

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

Does Spinal Alignment Influence Car Occupant Responses?

The influence of variation in whole spinal alignment patterns on vertebral kinematics under rear impact conditions

FUSAKO SATO



Division of Vehicle Safety
Department of Mechanics and Maritime Sciences
CHALMERS UNIVERSITY OF TECHNOLOGY
Gothenburg, Sweden 2019

Does Spinal Alignment Influence Car Occupant Responses?

The influence of variation in whole spinal alignment patterns on vertebral kinematics under rear impact conditions

FUSAKO SATO

ISBN 978-91-7597-860-4

©FUSAKO SATO, 2019

Doktorsavhandlingar vid Chalmers tekniska högskola. Ny serie

Nr 4541

ISSN 0346-718X

Department of Mechanics and Maritime Sciences

Chalmers University of Technology

SE-412 96 Gothenburg

Sweden

Telephone + 46 (0)31-772 1000

Printed at Chalmers Reproservice
Gothenburg, Sweden 2019

Does Spinal Alignment Influence Car Occupant Responses?

The influence of variation in whole spinal alignment patterns on vertebral kinematics under rear impact conditions

FUSAKO SATO

Division of Vehicle Safety, Department of Mechanics and Maritime Sciences
Chalmers University of Technology

Abstract

The susceptibility of women to Whiplash Associated Disorders (WADs) has been the focus of numerous epidemiologic studies. Summarising the epidemiologic WAD studies, women were found to be subject to up to three times higher risk of sustaining WADs than men. To improve occupant safety for both men and women, the overall aim of this thesis was to provide fundamental knowledge to understand how gender differences influence the injury mechanisms and risk of sustaining WADs. WADs are generally considered to be derived from cervical soft tissue damage caused by excessive cervical vertebral kinematics. This thesis has focused on the whole spinal alignment in automotive seated postures as one of the gender differences, and investigated its potential impact on cervical vertebral kinematics during a rear impact, clarifying gender specific dynamic characteristics of cervical vertebral kinematics.

Previous rear impact sled test series comprising female and male volunteers were reanalysed to determine the dynamic characteristics of inertia-induced cervical vertebral kinematics during rear impacts. For spinal alignment, image data of the spinal column in automotive seated postures, acquired with an upright open Magnetic Resonance Imaging (MRI) system, were analysed. Typical patterns of the whole spinal alignment, including average gender specific spinal alignment patterns, were obtained through Multi-Dimensional Scaling (MDS). Implementing these typical spinal alignment patterns in a whole-body occupant FE model, the potential impact of whole spinal alignment on cervical vertebral kinematics were investigated in reconstruction simulations of previous rear impact sled tests.

In the sled tests, the female subjects were subjected to a more pronounced cervical S-shape than the male subjects, beyond the voluntary muscle-induced cervical kinematics range for female subjects. The average gender specific spinal alignment patterns of the automotive seated posture included a slight kyphotic, or almost straight cervical spine, with a less-kyphotic thoracic spine for the female subjects, and a lordotic cervical spine with a more pronounced kyphotic thoracic spine for the male subjects. In the reconstructed simulations, the average female spinal alignment pattern demonstrated greater intervertebral displacements from the lower cervical spine to the upper thoracic spine with a more pronounced cervical S-shape, compared to the average male spinal alignment pattern. Greater elongation of the cervical ligaments occurred at intervertebral levels where greater intervertebral displacement was found.

Rear impact reconstruction simulations performed in this thesis demonstrated a potential impact of gender differences in whole spinal alignment on cervical vertebral kinematics and ligament elongation. The female spinal alignment trend may make women exposed to more significant deformation of the cervical soft tissues due to greater cervical vertebral kinematics during a rear impact. The findings may partially contribute to a greater understanding of the increased injury risk of women sustaining WADs.

KEYWORDS: automotive seated posture, cervical vertebral kinematics, female, MRI, Multi-Dimensional Scaling, neck injury, occupant, rear impact, spinal alignment, whiplash.

Acknowledgements

There are many people who have helped and supported me throughout this study. This study could not have been carried through without you. I would like to thank all of you:

My supervisors at Chalmers; Mats Svensson, Karin Brolin, and Jonas Östh, for having me over at Chalmers, and for all your advice, continuous support and encouragement. My stay in Gothenburg was a precious and very fun experience in my life. I enjoyed our many fruitful and interesting discussions tremendously at SAFER, JARI, conference venues, cafes in India, Swedish forests with reindeers, etc., and over Skype from across the world.

My supervisors at Japan Automobile Research Institute (JARI); Kunio Yamazaki, Tatsuo Fujikawa and Masao Nagai, for giving me the fantastic opportunity to be involved in collaborative research with Chalmers, and for believing in me and giving me the freedom to carry out this study in my own pace.

My project colleagues; Shigehiro Morikawa, Harumi Iguchi and Masahiro Yoshimura at Shiga University of Medical Science, Antonio Ferreiro Perez and Havier Montero at Fundación de Investigación HM Hospitales, Jacobo Antona Makoshi and Taichi Nakajima at JARI, and Sylvia Schick at Institute of Legal Medicine, Ludwig-Maximilians-Universitaet Muenchen, for obtaining image data by upright open MRI systems. Makiko Kouchi, Yuko Kawai and their colleagues at National Institute of Advanced Industrial Science and Technology (AIST), and Beatriz Nácher Fernández and her colleagues at Instituto de Biomecánica de Valencia for measuring body sizes. Moreover, Yusuke Miyazaki and Mamiko Odani at Tokyo Institute of Technology for your help and support with the analyses of spinal alignment by MDS. The teamwork has been invaluable.

Astrid Linder for all the inspiring advice and your generous support. All our discussions, both in Sweden and Japan, have inspired and stimulated me.

Elisabet Agar for the English language editing of this thesis. Your English made my thesis brilliant.

My colleagues at the Vehicle Safety Division, Chalmers and SAFER, and at JARI, for the assistance, encouragement and all the daily quick, but fun, chats. In particular, I would like to thank my colleagues, Mitsuru Ishii and Hiroyuki Kobari, for pushing me and giving me generous and great support. It would not have been possible to win such significant funding without you.

My friends in Sweden and Japan for making my days even more fun during my PhD study. Particularly, Anna Carlsson and the Ivarsson family, Patrick, Fusae and Erika. Thank you for taking care of me and spending wonderful time together. You have been essential for my survival here.

Lastly, very special thanks to my family and cats for your support and understanding. Especially my husband, Atsushi, thank you for always supporting me. My cats, Shiro, Kuro and Chataro, thank you for always cheering me up and endlessly giving me a helping paw.

Fusako Sato
February 2019
Gothenburg, Sweden

List of Appended Papers

This thesis is based on the work contained in the following papers.

PAPER I

Sato F, Nakajima T, Ono K, Svensson MY, Brolin K and Kaneoka K (2014)

Dynamic Cervical Vertebral Motion of Female and Male Volunteers and Analysis of its Interaction with Head/Neck/Torso Behaviour during Low-Speed Rear Impact

In: *Proceedings of International Research Council on Biomechanics of Injury (IRCOBI) Conference*, Berlin, Germany, pp. 227-249

Division of work between authors: Sato made the outline of this study. Ono and Kaneoka provided data from previous volunteer test series. Sato reanalysed and presented all data included in the paper with the help of Nakajima. The paper was written by Sato, and reviewed by all authors.

PAPER II

Sato F, Nakajima T, Ono K, Svensson MY and Kaneoka K (2015)

Characteristics of Dynamic Cervical Vertebral Kinematics for Female and Male Volunteers in Low-Speed Rear Impact, based on Quasi-Static Neck Kinematics

In: *Proceedings of International Research Council on Biomechanics of Injury (IRCOBI) Conference*, Lyon, France, pp. 261-277

Division of work between authors: Sato made the outline of this study. Ono and Kaneoka provided data from previous volunteer test series. Sato reanalysed and presented all data included in the paper with the help of Nakajima. The paper was written by Sato, and reviewed by all authors.

PAPER III

Sato F, Odani M, Miyazaki Y, Nakajima T, Antona-Makoshi J, Yamazaki K, Ono K, Svensson MY, Östh J, Morikawa S, Schick S and Ferreiro-Perez A (2016)

Investigation of Whole Spine Alignment Patterns in Automotive Seated Posture using Upright Open MRI Systems

In: *Proceedings of International Research Council on Biomechanics of Injury (IRCOBI) Conference*, Malaga, Spain, pp. 113-130

Division of work between authors: Sato made the outline of this study. Sato, Morikawa, Ferreiro-Perez, Nakajima, Antona-Makoshi, Schick, Svensson and Östh conducted the MRI scans. Sato, Odani and Miyazaki jointly analysed and presented all data included in the paper. The paper was written by Sato, and reviewed by all authors.

PAPER IV

Sato F, Miyazaki Y, Svensson MY, Brodin K, Yamazaki K, Morikawa S, Schick S and Ferreiro-Perez A (2018)

The Effect of Seatback Inclination on Spinal Alignment in Automotive Seated Postures

Prepared for journal submission

Division of work between authors: Sato made the outline of this study. Sato, Morikawa, Ferreiro-Perez, Svensson and Schick conducted the MRI scans. Sato and Miyazaki jointly analysed and presented all data included in the paper. The paper was written by Sato, and reviewed by all authors.

PAPER V

Sato F, Odani M, Miyazaki Y, Yamazaki K, Östh J and Svensson MY (2017)

Effects of Whole Spine Alignment Patterns on Neck Responses in Rear End impact

Traffic Injury Prevention, 18 (2), pp. 199-206

Division of work between authors: Sato made the outline of this study. Sato conducted all simulations. Sato, Odani and Miyazaki jointly analysed and presented all data of the spinal alignment. The paper was written by Sato, and reviewed by all authors.

Conference Presentations

Sato F, Nakajima T, Ono K, Svensson MY, Brolin K and Kaneoka K (2014) Dynamic cervical vertebral motion of female and male volunteers and analysis of its interaction with head/neck/torso behaviour during low-speed rear impact. In: *International Research Council on Biomechanics of Injury (IRCOBI) Conference*, Berlin, Germany.

Sato F, Odani M, Endo Y, Tada M, Miyazaki Y, Nakajima T, Ono K, Morikawa S and Svensson M (2015) Analysis of the alignment of whole spine in automotive seated and supine postures using an upright open MRI system. In: *Society of Automotive Engineers of Japan (JSAE) Annual Congress (Spring)*, Yokohama, Japan.

Sato F, Odani M, Endo Y, Tada M, Miyazaki Y, Nakajima T, Ono K, Morikawa S and Svensson M (2015) Whole spine alignment in automotive seated and supine postures by using an upright open MRI system. In: *The 25th Congress of the International Society of Biomechanics (ISB)*, Glasgow, UK.

Sato F, Nakajima T, Ono K, Svensson M and Kaneoka K (2015) Characteristics of dynamic cervical vertebral kinematics for female and male volunteers in low-speed rear impact based on quasi-static neck kinematics. In: *International Research Council on Biomechanics of Injury (IRCOBI) Conference*, Lyon, France.

S Sato F, Odani M, Miyazaki Y, Nakajima T, Antona-Makoshi J, Yamazaki K, Ono K, Svensson M, Östh J, Morikawa S, Schick S and Ferreiro-Perez A (2016) Investigation of whole spine alignment patterns in automotive seated posture using upright open MRI system. In: *International Research Council on Biomechanics of Injury (IRCOBI) Conference*, Malaga, Spain.

Sato F, Odani M, Miyazaki Y, Yamazaki K, Östh J and Svensson M (2016) A 50th Percentile female occupant FE model with the average spinal alignment pattern for females. In: *Annual Conference of the Association for the Advancement of Automotive Medicine (60th AAAM)*, Hawaii, US.

Sato F, Linder A, Svensson M, Brolin K and Yamazaki K (2017) Towards whiplash injury protection for both men and women. In: *Gender summit 10*, Tokyo, Japan.

Sato F, Yamazaki K, Miyazaki Y, Östh J and Svensson M (2017) Differences of the spinal alignment between females and males in a driving posture and its effects on spinal kinematics in rear-end impact. In: *The Bioengineering Conference, Annual Meeting of Bioengineering Division /The Japan Society of Mechanical Engineers (BED/JSME)*, Nagoya, Japan.

Sato F, Miyazaki Y, Konosu A, Yamazaki K, Svensson M, Brolin K, Morikawa S and Ferreiro-Perez A (2018) Investigating representative whole spinal alignments in a car occupant posture. In: *8th World Congress of Biomechanics (WCB)*, Dublin, Ireland. Finalist in the American Society of Mechanical Engineers Bioengineering Division (ASME/BED) PhD-level student paper competition and student bursary.

Sato F, Miyazaki Y, Svensson M, Brolin K, Yamazaki K, Konosu A, Morikawa S and Ferreiro-Perez A (2018) The effect of seat back inclination on spinal segmental angles in automotive seated postures. In: *International Research Council on Biomechanics of Injury (IRCOBI) Conference*, Athens, Greece.

