future studies on anticipatory and voluntary responses, with respect to passengers and drivers compared to responses from unprepared volunteers in autonomous lane changes. Besides, these experimental data including EMG signals, volunteer kinematics and boundary conditions has the potential to facilitate the development of anticipatory control strategies for active HBMs in pre-crash situations, such as evasive steering.

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Part II
Appended Papers A-B