Acronyms and Definitions

ALL	Anterior Longitudinal Ligament
BioRID	Biofidelic Rear Impact Dummy
C1–C7	Cervical vertebrae numbered from the atlas (C1) in the caudal direction
CC	Cervical Curvature
CL	Capsular Ligament
CT	Computed Tomography
Euro NCAP	European New Car Assessment Programme
FE	Finite Element
GHBMC	Global Human Body Model Consortium
ISL	Interspinous Ligament
JNCAP	Japanese New Car Assessment Programme
Kyphosis	Outward concave portion of the spine
L1–L5	Lumbar vertebrae numbered in the caudal direction
LF	Ligament Flavum
LL	Lumbar Lordosis
Lordosis	Inward concave portion of the spine
LTK	Lower Thoracic Kyphosis
MDS	Multi-Dimensional Scaling
MRI	Magnetic Resonance Imaging
NIC	Neck Injury Criterion
OC	Occipital Condyle
PLL	Posterior Longitudinal Ligament
PMHS	Post Mortem Human Subject
SS	Sacral Slope
STL	Stereolithography
T1–T12	Thoracic vertebrae numbered in the caudal direction
THUMS	Total Human Model for Safety
TS	T1 Slope
TTK	Total Thoracic Kyphosis
UN	United Nations
UTK	Upper Thoracic Kyphosis
WAD	Whiplash Associated Disorder

Table of Contents

Abstract	i
Acknowledgements	iii
List of Appended Papers.....	iv
Conference Presentations.....	vi
Acronyms and Definitions.....	ix
1 Introduction.....	1
2 Background.....	5
2.1 Whiplash Associated Disorder.....	5
2.2 Gender differences in dynamic kinematic responses in rear impacts.....	7
2.3 Anatomical gender differences of the cervical spine	9
2.4 Effects of spinal alignment in rear impacts	11
3 Aims	13
4 Summary of Papers	14
4.1 Summary of Paper I and II.....	16
4.2 Summary of Paper III and IV.....	19
4.3 Summary of Paper V	25
5 Discussion.....	27
5.1 Cervical kinematic responses in rear end impacts.....	29
5.2 Whole spinal alignment patterns in an automotive seated posture.....	30
5.3 Gender differences of the whole spinal alignment in one automotive seated posture....	32
5.4 Effects of spinal alignment patterns on vertebral kinematic responses in rear impact...33	
5.5 Effects of spinal alignment patterns on cervical ligamentous responses in rear impact.35	
5.6 Implications of actual whiplash injuries.....	37
5.7 Laboratory seat design.....	39
5.8 Volunteers.....	39
5.9 Towards WAD countermeasures for both men and women	40
6 Conclusions.....	43
7 References.....	45
8 Appendix.....	64

Does Spinal Alignment Influence Car Occupant Responses?

The influence of variation in whole spinal alignment patterns on vertebral kinematics under rear impact conditions

1 Introduction

The susceptibility of women to Whiplash Associated Disorders (WADs), sustained in vehicle crashes, has been the focus of numerous epidemiological studies over the past decades (Narragon 1965, Kihlberg 1969, O'Neill et al. 1972, Thomas et al. 1982, Otremski et al. 1989, Maag et al. 1990, Morris and Thomas 1996, Dolinis 1997, Temming and Zobel 1998, Chapline et al. 2000, Richter et al. 2000, Krafft et al. 2003, Jakobsson et al. 2004b, Storvik et al. 2009, Carstensten et al. 2012). Summarising the above epidemiological studies (Carlsson et al. 2010), injury statistical data reveal that women have on average double the risk of sustaining WADs compared to men, even in similar crash conditions. In addition, gender is a significant factor as the recovery time for women is longer than for men after sustaining WADs (Harder et al. 1998, Cassidy et al. 2000).

WADs occur more frequently in rear impacts than in any other type of automobile impact, even though they can be sustained in all impacts directions (Watanabe et al. 2000, Krafft et al. 2002, Stigson et al. 2015). As a preventive measure aimed at reducing the risk of sustaining WADs in rear impacts, cars have been equipped with several types of advanced whiplash protection seat concepts since the late 1990s (Jakobsson et al. 1997, Wiklund et al. 1997, Lundell et al. 1998, Sekizuka et al. 1998). Mechanical design features and mechanical properties of seats affect the risk of sustaining WADs (Foet-Bruno et al. 1991, Parkin et al. 1995, Viano 2008). According to insurance claims records (Kullgren et al. 2010 and 2013), several whiplash protection systems installed in front seats have indeed reduced the risk of sustaining WADs. The risk of permanent medical impairment due to WADs have been reduced by approximately 30% for women and 50% for men. Although these protection system technologies have proved more effective for men than women, some have only created risk reduction for men. Therefore, in order to prevent WADs more effectively for women as well as men, further investigation to reveal gender differences in the injury mechanisms of WADs is required.

The performance of occupant protection systems including whiplash protection seats have predominantly been developed and evaluated using physical crash test dummies representing

the 50th percentile male, in accordance to UN vehicle regulations, e.g., R17 (Seats, their anchorages and any head restraints), R94 (Protection of the occupants in the event of a lateral collision) and R95 (Protection of the occupants in the event of a frontal collision) (UNECE 2018) and consumer crash test programmes, e.g., the European New Car Assessment Programme (Euro NCAP) (EuroNCAP 2018), the Japan New Car Assessment Programme (JNCAP) (JNCAP 2018), etc. The anthropometry of the physical crash test dummies is equivalent to the 50th percentile male anthropometry (Schneider et al. 1983) and their properties represent the dynamic response of male occupants (see for instance Davidsson et al. 1999 for rear impacts).

For low severity rear impact testing, the only available physical crash test dummy is the male Biofidelic Rear Impact Dummy (BioRID II) (Davidsson et al. 1999). Hence, one potential reason for men being better protected than women may be due to the performance of whiplash protection seats having been adapted to the BioRID II. The 50th percentile male height and weight approximately correspond to the 95th and 90th percentile female body sizes, respectively (Welsh & Lenard 2001). Gender differences in anthropometry, mass distribution and dynamic response properties may affect the interaction between the torso/head and the seat back/head restraint. Subsequently, such anthropometrical differences may result in gender influencing the risk of sustaining WADs. Rear impact simulations performed with a mathematical model has revealed that female mass requires seats that are less stiff, indicating greater neck displacement for women in rear impacts due to a higher ratio of seat stiffness to torso mass, when compared to men (Viano 2003abc).

To enhance whiplash protection systems for both female and male occupants, the world's first 50th percentile female crash test dummy for finite element (FE) analysis, the EvaRID (Eva – female / RID – Rear-Impact Dummy) has only recently been developed. EvaRID is based on the BioRID II FE model and was developed to safeguard that the whole adult population, women as well as men, is represented (Linder et al. 2013, Carlsson et al. 2014). Rear impact test simulations conducted according to the Euro NCAP protocol have consistently demonstrated different dynamic responses, particularly peak values and timing, between the EvaRID and BioRID II FE models in the three crash pulses included in the test procedure (Linder et al. 2015 and 2018). Differences in the dynamic response between the EvaRID and BioRID II FE models have also been investigated in reconstruction simulations of real world rear impact accidents (Sato et al. 2017). In the accident reconstruction simulations conducted by exposing the EvaRID FE model to the crash pulses held on the accident data base of the Swedish insurance company Folksam, the trend for WAD injury criterion values calculated with the EvaRID FE model response were lower compared to the BioRID II FE model, despite WAD injury outcomes held on the data base being more severe for female occupants than male occupants. In addition, in the Euro NCAP rear impact test configuration a prototype 50th percentile female physical crash test dummy has shown a similar trend, demonstrating lower injury criteria values than the BioRID II (Schmitt et al. 2012). The prototype 50th percentile female physical crash test dummy was developed based on the BioRID II, representing the average female weight, height, rough dimensions and joint stiffness.

The above mentioned studies imply that separate injury criterion thresholds might be required to assess the risk of female occupants sustaining WADs, by applying lower injury criterion values corresponding to the same injury risk level, as male occupants. Further analysis of the Euro NCAP rear impact tests with the prototype 50th percentile female physical crash test dummy and the BioRID II (Schmitt et al. 2012), has suggested that the threshold of the Neck Injury Criteria (NIC) would be 12 m²/s² for the prototype 50th percentile female physical crash test dummy as well as the EvaRID FE model (Linder et al. 2013), to correspond with the threshold for the BioRID II, established to 15 m²/s² (Boström et al. 1996). However, the equivalent threshold for women still remains to be established. Thus, when establishing WAD injury criteria and thresholds for women it is important that values reflect any gender differences in dynamic response and injury biomechanics by answering the following question: Why do women have a higher risk of sustaining WADs?

WADs are generally considered to be due to damage to cervical soft tissues. From a perspective of biomechanical impact testing, cervical intervertebral motion was larger for female volunteers than male volunteers, when subjected to a rear impact (Ono et al. 2006). Furthermore, head-neck complexes of female Post Mortem Human Subjects (PMHSs) also demonstrated larger intervertebral motion during a simulated rear impact loading, compared to male PMHS head-neck complexes (Stemer et al. 2003, Stemper et al. 2004a). Larger cervical intervertebral motion may induce harmful local deformation in the cervical soft tissue. The above mentioned rear impact tests implied gender differences, which from a morphological and biomechanical aspect may affect vertebral motion, such as size, geometry, material properties, etc.

Human body FE models have become powerful tools for investigating injury biomechanics and developments in occupant/pedestrian protection system technologies in traffic safety. The commercially available human body FE models, the GHBMC (Gayzik et al. 2011, Cronin et al. 2012, Vavalle 2012, Park et al. 2013, Vavalle et al. 2014, Combust 2016, Davis et al. 2016) and the THUMS (Iwamoto et al. 2002, Watanabe et al. 2012, Iwamoto & Nakahira 2015), comprise a 5th percentile female, a 50th percentile and a 95th percentile male model, respectively. Yet, a 50th percentile commercial female model has not been developed for the GHBMC and THUMS human body model families, due to the non-requirement of an average female body size in UN vehicle regulations and consumer crash test programmes. For impact biomechanics research on neck injury, several human body FE models dedicated to the cervical spine have been developed (see for instance Yang et al. 1998, Halldin et al. 2000, Brodin & Halldin 2004, Kitagawa et al. 2008, Panzer & Cronin 2009, Panzer et al. 2011, Mustafy et al. 2014, Nightingale et al. 2016). These FE models are modelled on the average male cervical spine, except in a few studies (Mordoka 2004).

For example, from a morphological aspect, female and male cervical spines have inherent geometrical differences (Stemper et al. 2011). For instance, in size matched pairs in anthropometry, the necks of women are more slender and have significantly smaller vertebral dimensions, (Vasavada et al. 2008, Stemper et al. 2008, Stemper et al, 2009). Due to such differences in male and female cervical spines, only using existing male FE models when investigating gender differences in the risk of sustaining WADs, is challenging. Recently, a 50th

percentile female FE model has been developed for deeper investigation into female injury mechanisms (Östh et al. 2016b, Östh et al. 2017). To elevate our knowledge of the injury mechanisms related to WADs to the next level, we need to uncover the effect of gender specific morphological and biomechanical differences on cervical vertebral motion during an impact.

Based on the above, this thesis is focused on the spinal alignment as one of the morphological gender differences. To obtain fundamental knowledge in order to understand gender differences in the risk of sustaining WADs, female and male dynamic cervical vertebral kinematic characteristics during rear impacts were investigated with a focus on the potential impact of spinal alignment. A detailed background of this thesis is described in the following chapter.

2 Background

This chapter outlines the current status on WAD biomechanics studies and any related gender specific differences from a morphological aspect.

2.1 Whiplash Associated Disorder

Symptoms associated with WADs and their severity are diverse. Patients who have sustained WADs predominantly complain of neck pain, headache, stiffness around the neck, shoulder and upper back symptoms. WAD symptoms are frequently concomitant with other symptoms such as loss of mobility of the cervical spine, pain in other parts of the body, neurological signs such as tingling and numbness, dizziness, fatigue, as well as emotional disturbances such as anxiety and depression, unconsciousness, blurred vision, etc. (Nygren et al. 1985, Deans et al. 1987, Kenna and Mutagh 1989, Watkinson et al. 1991, Evans 1992, Radanov et al. 1995, Spitzer et al. 1995, Sturzenegger et al. 1995, Starling 2004, Sterner et al. 2004, Carroll et al. 2008, Holm et al. 2008). WADs are generally considered to be soft tissue injuries of the neck. However, due to difficulties in diagnosing soft tissue damage through current medical imaging techniques including X-rays, computed tomography (CT), and magnetic resonance imaging (MRI), the aetiology of symptoms frequently remains undetected and consequently the injury mechanisms of WADs have not been fully elucidated (Davis et al. 1991, Pettersson et al. 1994 and 1997, Barnsley et al. 1995, Ronnen et al. 1996, Wilmink et al. 2001, Uhrenholt et al. 2002, Krakens et al. 2002, 2003ab and 2006, Kaale et al. 2005ab, Elliott et al. 2006 and 2008ab, Binder et al. 2007, Myran et al. 2008, Ichihara et al. 2009, Lindgren et al. 2009, Dullerud et al. 2010, Vetti et al. 2011, Anderson et al. 2012, Li et al. 2013). Nevertheless, experimental studies comprising PMHSs and animals have demonstrated that cervical soft tissue structures, including ligaments, facet joints and capsules, intervertebral discs, vertebral arteries, and muscles, become damaged under rear impact loading (MacNab et al. 1964, Ommaya et al. 1968, Nibu et al. 1997, Panjabi et al. 1998a and 2004, Deng et al. 2000, Yoganandan et al. 2000 and 2001, Ivancic et al. 2004 and 2008, Quinn et al. 2007). Autopsy studies have reported similar cervical soft tissue damage as seen in the PMHS and animal experiments (Sehonstrom et al. 1993, Jónsson et al. 1994, Taylor et al. 1993 and 1996, Nibu et al. 1997).

Dynamic kinematic responses of occupants in rear impacts

During a rear impact, the torso of a properly restrained occupant starts to be pushed forward by the seat back while the head remains in situ due to inertia. At the moment of impact, the head would be behind the torso. This sudden relative displacement between the head and the torso produces a S-shape of the cervical spine. Thereafter, the head contacts the head restraint

followed by the head and torso rebound from the head restraint and seat back (Matsushita et al. 1994, Siegmund et al. 1997, Davidsson et al. 1998, Deng et al. 2000, Pramudita et al. 2007, White et al. 2009, Carlsson et al. 2011). During the cervical S-shape phase, cervical segments are exposed to flexion in the upper cervical spine and extension in the lower cervical spine (Svensson et al. 1993, Grauer et al. 1997, Ono et al. 1997 and 2006, Kaneoka et al. 1999 and 2002, Luan et al. 2000, Deng et al. 2000, Cusick et al. 2001, Yoganandan et al. 2002, Stemper et al. 2003, White et al. 2009, Stemper et al. 2011). The S-shape of the cervical spine was observed only in impact conditions and is characterised as a nonphysiologic curvature in comparison of cervical vertebral kinematics between rear impact motion and voluntary neck extension motion with a male volunteer (Ono et al. 1997). The cervical S-shape indicates nonphysiologic loads and excessive local tensile, compression and shear in the cervical soft tissue, although it must be verified with more volunteers. More pronounced cervical S-shape may result in increased nonphysiologic loads and local distortions. Hence, previous papers have hypothesised that neck injuries related to WADs may potentially be caused by the S-shape, albeit different theories on why the S-shape causes WADs has also been discussed.

Theories of WAD injury mechanisms

Aldman et al. (1986) hypothesised that the rapid relative displacement between the head and torso, observed during rear impacts, has the ability to generate transient pressure gradients in the spinal canal which could potentially damage the spinal nerve roots, leading to symptoms associated with WAD. Experimental studies with pigs demonstrated such transient pressure gradients in the spinal canal during a rapid relative displacement between the head and torso (Svensson et al. 1993, Örtengren et al. 1996). A series of rear impact sled tests with PMHSs support this hypothesis (Eichberger et al. 2000).

During the S-shape of the cervical spine, in the upper cervical segments, the vertebrae rotated in flexion relative to the lower adjacent vertebra, resulting in compression at the anterior region of the intervertebral discs, moving the facet joints away superiorly and posteriorly from the lower adjacent facet. On the other hand, in the lower cervical segments, the vertebrae rotated in extension relative to the lower adjacent vertebrae, resulting in tension at the anterior region of the intervertebral discs and compression at the posterior region of the facet joints, with the upper facet sliding posteriorly along the lower adjacent facet, especially at C5/C6 (Grauer et al. 1997, Kaneoka et al. 1999 and 2002, Deng et al. 2000, Luan et al. 2000, Panjabi et al. 2004a and 2004b, Pearson et al. 2004). Based on experimental simulations of rear impacts with PMHS head-neck complexes, it was hypothesised that the lower cervical segments were injured in local hyperextension during the S-shape phase prior to full hyperextension of the cervical spine (Grauer et al. 1997, Cholewicki et al. 1998, Panjabi et al. 1998abcd and 2004ab, Pearson et al. 2004).

Through a sequential X-ray analysis of the cervical spine during rear impacts in male volunteers, Kaneoka et al. (1999 and 2000) hypothesised that the compression of the facet joints could cause pinching and inflame the synovial folds, while the tension of the intervertebral discs

would potentially cause stretching of the anterior longitudinal ligament. If the vertebral extension is large enough it may cause damage to the articular cartilage of the facet joints or detach the discs from the vertebral rim. Rear impact sled tests with PMHS head-neck complexes demonstrated compression of the facet joints, and excessive axial elongation at the anterior region of the intervertebral discs, beyond physiologic limits (Cusick et al. 2001, Yoganandan et al. 2002, Ivancic et al. 2004, Panjabi et al. 2004a and 2004b, Pearson et al. 2004). These PMHS studies support the hypothesis.

Excessive strain of the facet joint capsule is another hypothesis related to facet joints (Deng et al. 2000, Luan et al. 2000, Winkelstein et al. 2000, Siegmund et al. 2001 and 2008, Yoganandan et al. 2002, Yang et al. 2003, Panjabi et al. 2004a, Pearson et al. 2004, Ivancic et al. 2008). In an investigation of PMHSs in rear impact sled tests conducted by Deng et al. (2000), Luan et al. (2000) concluded that the facet joint capsules were dominantly stretched by shear at the lower cervical segments and flexion-tension at the upper cervical segments during the S-shape of the cervical spine. The peak strains of the facet joint capsules occurred before the head contacted the head restraint (Deng et al. 2000). In experimental rear impact simulations with pairs of adjacent cervical vertebrae and PMHS head-neck complexes, strains of the facet joint capsules were observed beyond the sub-catastrophic failure injury range (Winkelstein et al. 2000, Siegmund et al. 2000, Pearson et al. 2004). Partial rupture occurred in the facet joint capsules under shear and tension loadings prior to failure.

Consequently, under experimental demonstrations based on the above hypotheses, greater vertebral motion produced during the cervical S-shape in a very short space of time, is generally considered related to soft tissue injury and a considerably increased risk of sustaining WAD.

2.2 Gender differences in dynamic kinematic responses in rear impacts

Whole body kinematics of occupants during vehicle crashes have been studied through biomechanical tests subjecting human volunteers and PMHSs to simulated impacts. Those biomechanical impact tests were usually conducted with male volunteers and PMHSs. Hence, the majority of data on dynamic kinematic response were derived from male volunteers and PMHSs. Studies on rear impacts are not an exception to this trend. Due to the limited number of female volunteer tests (Szabo et al. 1994, Siegmund et al. 1997, van den Kroonenberg et al. 1998, Hell et al. 1999, Welcher et al. 2001, Croft et al. 2002, Ono et al. 2006, Pramudita et al. 2007, Dehner et al. 2008, Linder et al. 2008, Schick et al. 2008, Carlsson et al. 2010 and 2012) and PMHSs (Yoganandan et al. 2000), the dynamic kinematic response of female occupants in rear impacts are not fully understood, when compared to male occupants.

Despite the limited number of female subjects, gender differences in dynamic kinematic responses of occupants during rear impacts have been analysed. In overall motion analyses, female volunteers tended to be exposed to greater forward accelerations of the head and T1 with more pronounced rebound motion but lower Neck Injury Criterion (NIC) values, compared to male volunteers (Szabo et al. 1994, Siegmund et al. 1997, van den Kroonenberg et al. 1998, Hell et al. 1999, Welcher et al. 2001, Croft et al. 2002, Linder et al. 2008, Schick et al. 2008, Carlsson et al. 2010 and 2012).

Some studies comprising human volunteers have attempted to analyse dynamic inertia-induced kinematic responses of cervical vertebrae during rear impact, using a cineradiography system (Matsushita et al. 1994, Ono et al. 1997, 1999 and 2006, Kaneoka et al. 1999 and 2002, Pramudia et al. 2007). Sequential X-ray images of the cervical spine, obtained by a cineradiography system, showed greater intervertebral angular displacements with a more pronounced S-shape of the cervical spine for female volunteers than male volunteers in rear impact sled tests (Ono et al. 2006). The study illustrated only the maximum intervertebral angular displacements of the cervical spine, and does not contain detailed data regarding cervical vertebral kinematics during an impact. PMHS head-neck complexes fitted with retro-reflective targets inserted into each vertebra also indicate such gender differences in rear impact sled tests. Female head-neck complexes demonstrated greater intervertebral displacements with a more pronounced S-shape of the cervical spine (Stemper et al. 2003 and 2004a). These experimental studies with head-neck complexes provide a hint of gender difference which may affect the vertebral motion from a morphological and biomechanical aspect, such as size, geometry, material properties, etc. Nevertheless, data on inertia-induced cervical vertebral kinematics of women during rear impacts are limited. Since the above studies on the cervical vertebrae have mainly been carried out on male volunteers, detailed knowledge of gender differences on cervical vertebral kinematics are lacking. Furthermore, factors causing greater intervertebral displacements for women have not been clarified yet.

As a comparison to muscle-induced cervical vertebral kinematics under quasi-static voluntary neck extension motion, dynamic characteristics of inertia-induced cervical vertebral kinematics in a rear impact sled test have been investigated (Ono et al. 1997). In quasi-static voluntary neck extension motion, vertebral angular displacement relative to the horizontal plane increased gradually from the lower to the upper vertebrae, without the S-shape deformation of the cervical spine, throughout the entire time history of neck extension motion. On the other hand, in a rear impact condition, vertebral angular displacement relative to the horizontal plane was largest at C5 around the timing of the peak of the cervical S-shape. This comparison of cervical vertebral kinematics between dynamic and quasi-static conditions focused on one male volunteer. Any gender differences in dynamic inertia-induced cervical vertebral kinematics against quasi-static muscle-induced cervical vertebral kinematics, have not yet been well analysed.

In quasi-static voluntary neck bending experiments, gender differences in cervical kinematics have been demonstrated. The total range of cervical intervertebral flexion-extension angles is greater for women than men (Lind et al. 1989, Youdas et al. 1992, Yukawa et al. 2012), while the total range of cervical intervertebral retraction-protrusion displacements is greater for men

than women (Hanten et al. 2000). Such gender differences might also affect the fact that the risk of sustaining WADs is higher for women.

Consequently, there is a need to obtain dynamic characteristics of inertia-induced cervical vertebral kinematics against quasi-static muscle-induced cervical vertebral kinematics, for both men and women, to investigate any gender differences related to the risk of sustaining WADs.

2.3 Anatomical gender differences of the cervical spine

The gender differences of cervical vertebral kinematics observed in volunteer and PMHS testing are attributed to morphological differences, as well as biomechanical and muscular differences between men and women. In general, the anthropometrical dimensions of the neck and geometrical dimensions of the cervical vertebrae are smaller for women than men (Stemper et al. 2011). In neck anthropometry, the neck circumference is less for women, while the difference in head circumference is negligible between the genders (Vasavada et al. 2001, Valkeinen et al. 2002, Harty et al. 2004, Mordaka 2004), even in comparison between size matched men and women based on neck length, seated height, and stature (DeRosia 2008, Vasavada et al. 2008). In cervical vertebral geometry, height, depth and width of the vertebral bodies and depth of facets are significantly smaller in women than men (Katz et al. 1975, Liguoro et al. 1994, DeRosia 2008, Stemper et al. 2008 and 2009), and the ratio of the vertebral body height divided by depth is smaller in women than men (Hukuda & Kojima 2002, Frobine et al. 2002, Vasavada et al. 2008). The facet joint cartilage gaps are significantly greater while the cartilage thickness is significantly smaller for women than for men (Yoganandan et al. 2003). In a paper compiling previous studies (Brolin et al. 2015), the cervical vertebral height, depth and width for women is 86-98% of the measurements for men in size matched volunteers, based on both neck length and standing height, and 86-95% of men in size matched volunteers with regard to seated height, head circumference, and stature. Thus, narrower necks with smaller vertebral bodies in women indicate less support area and muscle volume of the neck and cervical spinal region than in men. This contributes to reduced neck strength for women. Furthermore, female necks have 20-32% less strength in flexion and extension (Vasavada et al. 2008, Zheng 2011).

The variation in alignment of cervical vertebrae (cervical spinal alignment) (Figure 1) also show gender differences. In an asymptomatic population measured in an upright seated position, cervical lordotic alignment was observed in the majority, and non-lordotic alignment was observed in 36% (Matsumoto et al. 1998) and 38% (Takeshima 2002). Women are more likely to present non-lordosis (kyphotic or straight) than men, while men statistically present more pronounced lordosis (Helliwel 1994, Haedacker et al. 1997, Matsumoto 1999, Been et al. 2017). Gender is an independent factor significantly correlating with non-lordotic alignment. In an investigation of the relationship between cervical spinal alignment and stature, tall women

tended to present straight alignment more frequently compared to short women, while there is no significant relationship between stature and curvature for men (Klinich et al 2004). In line with this finding, cervical facet joint angles have also been investigated (Milne 1991, Boyle et al. 1996, Kasai et al. 1996, Parenteau et al. 2013). However, small and inconsistent gender differences were indicated. The cervical spinal alignment and/or posture may affect the facet joint angles.

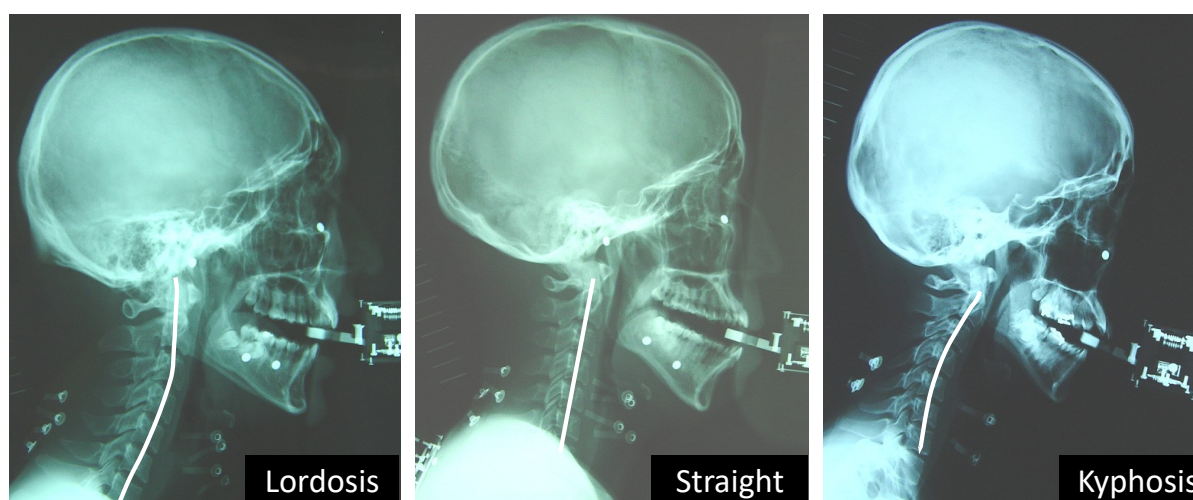


Figure 1. Variations in the cervical spinal alignment. Image data from the data set of the rear impact sled tests in Paper I and II

At the cervicothoracic junction, the thoracic inlet defined as the angle between the lines from the top of the manubrium to the centroid of the cranial T1 end plate and the horizontal plane, inclined further forward for men than women due to a thicker thoracic cage for men compared to women (Lee et al. 2014). A forward-inclined thoracic inlet was associated with pronounced cervical lordosis, while a smaller anteroposterior diameter of the upper thoracic cage was associated with cervical hypolordosis. These findings observed at the cervicothoracic junction are consistent with the trend of cervical spinal alignment in both genders.

In gender-dependent morphological differences described above, Dehner et al. (2008) focused on the anthropometric variation of the neck. In a series of rear impact sled tests with eight female volunteers, the anthropometric variations affected the neck kinematics and the NIC value. The neck length correlated with the NIC, and longer necks demonstrated greater NIC values. Kitagawa et al. (2015) focused on the size of the neck and vertebrae. Rear impact simulations were conducted with average male and female sized whole-body human FE models. An average male cervical spine FE model was installed in both the male and female size whole-

body human FE model. To resemble the average female size, the average male cervical spine model was scaled down by approximately 86%. Size differences of the neck and vertebrae in both genders affected the gender differences in cervical spine motion rather than muscular strength. Despite such a simplistic approach, the series of rear impact simulations highlighted that the size of the neck and vertebrae is one of the key factors to take into account when investigating influences of gender-dependent anatomical differences, with regard to WAD injury mechanisms. John et al. (2018) focused on the geometrical variations of the cervical vertebrae, subjecting a C5/C6 spinal segment FE model to simulated rear impact loading (Stemper et al. 2003, Östh et al. 2007) with seven geometrical parameters overlapping the ranges of gender variations; 1) height of intervertebral disk, 2) facet joint slope, 3) height of facet articular processes, 4) length of posterior processes, 5) anteroposterior depth of vertebral body and facet joints, 6) curvature of the segment ranging from lordotic to straight, and 7) size of the segment. The response of the C5/C6 FE model was most affected by the anteroposterior depth of vertebral body and facet joints, and the curvature of the C5/C6 segment. The study concluded that the female specific morphological characteristics of the cervical segment with smaller vertebrae and a straighter spinal alignment, resulted in greater intervertebral kinematics, and might contribute to the higher injury risk of women sustaining WADs.

The studies described above demonstrate the importance of gender-dependent morphological differences, including anthropometry of the neck, geometry of the cervical vertebrae and relative position of the vertebrae (segmental alignment), for investigation of gender differences on WAD injury mechanisms. Spinal alignment is the focus of the following section.

2.4 Effects of spinal alignment in rear impacts

In the gender-dependent anatomical differences described in the preceding section, cervical spinal alignment has been considered one of the possible causes of gender differences in dynamic inertia-induced vertebral kinematics observed in rear impact sled tests with PMHS head-neck complexes (Stemper et al. 2003 and 2004a) and human volunteers (Ono et al. 2006). Due to load transmission between the head and the torso through the cervical spine, cervical spinal alignment can affect vertebral kinematics during impact.

Experimental investigations with PMHS head-neck complexes have demonstrated that the initial cervical spinal alignment affect the severity of neck injuries (Maiman et al. 1983 and 2002, Yoganandan et al. 1986, Liu & Dai 1989, Pintar et al. 1995, Yoganandan et al. 1999). A series of rear impact sled tests with one male volunteer showed that cervical vertebrae in kyphotic cervical spinal alignment rotated significantly more than cervical vertebrae in lordotic cervical spinal alignment (Ono et al. 1997). In a series of rear impact computer simulations (Stemper et al. 2005), the influence of initial cervical spinal alignment was investigated with a mathematical head-neck model as to elongation of the facet joint capsular ligaments in lordotic,

straight and kyphotic cervical spinal alignment. Kyphotic cervical spinal alignment was exposed to larger elongation of the facet joint capsular ligaments than lordotic or straight cervical spinal alignment. As women are more likely than men to present non-lordotic cervical spinal alignment (Helliwel 1994, Haedacker et al. 1997, Matsumoto 1999), described in the preceding section, such a gender difference of cervical spinal alignment implies that women may inherently be at an increased risk of sustaining WADs than men.

Human volunteer sled tests have also demonstrated the influence of the interaction between the torso and seat back on cervical vertebral kinematics during rear impacts (Ono et al. 1999). In rear impact reconstruction simulations with a whole-body human FE model, cervical vertebral kinematics were affected by the initial position of the thoracolumbar spine against the seat back (Sato et al. 2010). Thoracolumbar kinematics is contributory to determining T1 kinematics which can directly affect cervical spinal kinematics. It is important to include the effects of T1 kinematics when investigating potential WAD producing mechanisms. The initial spinal alignment, not only the cervical spine but also the thoracolumbar spine through C2 to the sacrum, resting against a seat back is therefore one of the essential key factors for further investigation into WAD injury mechanisms. However, whole spinal alignment in automotive seated postures has not been well documented, particularly not for women (Chabert et al. 1998). Although whole spinal alignment has been investigated with regard to each vertebral angle, generally in standing postures (Jassen et al. 2009) or in supine (Parenteau et al. 2014), detailed knowledge of gender differences of the whole spinal alignment in automotive seated postures is still lacking.

In a pilot study to investigate whole spinal alignment in the seated posture (Sato et al. 2015), the intervertebral angles from C2 through to the sacrum showed different trends, even in the thoracic region when comparing the seated posture to the supine posture. Comparing the upright seated and standing posture, a medical image study demonstrated that cervical spinal alignment was affected by different postures (Morimoto et al. 2018). Spinal alignment was also affected by the orientation of gravity in a comparison of the cervical spinal alignment between seated upright and inversed postures (Newell 2014, Newell et al. 2014 and 2018). To investigate spinal alignment in the seated posture, it was therefore essential to expose volunteers to appropriate orientation of gravity in the seated posture.

3 Aims

The ultimate goal of this thesis is to contribute to the understanding of how gender differences influences the injury mechanisms and risk of sustaining WADs, in order to improve occupant safety for both men and women. To obtain fundamental knowledge, this thesis focuses on the gender difference of the whole spinal alignment in automotive seated postures and its potential impact on cervical kinematics during a rear impact, clarifying gender specific dynamic characteristics of cervical kinematics.

Consequently, the specific aims of this thesis were to:

- Clarify the dynamic characteristics of inertia-induced cervical kinematic responses in a rear impact for women and men (Paper I and II).
- Clarify typical patterns in whole spinal alignment in an automotive seated posture, including average gender specific spinal alignment patterns (Paper III and IV).
- Investigate potential impacts of spinal alignment patterns on cervical kinematic responses during a rear impact (Paper V) and evaluate injury metrics (Appendix)

4 Summary of Papers

This thesis comprises five papers. The overview of this thesis, including the five papers, is illustrated in Figure 2 and the papers are summarised as follows:

In Paper I and II, the previous experimental data sets of rear impact sled tests comprising female and male volunteers were reanalysed to determine dynamic characteristics of inertia-induced cervical vertebral kinematics for women and men during rear impacts.

In Paper III and IV, image data of the spinal column, acquired with an upright open MRI system were analysed to obtain typical patterns of whole spinal alignment in an automotive seated posture with two different seat back angles, including average gender specific spinal alignment patterns. The posture was defined in accordance with the rear impact sled test in Paper I.

In Paper V, the potential impact of the whole spinal alignment patterns obtained in Paper III were investigated in reconstruction simulations of the rear impact sled tests in Paper I with a whole-body occupant FE model.

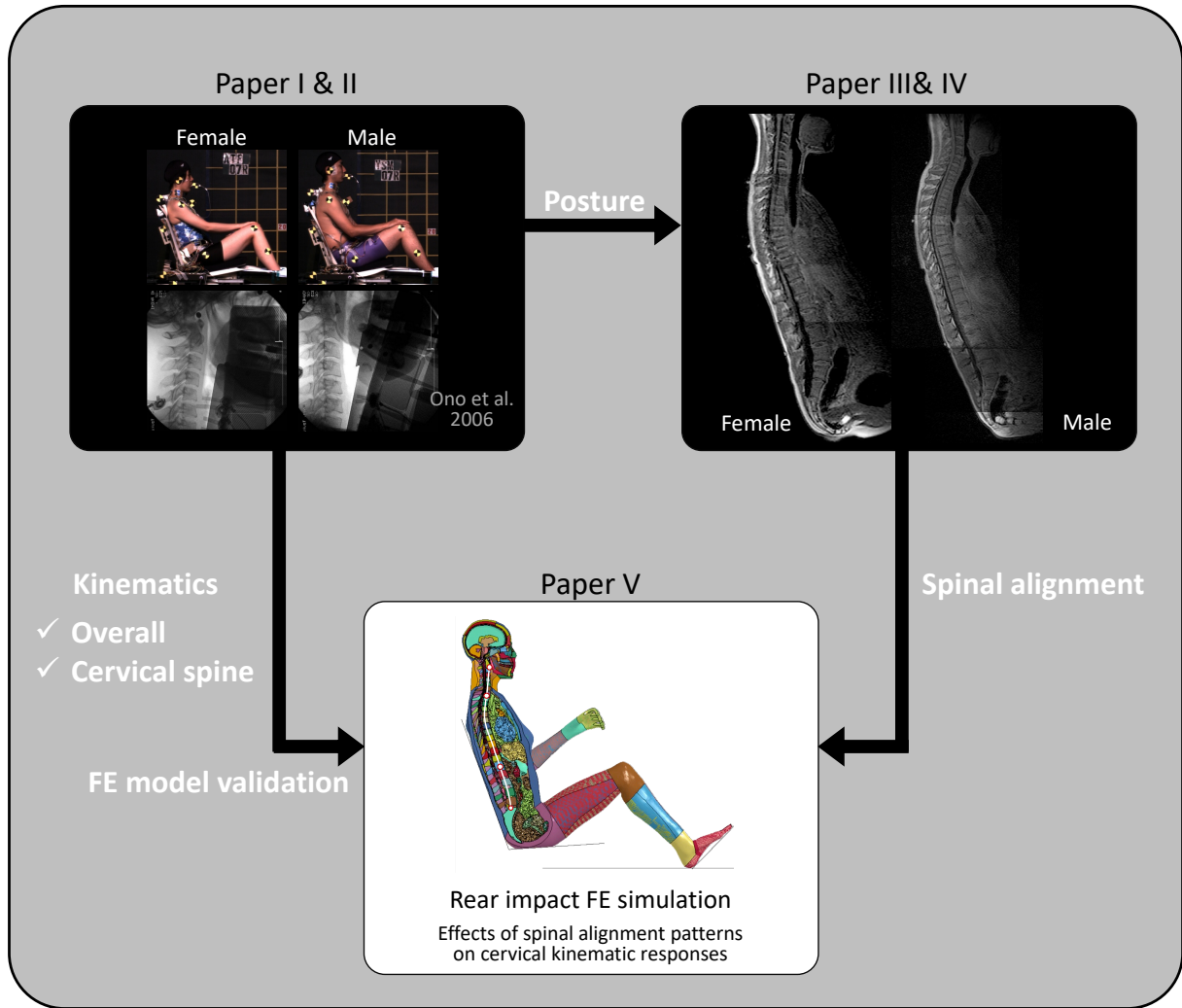


Figure 2. Overview of this study

4.1 Summary of Paper I and II

Title of Paper I: Dynamic Cervical Vertebral Motion of Female and Male Volunteers and Analysis of its Interaction with Head/Neck/Torso Behaviour during Low-Speed Rear Impact

Title of Paper II: Characteristics of Dynamic Cervical Vertebral Kinematics for Female and Male Volunteers in Low-speed Rear Impact, based on Quasi-static Neck Kinematics

The aim of Paper I and II was to clarify the dynamic characteristics of inertia-induced cervical kinematic responses for both women and men in low-speed rear impact conditions.

To investigate differences in dynamic inertia-induced cervical kinematic responses for men and women in rear impacts, experimental data previously obtained by rear impact sled tests with female and male volunteers (Ono et al. 2006) were reanalysed in Paper I. The main focus of that study was the peak values of strain at the facet joint capsules, while gender differences of cervical vertebral kinematics were not well reported. The female and male volunteers participating in the sled tests were also subjected to quasi-static neck bending tests to quantify muscle-induced cervical vertebral kinematics. However, the results of the quasi-static neck bending tests have not yet been published. Hence, in Paper II, the muscle-induced cervical vertebral kinematics were reanalysed using the aforementioned data, and compared to the inertia-induced cervical vertebral kinematics, to clarify the dynamic characteristics for both women and men.

Methods in Paper I: Two series of rear impact sled tests comprising female and male volunteers were reanalysed to investigate gender differences of inertia-induced cervical kinematic responses. The first one, an inclined-sled test series comprising 12 male subjects which is presented in Ono et al. (1997 and 1999), and eight female subjects which has not been published previously. Overall kinematics were captured by high-speed video camera. The second test series is a mini-sled test series comprising four male and two female subjects, conducted by Ono et al. (2006). Sequential X-ray images of cervical vertebrae were acquired by a cineradiography system as well as overall kinematics captured by high-speed video camera. In both rear impact sled test series, a laboratory seat consisting of two rigid planes with a seat back inclined by 20° from the vertical level was used, respectively. Due to the limited number of subjects in the second test series, general characteristics of inertia-induced overall head, neck and T1 responses, were complemented with the first test series. Thereafter, inertia-induced cervical kinematic responses were analysed with X-ray sequential images.

Methods in Paper II: The inertia-induced cervical kinematic responses obtained in the second sled test series in Paper I was compared to quasi-static muscle-induced cervical kinematics in

voluntary neck bending motions. The voluntary quasi-static neck bending test series, which remains unpublished, was conducted in the same period as the second sled test series in Paper I. The test series comprised four male and two female subjects, and an additional five male and two female subjects; a total of nine male and four female subjects. The quasi-static muscle-induced cervical kinematics in maximum neck extension, flexion and retraction motion, were obtained from sequential X-ray images of cervical vertebrae acquired by a cineradiography system.

Results in Paper I: Findings in Paper I are summarised in Figure 3. For overall kinematics, the female subjects exhibited peak flexion of the head relative to the neck link, defined as a line between T1 and the occipital condyle, while the neck link rotated in extension at the time of peak flexion of the head relative to the neck link (Figure 3). On the other hand, the male subjects exhibited flexion in both the head relative to the neck link and neck link relative to T1, up to 100ms. For cervical vertebral kinematics, close to the time of peak flexion of the head relative to the neck link, the cervical spine was exposed to the peak S-shape in both female and male subjects. The female subjects exhibited greater intervertebral angles in both flexion at the upper cervical segments and extension at the lower cervical segments than the male subjects, when exposed to a more pronounced S-shape. The overall kinematics corresponded to the cervical vertebral kinematics, and supports the cineradiography data.

Results in Paper II: When comparing the peak cervical S-shape observed in the dynamic inertia-induced cervical vertebral kinematics to the maximum voluntary retraction, C4/C5 through C6/C7 at the peak S-shape rotated greater for the female subjects in extension than at the maximum voluntary retraction. In contrast, for the male subjects, the peak S-shape remained in the range of maximum voluntary retraction. In addition, the normalised rearward displacement of C6/C7 at the peak S-shape exceeded the maximum voluntary extension for the female subjects. When looking at the peak cervical extension observed in the dynamic inertia-induced cervical vertebral kinematics, the vertebral angular displacement at C5/C6 was the greatest and exceeded the voluntary extension, especially for the female subjects. The normalised rearward displacement of C5/C6 and C6/C7 in the X-direction exceeded the maximum voluntary extension for both genders.

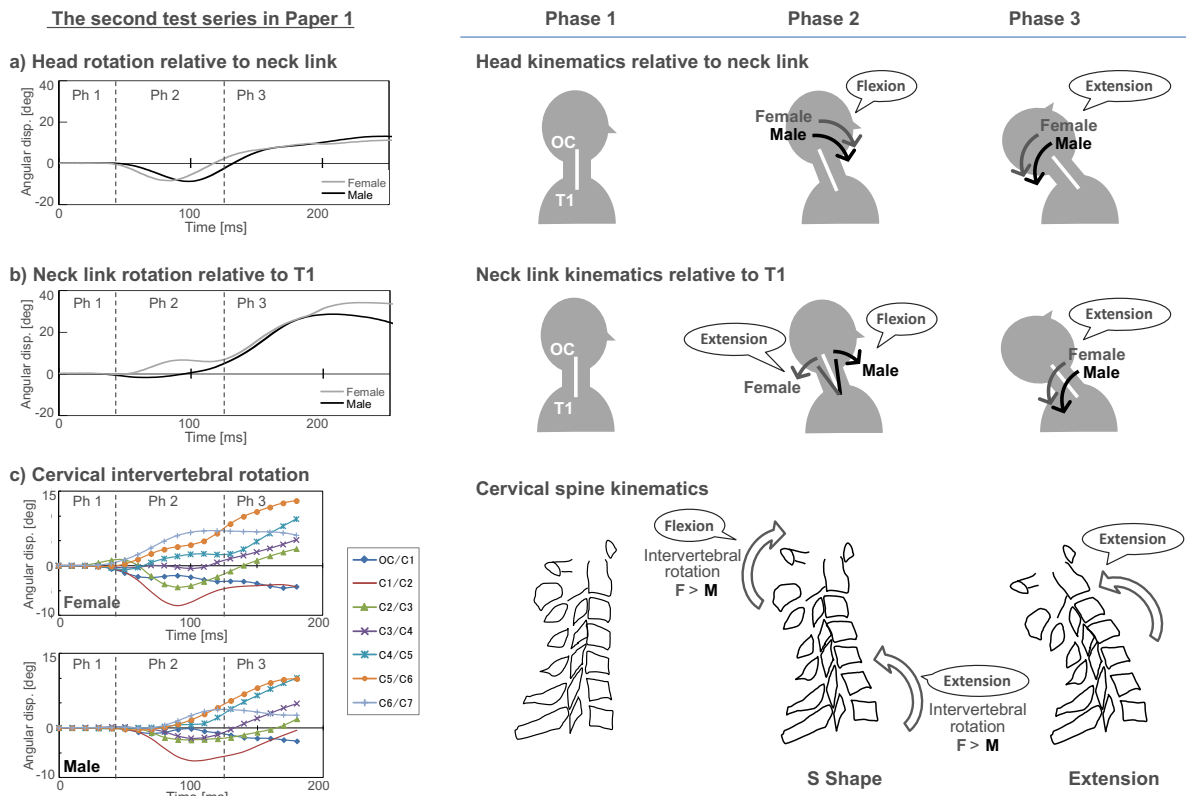


Figure 3. Time histories of the head, neck link and intervertebral angular displacement, and schematic of overall and vertebral kinematics during a rear impact. The neck link is defined as the line from the centre of T1 to the centre of OC. The positive side is extension and the negative is flexion. Time histories were divided into three phases based on the head rotation relative to the neck link shown in (a): Phase1 - remaining in the initial position, Phase 2 - rotating in flexion, and Phase 3 - rotating in extension.

4.2 Summary of Paper III and IV

Title of Paper III: Investigation of Whole Spine Alignment Patterns in Automotive Seated Posture Using Upright Open MRI Systems

Title of Paper IV: The Effect of Seatback Inclination on Spinal Alignment in Automotive Seated Postures

The aim of Paper III and IV was to clarify typical patterns of the whole spinal alignment in an automotive seated posture with two different seat back angles, including average gender specific spinal alignment patterns.

In Paper III, typical patterns of the whole spinal alignment, including average gender specific spinal alignment patterns, were investigated with a 20° seat back angle in the same seated posture and the same seat configuration as in the second sled test series in Paper I. In Paper IV, changing only the seat back angle, average gender specific spinal alignment patterns with a 25° seat back angle were investigated as were those with the 20° seat back angle. Thereafter, the effect of seat back inclination on spinal alignment was looked at in comparisons to spinal alignment in the 20° and 25° seat back angles.

Methods in Paper III: Image data of the spinal column in one seated posture were acquired for eight female and seven male volunteers by an upright open MRI system. A non-metallic wooden seat with a 20° seat back angle, designed to correspond to the seat of the second sled test series in Paper I, was installed in a MRI system. Subjects were seated as per the procedure in the second sled test series in Paper I. The whole spinal alignment, defined as the centre of the vertebral bodies from C2 to the sacrum, was extracted from the image data. Each spinal alignment was rotated and normalised so that C2 was located at 1 on the normalised z-axis and the sacrum at the origin. Then, patterns of whole spinal alignments were investigated through Multi-Dimensional Scaling (MDS), a statistical method for high-dimensional data facilitating visualisation of similarities of investigated objects in reduced data dimensions, generally two or three dimensions less (Cox et al. 2000, Borg et al. 2005). A distance matrix applied as the input data for MDS consisted of all possible inter-individual distances between two subjects, defined as the sum of squared Euclidean pairwise distances between corresponding vertebrae. By applying MDS to the distance matrix, a two-dimensional distribution map of the whole spinal alignment was obtained. On the distribution map, representative whole spinal alignments for all subjects were estimated at the intersections of the 50% probability ellipse with the axes of the 1st and 2nd MDS dimensions by the weighted average of all spinal alignments. Average whole spinal alignment for female and male subjects were also estimated at the average point on the distribution map, respectively.

Methods in Paper IV: Image data of the spinal column in the 20° and 25° seat back angles were acquired by an upright open MRI system for an additional three female and five male volunteers. All MRI scans and MDS analyses, including subjects in Paper III (eight females and seven males), were conducted as per the procedure in Paper III. Only the seat back angle was altered from 20° to 25° when scanning the spinal column. MDS was applied to a data set of the whole spinal alignment for 11 female and 12 male subjects (all subjects in Paper III and Paper IV) with the 20° seat back angle, and for three female and five male subjects (subjects recruited in Paper IV) with the 25° seat back angle, respectively. On the distribution maps for the 20° and 25° seat back angles, representative whole spinal alignments with the 20° and 25° seat back angles for all subjects were estimated at the intersections of the 50% probability ellipse with the axes of the 1st and 2nd MDS dimensions by the weighted average of all spinal alignments. Average gender specific spinal alignments with the 20° and 25° seat back angles were also estimated at the average female or male point on the distribution maps for the 20° and 25° seat back angles. In addition, spinal segmental angles were obtained to clarify the effect of seat back inclination on spinal alignment.

Results in Paper III: Examples of the midsagittal images for female and male subjects are shown with dots indicating the spinal alignment in Figure 4. On the distribution map of whole spinal alignment, the maximum variance of whole spinal alignment (the 1st MDS dimension) illustrated that whole spinal alignment tended to shift the combination from a kyphotic cervical and less-kyphotic thoracic spine with a peak of the thoracic kyphosis at a higher vertebral level, to a lordotic cervical and more pronounced kyphotic thoracic spine with a peak of the thoracic kyphosis at a lower vertebral level. The peak of the thoracic kyphosis is at the most rearward vertebra of the thoracic spine. The 2nd maximum variance of whole spinal alignment (the 2nd MDS dimension) illustrated that the thoracolumbar spine tended to shift from rearward to forward. These trends were observed in the representative spinal alignments estimated at the intersections of the 50% probability ellipse and the axes of the 1st and 2nd MDS dimensions, shown in Figure 5. The estimated average spinal alignment for each gender, shown in Figure 6, illustrated the variation indicated in the 1st MDS dimension because the average MDS score of the 2nd MDS dimension was close to zero for both genders. The estimated average spinal alignment pattern was slightly kyphotic, or almost straight cervical and less-kyphotic thoracic spine for the female subjects, and lordotic cervical and more pronounced kyphotic thoracic spine for the male subjects.

Results in Paper IV: Firstly, due to the low total number of subjects in both Paper III and IV, what effect the additionally recruited subjects in Paper IV had on the overall trend of whole spinal alignment patterns, with the 20° seat back angle observed in Paper III, was looked at. Trends in spinal alignment patterns obtained by an MDS analysis comprising all subjects in Paper III and Paper IV correlated with the results observed in Paper III. The average gender specific spinal alignment with the 25° seat back angle was located rearward of the spinal alignment with the 20° seat back angle from L2 to C2, and came close at C2, exhibiting a similar spinal alignment pattern to that with the 20° seat back angle for both the female and male

subjects, as shown in Figure 7. The spinal segmental angles are summarised in Table 1 and Figure 8. Subjects were categorised into two groups, in accordance to the major trend of the spinal alignment patterns observed in the MDS analysis, based on gender as well as the values of cervical curvature (CC) (cervical lordosis with a positive value of CC or cervical kyphosis with a negative value of CC). In the category of subjects based on the CC values, as shown in Figure 8b, significant differences were observed for both the 20° and 25° seat back angle, in CC, T1 slope (TS), total thoracic kyphosis (TTK), upper thoracic kyphosis (UTK) and lower thoracic kyphosis (LTK) in subjects with positive and negative CCs. The absolute average value of TS, TTK, LTK, and lumbar lordosis (LL) were greater for subjects with positive CCs than subjects with negative CCs. When comparing the 20° and 25° seat back angles, the absolute average value of TTK, LTK, LL and SS tended to be greater for the 25° seat back angle. The most prominent influence of seat back inclination on spinal alignment was shown in TTK displaying a significant difference for subjects with positive CCs. TS and UTK indicated similar angles in both the 20° and 25° seat back angles. Hence, the effect of seat back inclination may be observed most predominantly in LTK. The differences in TTK, LTK and LL for the two seat back angles were greater for spinal alignments with positive CCs than for spinal alignments with negative CCs. As shown in Figure 8c, the female subjects in this study tended to towards negative CC. Findings observed between spinal alignments with positive CCs and negative CCs may affect differences in the average gender specific spinal alignment.

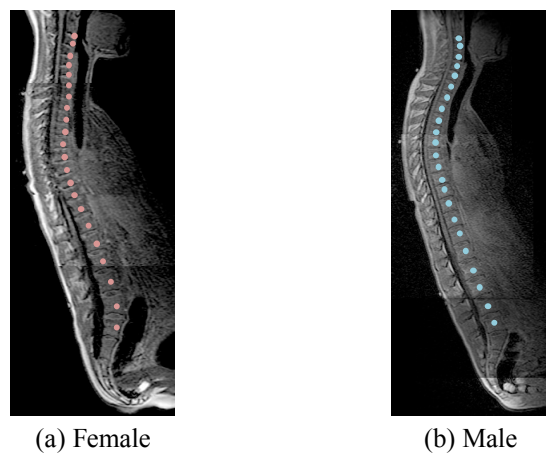


Figure 4. Midsagittal images of the seated posture for one female (a) and one male (b) subject. Dots indicate the spinal alignment defined in this study.

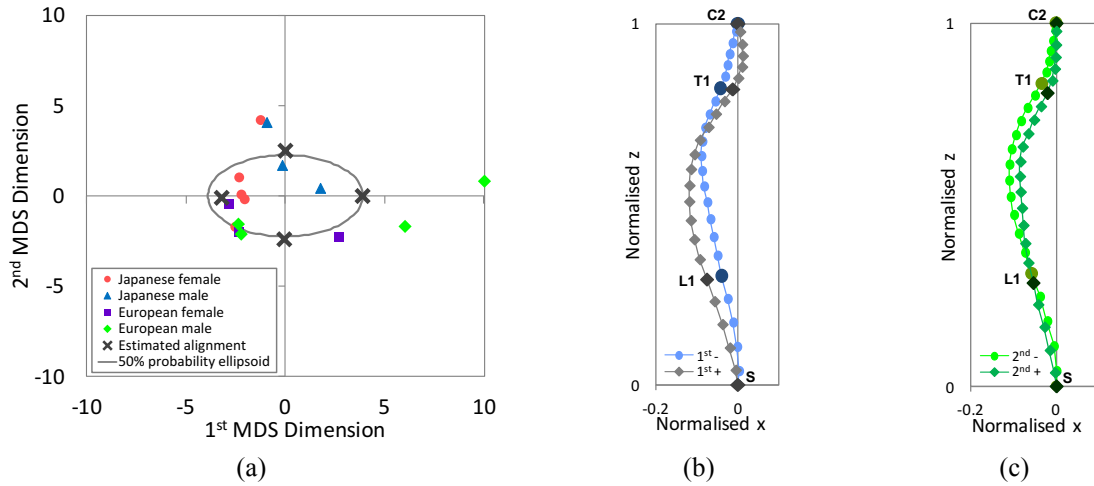


Figure 5. Two-dimensional distribution map for whole spinal alignments with the 50% probability ellipse (a) and representative whole spinal alignment patterns estimated on the 50% probability ellipse (b)(c). ‘1st-’ and ‘1st+’ indicate the representative spinal alignment patterns estimated at the intersections of the 50% probability ellipse and the axes of the 1st MDS dimension in the negative and positive regions of the 1st MDS dimension, respectively. The ‘2nd-’ and ‘2nd+’ indicate the representative spinal alignment patterns estimated at the intersections of the 50% probability ellipse and the axes of the second MDS dimension in the negative and positive regions of the second MDS dimension, respectively. The spinal alignments were rotated and normalised so that C2 was located at 1 on the normalised Z-axis with the sacrum at the origin. The right side of chart (b) and (c) represent the abdominal side and the left side of chart (b) and (c) represent the dorsal side.

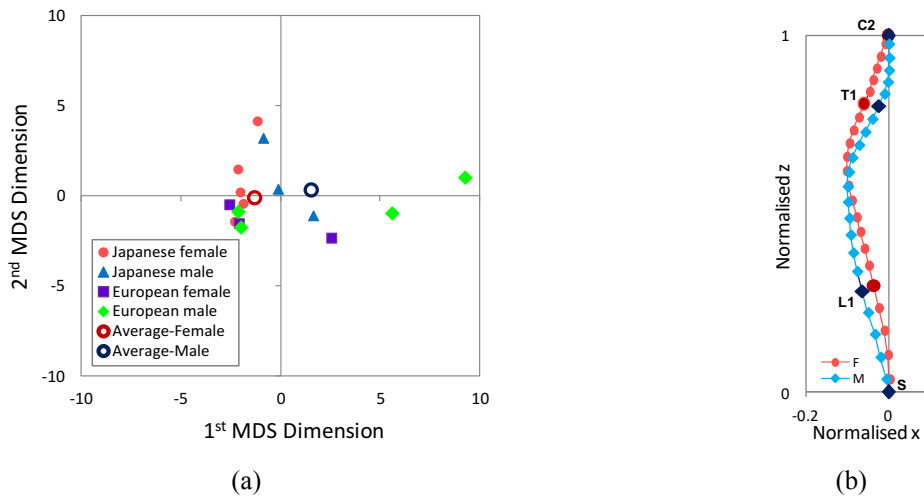


Figure 6. Two-dimensional distribution map for whole spinal alignments with the average MDS score for the female and male subjects (a) and whole spinal alignment patterns estimated on the average MDS score for the female and male subjects (b). The ‘F’ and ‘M’ indicate spinal alignments estimated at the average MDS score for female and male subjects, respectively. The spinal alignments were rotated and normalised so that C2 was located at 1 on the normalised Z-axis with the sacrum at the origin. The right side of chart (b) represents the abdominal side and the left side of chart (b) represents the dorsal side.

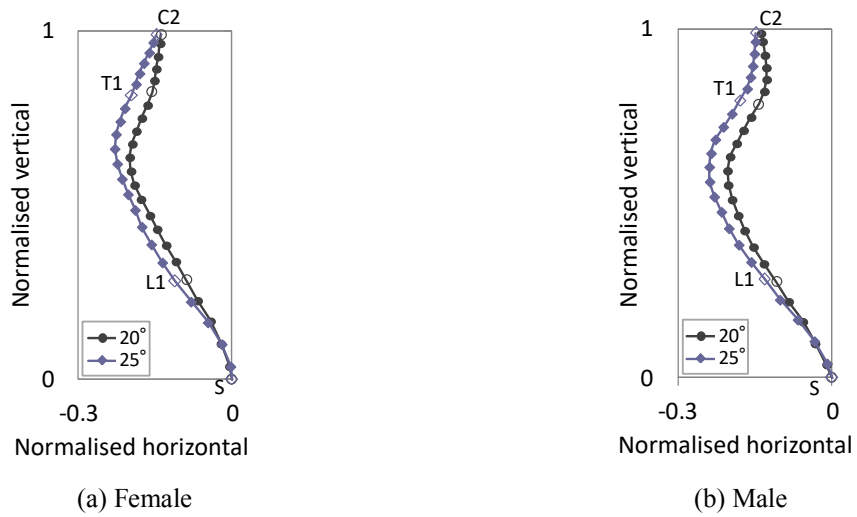


Figure 7. Average gender specific spinal alignments with 20° and 25° seat back angles for the female subjects (a) and male subjects (b). Spinal alignments were calculated with the normalised spinal alignments, and thereafter rotated back to the original positions.

Table 1 Angular measurements of the spinal segments

Angular measurements	Descriptions
Cervical curvature (CC)	Angle between C2 and C7 (Harrison et al. 2000)
T1 slope (TS)	Angle of T1 from horizontal line (Armijo-Olivo et al. 2006, Rocabado et al. 1983, Park et al. 2015)
Total thoracic kyphosis (TTK)	Angle between T1 and T12 (Berthonnaud et al. 2005, Mac-Thiong et al. 2007, Roussouly et al. 2005)
Upper thoracic kyphosis (UTK)	Angle between T1 and T4 (Berthonnaud et al. 2005, Mac-Thiong et al. 2007, Roussouly et al. 2005)
Lower thoracic kyphosis (LTK)	Angle between T4 and T12 (Berthonnaud et al. 2005, Mac-Thiong et al. 2007, Roussouly et al. 2005)
Lumbar lordosis (LL)	Angle between L1 and sacrum (Berthonnaud et al. 2005, Mac-Thiong et al. 2007, Roussouly et al. 2005)
Sacral slope (SS)	Angle of sacrum from the horizontal line (Berthonnaud et al. 2005, Mac-Thiong et al. 2007, Roussouly et al. 2005)

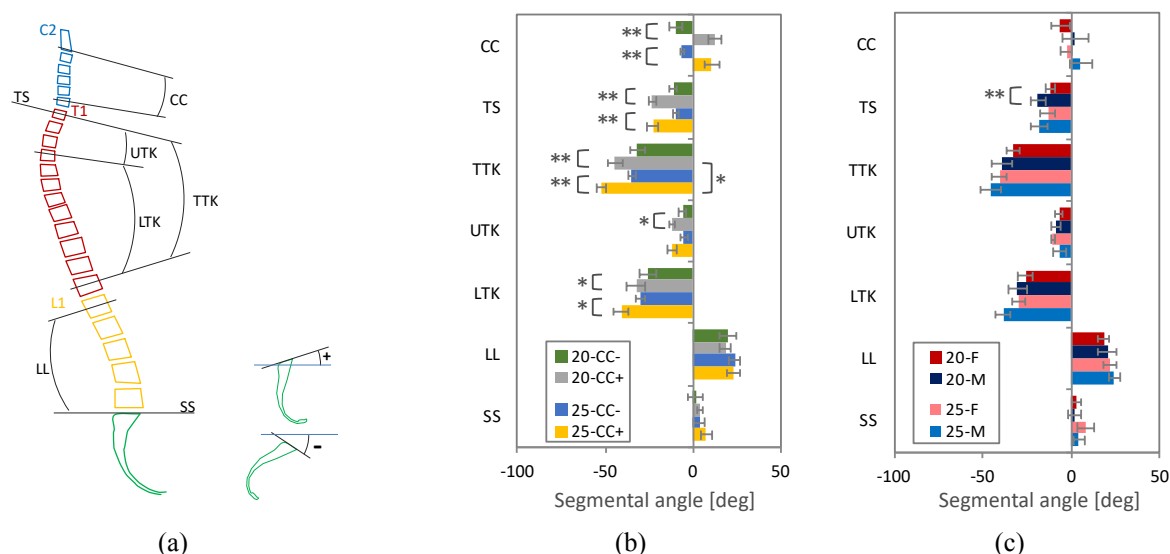


Figure 8. a) Definitions of the angular parameters for the spinal segments (a). The average segmental angles with standard deviation in brackets and p-value from t-test (** < 0.05, * < 0.1), comparing the negative CC (CC-) and positive CC (CC+) groups (b) and male and female (M and F) subjects (c). Figures in legends indicate the seat back angles from the vertical line. Each vertebra angle was defined as the angle of the median plane between the superior and inferior endplates of the vertebral body on the midsagittal plane. The angle of the inferior and superior endplates was used for C2 and the sacrum, respectively. The positive angle indicates a lordotic curvature or upward angle from the horizontal plane, while the negative angle indicates a kyphotic curvature or downward angle from the horizontal plane.

4.3 Summary of Paper V

Title of Paper V: Effects of Whole Spine Alignment Patterns on Neck Responses in Rear End Impact

The aim of Paper V was to develop a 50th percentile female FE model and to investigate any potential impacts of spinal alignment patterns on vertebral kinematics during a rear impact.

The second sled test series in Paper I were reconstructed with a whole-body human FE model of average female body size. The influence of whole spinal alignment patterns obtained in Paper III on spinal kinematic responses in a rear impact was investigated. Paper V contains only intervertebral angular displacements. For this thesis, the facet joint displacements and the spinal ligament elongation were additionally analysed with the reconstruction simulations conducted in Paper V. The methods and results of the additional analysis descriptions are in the Appendix.

Methods in Paper V: A whole-body occupant FE model of an average female body size (162 cm stature, 62 kg weight; the 50th percentile female body size established by Schneider et al. 1983) was developed by scaling and modifying the THUMS AF 05 version 4 (Toyota Motor Corporation 2011). The model was validated with respect to the female volunteer data of the second sled test series in Paper I. For the validation, the average female whole spinal alignment pattern obtained in Paper III (Figure 5b), was implemented in the whole-body occupant model with the same seated posture as that of the female volunteers in the second sled test series in Paper I, as shown in Figure 9. Thereafter, the average male spinal alignment pattern (Figure 9) and four typical spinal alignment patterns obtained from all subjects in Paper III (Figure 5b and 5c) were implemented separately in the validated whole-body occupant models. Additional FE simulations of the sled test with the five models were conducted to investigate effects of whole spinal alignment patterns on vertebral motion during a rear impact.

Results in Paper V: In all simulations, the spine was straightened along the seat back until around 100 ms. At around 100 ms, a peak of the extension of each thoracic vertebra occurred. The maximum cervical S-shape defined as the instant the C2/C3 showed the largest flexion (Stemper et al. 2003) occurred at around 70-80 ms. In a comparison of the occupant models with the average female and male spinal alignments, the spine appeared to begin to straighten from T7 for the average female spinal alignment and L1 for the average male spinal alignment. The average female spinal alignment exhibited larger intervertebral angular displacement in the cervical spine and smaller intervertebral angular displacement in the thoracolumbar spine than the average male spinal alignment, as shown in Figure 10. In the cervical spine, this trend was

observed especially at C5/C6. Likewise, for all simulations with the six different spinal alignments, the spinal alignment patterns with a slightly kyphotic or almost straight cervical and less-kyphotic thoracic spine ('1^{st-}' in Figure 5b and the average female in Figure 6b) exhibited greater angulation in the cervical spine and smaller angulation in the thoracic spine than the spinal alignment patterns with the lordotic cervical and more pronounced kyphotic thoracic spine ('1^{st+}' in Figure 5b and the average male in Figure 6b). Vertebral motions concentrated in the cervical spine for the spinal alignment patterns with the slightly kyphotic or almost straight cervical and less-kyphotic thoracic spine ('1^{st-}' and the average female).

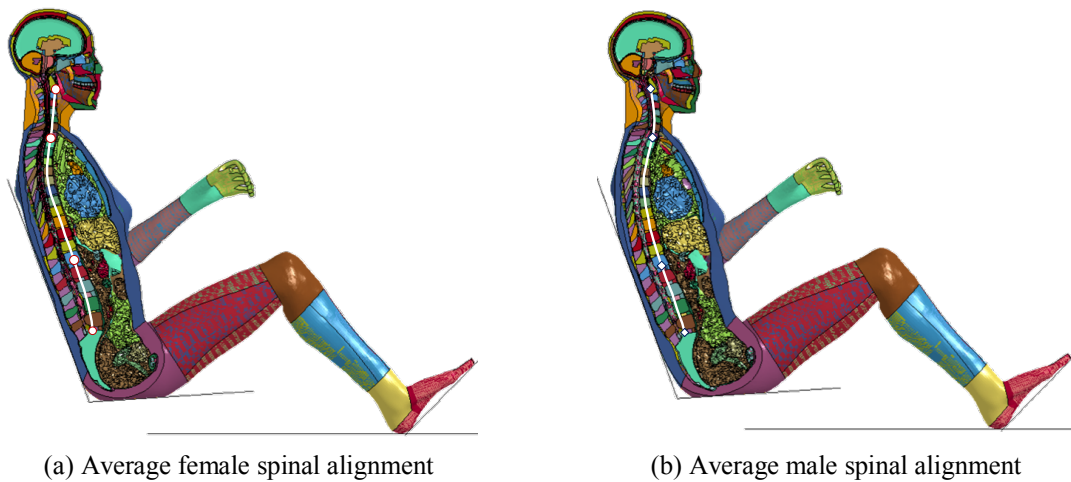


Figure 9. Whole-body occupant FE model of an average female body size with the average female spinal alignment (a) and the average male spinal alignment (b). The spinal alignments implemented in the model were derived from Paper III.

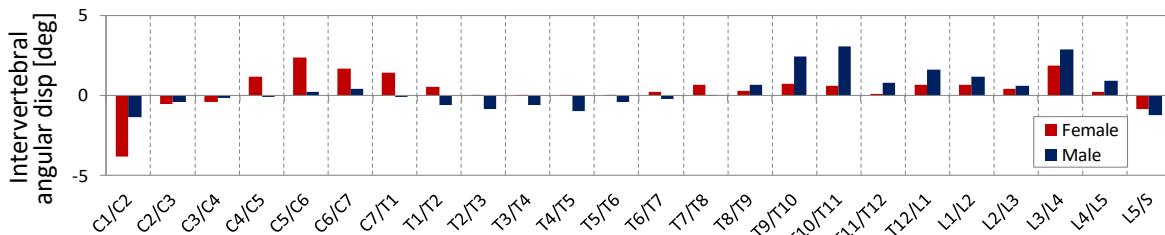


Figure 10. Intervertebral angular displacement at the time of maximum cervical S-shape for the whole-body occupant FE model with the average female spinal alignment and the average male spinal alignment. The positive side is extension and negative is flexion.

5 Discussion

To obtain fundamental knowledge in order to understand gender differences in the risk of sustaining WADs, this thesis has focused on gender specific typical patterns of whole spinal alignment in an automotive seated posture, and any potential impact on dynamic characteristics of cervical vertebral kinematics during rear impacts, for men and women.

According to certain hypotheses of WAD injury mechanisms, as described in Chapter 2, it is highly likely that greater cervical vertebral kinematics produced in a very short time during the S-shape of the cervical spine, is related to cervical soft tissue injury and an increased risk of sustaining WAD. In Paper I and II, previous volunteer data of rear impact sled tests were reanalysed in order to understand gender differences in the dynamic characteristics of cervical vertebral kinematics. During the rear impacts analysed, the female subjects were exposed to a more pronounced S-shape of the cervical spine than the male subjects, beyond the range of voluntary muscle-induced cervical vertebral kinematics for female subjects.

Cervical spinal alignment has been considered as one of the possible causes of differences in cervical vertebral kinematics during an impact, resulting in differences in neck injury severity (Maiman et al. 1983 and 2002, Yoganandan et al. 1986 and 1999, Liu et al. 1989, Pintar et al. 1995, Ono et al. 1997, Stemper et al. 2005). These earlier studies have investigated the relation between cervical spinal alignment and the response of the cervical spine, using PMHS head-neck complexes, a mathematical head-neck model or just one male volunteer. The cervical spine is continuously linked to the thoracolumbar spine, hence cervical spinal alignment is dependent on thoracolumbar spinal alignment. External force transmitted from the seat back to the torso is transferred to the cervical spine gradually via the thoracolumbar spine. Thus, thoracolumbar spinal alignment may potentially also have an impact on cervical vertebral kinematics, as well as cervical spinal alignment. In this thesis, analysis of typical patterns of whole spinal alignment, from C2 to the sacrum, in an automotive seated posture was performed, including analysis of average gender specific spinal alignments in Paper III and IV. The average gender specific spinal alignment patterns established include slight kyphotic, or almost straight cervical and less-kyphotic thoracic spine for the female subjects, and lordotic cervical and more pronounced kyphotic thoracic spine for the male subjects. The seated posture adopted for the analysis on whole spinal alignment corresponds to the posture used in the rear impact sled tests in Paper I and II.

In Paper V, the effect whole spinal alignment pattern has on cervical vertebral kinematics were investigated with different spinal alignment patterns obtained in Paper III and IV. In the reconstruction simulations of the rear impact sled test in Paper I and II, the average female spinal alignment pattern demonstrated greater vertebral kinematics from the lower cervical spine to the upper thoracic spine with a more pronounced S-shape of the cervical spine, compared to the average male spinal alignment pattern. The average male spinal alignment pattern exhibited greater vertebral kinematics from the lower thoracic spine to the lumbar spine. In the rear impact reconstruction simulations, larger elongation of the spinal ligaments likely appeared at intervertebral levels where larger vertebral displacements were found. The average

female spinal alignment pattern was exposed to larger spinal ligament elongation in the cervical spine, than the average male spinal alignment pattern.

The findings in Paper III, IV and V are in line with the findings in Paper I and II. Hence, the spinal alignment trend in females, may make women exposed to larger elongation of the cervical soft tissues, including the cervical spinal ligaments, due to greater intervertebral displacements during a rear impact. Consequently, women may be subject to an increased risk of sustaining WADs. This chapter presents a detailed discussion about the above issues in the sections below.

5.1 Cervical kinematic responses in rear end impacts

The dynamic inertia-induced cervical kinematics obtained in the second sled test series in Paper I, was compared to the quasi-static muscle-induced cervical kinematics obtained in the voluntary neck bending motions described in Paper II. Until around 110 ms in the dynamic inertia-induced cervical kinematics for both genders, OC and C1 rotated in flexion relative to C7, while other vertebrae rotated in extension. Afterwards, all vertebrae rotated in extension relative to C7. On the other hand, in the quasi-static muscle-induced cervical kinematics, all vertebrae rotated in extension relative to C7 when the cervical spine was moving voluntarily in neck extension. Cervical S-shape deformation was not observed in the quasi-static muscle-induced cervical kinematics. Such differences in cervical vertebral kinematics between dynamic inertia-induced and quasi-static muscle-induced responses support former studies with one male subject (Ono et al. 1997 and 1999). The main characteristic of dynamic inertia-induced cervical kinematics is represented by the cervical S-shape, followed by the transition from the S-shape to the extension phase (Matsushita et al. 1994, Grauer et al. 1997, Yoganandan et al. 1998, Kaneoka et al. 1999, Deng et al. 2000, Luan et al. 2000, Cusick et al. 2001, Panjabi et al. 2004b).

The extension of the lower cervical spine at C4/C5, C5/C6 and C6/C7 was considerably greater, while the flexion of the upper cervical spine at OC/C1, C1/C2 and C2/C3 was only slightly more prominent for female subjects compared to male subjects, in the maximum S-shape of dynamic inertia-induced cervical kinematics, with the greatest peak flexion angle at C1/C2 during the time between 90 ms to 100 ms. The female subjects were exposed to a more pronounced peak cervical S-shape than the male subjects. This cervical kinematic response trend is correlate with the rear impact sled test series with female and male PMHS head-neck complexes by Stemper et al. (2003 and 2004a). The more pronounced S-shape of the cervical spine indicates larger local intervertebral displacements that may produce more severe strain and loading on the cervical soft tissues, including the facet joint capsules (Deng et al. 2000, Luan et al. 2000, Winkelstein et al. 2000, Siegmund et al. 2001, Yoganandan et al. 2002, Yang et al. 2003, Pearson et al. 2004). A more pronounced cervical S-shape also indicates higher pressure magnitudes in the spinal canal during whiplash motion (Yao et al. 2016). It has been suggested that these pressure transients produce dorsal root ganglion injuries (Örtengren et al. 1996). Therefore, gender differences in the cervical S-shape phase could potentially become part of the explanation for the increased injury risk of women sustaining WADs.

Since the voluntary neck retraction causes flexion in the upper vertebrae and extension in the lower vertebrae, similar to the cervical S-shape observed in the dynamic inertia-induced cervical kinematics, the peak S-shape in dynamic inertia-induced cervical kinematics was compared to the voluntary neck retraction at its maximum position in the quasi-static muscle-induced cervical kinematics. For the female subjects, C4/C5 through C6/C7 showed larger extension angles in the peak cervical S-shape than maximum voluntary retraction, while the peak cervical S-shape was in the maximum voluntary retraction range for the male subjects. It has been assumed in this thesis that the voluntary quasi-static muscle-induced cervical kinematics would be within a non-injurious range. It has been hypothesised that in cases where

the voluntary quasi-static muscle-induced cervical kinematics range has been exceeded, that the additional vertebral displacement has the potential of being harmful (Panjabi et al. 1999). It is therefore feasible that this result partly explains why women are exposed to a higher WAD injury risk.

5.2 Whole spinal alignment patterns in an automotive seated posture

Through MDS analyses on a data set of spinal alignments, typical spinal alignment patterns in one automotive seated posture with the seat back at a 20° angle were investigated with eight female and seven male subjects in Paper III and V, and with an additional three female and five male subjects (total 11 female and 12 male subjects) in Paper IV. Since MDS detects meaningful underlying dimensions in a data set, spinal alignment patterns can be classified by applying a MDS analysis on a set of spinal alignment data (Mochimaru et al. 2000, Miyazaki et al. 2005). On a distribution map obtained by the MDS analysis, whole spinal alignments at the intersection of the 50% probability ellipse with the axes of the two MDS dimensions were estimated to interpret underlying spinal alignment patterns portrayed along each MDS dimension. Comparing the estimated spinal alignments on the axis of the 1st MDS dimension (Figure 5b), the largest variation in spinal alignment due to individual differences showed a prominent relationship between the cervical and thoracic spinal alignment. Cervical lordosis occurred together with more pronounced thoracic kyphosis than cervical kyphosis. Indeed, the combination shifted from slight kyphotic or almost straight cervical spine with less-kyphotic thoracic spine, to lordotic cervical spine with more pronounced kyphotic thoracic spine, with an increase in the MDS score of the 1st MDS dimension when looking at the spinal alignments one by one along the 1st MDS dimension, as shown in Figure A1b and A1c of Paper V. The 1st MDS dimension in Paper III and V, and Paper IV, accounted for 67% and 56% of the total inter-subject variance in whole spinal alignment, respectively. A significant part of the variety in spinal alignment can be explained by the 1st MDS dimension.

In Paper III, a MDS analysis was also conducted exclusively on cervical spinal alignments from C2 to T1. The distribution map of cervical spinal alignments illustrated that the pattern of cervical spinal alignment shifted from kyphotic to lordotic through straighter alignment along the 1st MDS dimension, as shown in Figure 8 of Paper III. Reed & Jones (2017) reanalysed sagittal X-ray images of the head and the cervical spine, captured in a previous study by Snyder et al. 1975, of a total of 140 female and male volunteers seated on a hard seat resembling a vehicle seat. In their principal component analysis on cervical spines, the first principal component illustrated slightly kyphotic and pronounced lordotic cervical spinal alignments obtained at \pm three standard deviations of the principal component score, respectively, with a straighter cervical spinal alignment obtained at the mean principal component score. The results

are similar to the results in this thesis, and thus support the observation of cervical spinal alignments on the distribution map in this thesis.

According to findings through the MDS analyses of the spinal alignment, described above, spinal alignments were classified into two groups based on the CC angle (Tables 1) in the investigation of spinal segmental angles in Paper IV. The absolute values of the average TS, TTK, UTK and LTK angles were significantly greater for subjects with positive CC (lordotic) than subjects with negative CC (kyphotic) in the 20° seat back angle condition, as shown in Figure 8. In the 25° seat back angle condition, the absolute values of the average TS, TTK and LTK angles were significantly greater for subjects with positive CC. The comparison of the estimated spinal alignments at the intersections of the 50% probability ellipse with the axis of the 1st MDS dimension on the distribution map (Figure 5b) illustrated those findings in the spinal segmental angles.

In previous studies of spinal alignment, cervical lordosis tended to have a more pronounced thoracic kyphosis (Hardacker et al. 1997, Erkan et al. 2010, Ames et al. 2013, Endo et al. 2016) with greater C7 (Endo et al. 2016) and T1 inclination (Ames et al. 2013, Lee et al. 2014, Park et al. 2015) in the standing posture. Conversely, cervical kyphosis tends to have a less-kyphotic thoracic spine with smaller C7 and T1 inclination. T1 inclination has been suggested as a predictor of whole spinal alignment in the standing posture due to relationships along the cervical, thoracic and lumbar spines (Knott et al. 2010, Jun et al. 2014, Lee et al. 2015). Spinal alignment trends in the automotive seated posture, observed in Paper III, IV and V, were similar to previous findings in the standing posture.

For the lumbar region, in Paper IV, the average LL angle indicated a similar value between subjects with positive CC (lordotic) and negative CC (kyphotic) in both the 20° and 25° seat back angle conditions, as shown in Figure 8b. The comparison of the estimated spinal alignments at the intersections of the 50% probability ellipse with the axis of the 1st MDS dimension on the distribution map (Figure 5b) does not illustrate a pronounced difference in the lumbar spine, such as in the cervical and thoracic spine. In addition, the MDS score on the 1st MDS dimension for the whole spinal alignment does not correlate with that for the lumbar spinal alignment, as described in Paper III.

On the other hand, previous studies have reported that cervical lordosis tends to have a more pronounced thoracic kyphosis and less lumbar lordosis due to maintaining spinal balance (Gore et al. 1986, Roussouly et al. 2011, Ames et al. 2013). However, another study has indicated that the cervical curvature does not have a prominent relationship with lumbar lordosis and sacral slope (Endo et al. 2016). In this thesis, the laboratory seat used in Paper III, IV and V consisted of two stiff flat plates. The subjects leaned in for good contact with the flat plane seat back along the entire back. Thus, the lumbar spine was straightened along the seat back. Due to flexibility in the lumbar spine, this may not cause any significant difference in the lumbar spine between subjects with positive CC (lordotic) and negative CC (kyphotic) in both the 20° and 25° seat back angle conditions.

5.3 Gender differences of the whole spinal alignment in one automotive seated posture

Average gender specific spinal alignments were estimated at the average gender points on the distribution map of spinal alignment in Paper III, IV and V. The average spinal alignments include almost straight cervical and less-kyphotic thoracic spine for the female subjects, and lordotic cervical and more pronounced kyphotic thoracic spine for the male subjects, as shown in Figure 6b. On the distribution map of spinal alignments (Figure 6a), the average gender specific points were almost on the axis of the 1st MDS dimension, located at the left side against the origin for female subjects and the right side for male subjects, within the 50% probability ellipse. The origin indicates the average of all data. Therefore, average gender specific spinal alignments were in line with the trend observed along the 1st MDS dimension, with a smaller difference than that between the estimated spinal alignments at the intersections of the 50% probability ellipse and the axis of the 1st MDS dimension.

In the investigation of spinal segmental angles in Paper IV, the average CC angle was greater for male subjects than for female subjects in both the 20° and 25° seat back angle conditions, as shown in Figure 8. The absolute values of the average TS, TTK and LTK angles were greater for male subjects than for female subjects in both the 20° and 25° seat back angle conditions. The comparison of the estimated average gender spinal alignments (Figure 6b) illustrated similar findings in the spinal segmental angles. However, only the TS in the 20° seat back angle condition indicated a significant difference between genders.

As reported in previous studies on the variation in cervical spinal alignment in the standing or upright seated postures (Helliwel et al. 1994, Haedacker et al. 1997, Matsumoto et al. 1998), gender is an independent factor which correlates significantly with non-lordosis. Women are more likely to present non-lordosis (kyphotic or straight). Conversely, men present more pronounced lordosis. In Paper III, IV and V, the average gender specific spinal alignments in the cervical spine were almost straight for females and lordotic for males. The average CC angle was positive for male subjects, whereas negative for female subjects. Findings in this thesis correlate with previous studies.

At the cervicothoracic junction, relationships along cervical spinal alignment, C7 or T1 inclination and thoracic kyphosis have been investigated with a focus on gender differences (Lee et al. 2014, Park et al. 2015, Endo et al. 2016). Decrease in the C7 and T1 inclination is associated with kyphosis, or an increase in hypo-lordosis in cervical spinal alignment, and less kyphosis in thoracic spinal alignment. Men tend to have greater C7 and T1 inclination (more forward-inclined C7 and T1), while women tend to have shorter C7 and T1 inclination (less forward-inclined C7 and T1). With decreasing T1 inclination, women are more likely to present a hypo-lordotic or kyphotic cervical spine and a less kyphotic thoracic spine than men. The average female spinal alignments obtained in Paper III, IV and V portrayed a less forward inclination around C7 and T1 displaying a straighter cervical and thoracic spine than the average male spinal alignment, as shown in Figure 6b. In Paper IV, the average CC angle and the absolute angles of the average TS, TTK and LTK were smaller for female subjects than for

male subjects, with a significant difference in the TS. The gender differences observed in this thesis are in agreement with the above mentioned previous studies.

Since the CC of the female subjects in Paper IV tended to be negative, the trends observed in a comparison between subjects with negative (kyphotic) and positive (lordotic) CC (Figure 8b) might affect differences between genders (Figure 8c). Therefore, the average female exhibited less TS with less-kyphotic thoracic alignment, and thus straighter cervicothoracic spinal alignment than the average male, despite no significant differences observed in the CC, TTK and LTK. In the MDS analyses in Paper III, IV and V, the average gender specific points were almost on the axis of the 1st MDS dimension on the distribution map of spinal alignment (Figure 6a). Consequently, the average female point was positioned opposite the average male point across the origin, which may suggest gender as one of the factors affecting the largest inter-individual variance in spinal alignment.

Study of the lumbar region in this thesis only revealed minor average gender specific spinal alignment and LL differences. In a report by Endo et al. (2014), lumbar lordosis is significantly greater for women than men in the upright seated position, while the present study focused on an automotive seated posture instead of an upright seated posture. As mentioned in the preceding section (5.2), subjects in this thesis were seated deeply on a stiff laboratory seat leaning the entire back against the flat plane seat back. This caused the lumbar spine to straighten along the seat back, showing no significant gender differences, such as in the upright seated posture. Consequently, differences in seated posture may affect the degree of lumbar lordosis.

5.4 Effects of spinal alignment patterns on vertebral kinematic responses in rear impact

The effect of spinal alignment on vertebral kinematics was investigated through rear impact simulations with six different whole spinal alignments in Paper V obtained from Paper III. Paper V looked only at intervertebral angular displacements. Based on WAD injury mechanism theories, additional analysis on the facet joint displacements were conducted using the simulation results published in Paper V of this thesis. The methods and results of the additional analysis are described in the Appendix.

At the time of maximum cervical S-shape which occurred at around 70-80 ms in the whole-body occupant FE model simulations in Paper V, intervertebral angular displacements and facet joint displacements were concentrated from the lower cervical spine to the upper thoracic spine, in a slightly kyphotic or almost straight cervical spine and less-kyphotic thoracic spine ('1st-' in Figure 5b and the average female in Figure 6b), as shown in Figure A1. On the other hand, similar displacements were more concentrated from the lower thoracic spine to the lumbar spine

in the lordotic cervical and more pronounced kyphotic thoracic spine ('1^{st+}' in Figure 5b and the average male in Figure 6b). Looking at the trajectory of the whole spine against the laboratory seat (Figure 2 of Paper V) at an earlier stage of the rear impact until 100 ms, it was observed that average female spinal alignment initiated straightening of the spine from a higher vertebral level (T7), while straightening began from a lower vertebral level (L1) for average male spinal alignment. Therefore, spinal alignment in a more pronounced kyphotic thoracic spine ('1^{st+}' and the average male) may have larger vertebral displacements in the lower vertebral levels, from the lower thoracic spine to the lumbar spine. For spinal alignments with a less kyphotic thoracic spine ('1^{st-}' and the average female), larger vertebral displacements were observed in the upper vertebral levels, from the lower cervical spine to the upper thoracic spine. Simulation results suggest that variations in thoracic spinal alignment have a potential impact on cervical vertebral kinematics. The differences in thoracolumbar vertebral kinematics resulted in different T1 kinematics (Figure 2 and 3 of Paper V). Among spinal alignment patterns, this may cause a difference in load transmission of the neck, from the trunk to the head.

In the cervical region, at the time of the maximum cervical S-shape, intervertebral extension and facet joint posterior shear were greater at the lower intervertebral levels of the cervical spine (especially C5/C6) in a slightly kyphotic or almost straight cervical spine and less-kyphotic thoracic spine ('1^{st-}' and the average female), when compared to a lordotic cervical and more pronounced kyphotic thoracic spine ('1^{st+}' and the average male), as shown in Figure A1. Similarly, Östh et al. (2017) conducted a parameter study of different cervical spinal alignments with a 50th percentile female head-neck FE model, given the same prescribed motion of T1. Intervertebral angular displacements and facet joint displacements were greater at the lower intervertebral levels of the cervical spine (C5/C6 and C6/C7) for an almost straight cervical spine, when compared to a more pronounced lordotic cervical spine. In both the simulations with the whole-body occupant FE model and the head-neck FE model, straighter cervical spinal alignment exhibited greater intervertebral displacements than the lordotic cervical spinal alignment. Simulation results suggest that variations in the cervical spinal alignment have a potential impact on cervical vertebral kinematics as well as the thoracic spinal alignment. The cervical spine is linked continuously from the thoracic spine, and the cervical and thoracic spines depend on each other. This thesis illustrates a relationship trend between the cervical and thoracic spinal alignment patterns in Paper III. Hence, the whole spinal alignment pattern could affect cervical vertebral kinematics directly by T1 vertebral kinematics and the variations in cervical spinal alignment pattern.

Indeed, in the second sled test series in Paper I, two female subjects had kyphotic cervical spines. Then, two male subjects presented with lordotic cervical spines, and the other two male subjects straight cervical spines. As described in an earlier section (5.1), the female subjects exhibited a more pronounced maximum cervical S-shape with greater intervertebral extension and posterior displacement at C4/C5, C5/C6 and C6/C7, compared to the male subjects. The simulation results mentioned above demonstrate a similar trend as seen in the volunteer sled test.

In the rear impact reconstruction simulations conducted in this thesis, only the spinal alignment was changed. The skeletal bone geometry including size was identical in the simulations with the whole-body occupant FE model. Stemper et al. (2011) have indicated that women have less support in the cervical region with a more slender neck and smaller vertebral bodies than men, backed up by biomechanical and morphological literature on anatomical gender differences with size matched volunteers (DeRosia 2008, Stemper et al. 2008 and 2009, Vasavada et al. 2008). Kitagawa et al. (2015) demonstrated through FE analysis that gender differences in cervical spine motion were affected by size differences rather than muscular strength. John et al. (2018) demonstrated the effect of geometrical gender differences of the cervical vertebrae on vertebral kinematics with a C5/C6 segment FE model. Hence, any anthropometric and geometrical differences may contribute to cervical vertebral kinematics during impact, and lead to more pronounced gender differences in intervertebral displacement, when applied to the occupant FE models utilised in this study.

5.5 Effects of spinal alignment patterns on cervical ligamentous responses in rear impact

To investigate the potential impact of spinal alignment on sustaining WADs, the elongation of the cervical ligaments was additionally analysed for this thesis, as shown in the Appendix, using the rear impact reconstruction simulations with the whole-body occupant FE model in Paper V. It was found that spinal alignment patterns have an influence on the elongation of the cervical ligaments as well as the vertebral kinematics during impact. The cervical ligaments had larger elongation for a slightly kyphotic or almost straight cervical spine and less-kyphotic thoracic spine ('1^{st-}' in Figure 5b and the average female in Figure 6b), compared to a lordotic cervical and more pronounced kyphotic thoracic spine ('1^{st+}' in Figure 5b and the average male in Figure 6b). Larger elongation of the cervical ligaments likely appeared at intervertebral levels where intervertebral displacement was found to be more significant.

For the ALL, greater elongation occurred together with greater intervertebral extension and facet joint posterior shear at the lower intervertebral levels. Kaneoka et al. (1999 and 2000) indicated that intervertebral extension and facet joint posterior shear at the lower intervertebral levels during the cervical S-shape resulted in tension at the ALL and the anterior region of the intervertebral discs. Findings in this thesis are in line with these previous studies. Greater intervertebral extension and facet joint posterior shear had greater ALL elongation for a slightly kyphotic or almost straight cervical spine and less-kyphotic thoracic spine ('1^{st-}' and the average female), compared to a lordotic cervical and more pronounced kyphotic thoracic spine ('1^{st+}' and the average male).

The largest CL elongation was observed at C6/C7 followed by C5/C6 and C3/C4. Luan et al. (2000) have described that the CL elongation was caused mainly by flexion-tension at upper

intervertebral levels and shear at lower intervertebral levels, based on PMHS sled tests conducted by Deng et al. (2000). Similarly, in this thesis, C3/C4 exhibited intervertebral flexion, and C5/C6 and C6/C7 exhibited facet joint posterior shear with intervertebral extension and facet joint posterior distraction. Greater intervertebral and facet joint kinematics resulted in greater CL elongations for a slightly kyphotic or almost straight cervical spine and less-kyphotic thoracic spine ('1^{st-}' and the average female), when compared to a lordotic cervical and more pronounced kyphotic thoracic spine ('1^{st+}' and the average male). However, C2/C3 and C4/C5 had smaller CL elongations, even though the intervertebral flexion at C2/C3 and the facet joint posterior shear with intervertebral extension and facet joint posterior distraction at C4/C5 was of a similar magnitude to C3/C4, and C5/C6 and C6/C7, respectively. Kaneoka et al. (1999 and 2000) also indicated the shift of the instantaneous axis of rotation of the cervical vertebra during the rapid cervical S-shape deformation. The instantaneous axis of rotation of the cervical vertebra might affect the CL elongation. Future studies should address the relation between CL elongation and such vertebral kinematics including the instantaneous axis of rotation.

Furthermore, regarding the vertebral kinematics related to the CL elongation, intervertebral extension was highest at C5/C6, while the facet joint posterior shear was highest at C4/C5. According to cervical vertebral kinematics during the rapid cervical S-shape deformation of volunteers in Paper I, intervertebral extension and posterior translation, which related to the facet joint posterior shear occurring at virtually the same time. These findings imply that it might be difficult to predict injured intervertebral levels with only intervertebral extension or facet joint posterior shear. However, both the intervertebral extension and facet joint posterior shear demonstrate a similar trend for all spinal alignment patterns, indicating greater magnitudes for a slightly kyphotic or almost straight cervical spine and less-kyphotic thoracic spine ('1^{st-}' and the average female), compared to a lordotic cervical and more pronounced kyphotic thoracic spine ('1^{st+}' and the average male). Hence, it may be possible to use the intervertebral extension and facet joint posterior shear for prediction of injury on the CL. In addition, posterior distraction shows a similar trend in intervertebral angular displacement, which may indicate that vertebral angular displacement can predict facet joint posterior distraction. On the other hand, anterior distraction shows only insignificant magnitudes in the reconstruction simulations, which may be an indication of facet joint anterior distraction not contributing significantly to WADs.

The ISL elongation was greater at C2/C3 and C3/C4 for all spinal alignment patterns. The ISL is located in the posterior region of the cervical spine. Therefore, the intervertebral flexion at C2/C3 and C3/C4 resulted in greater elongation. The ISL elongation was greater than the elongation of other cervical ligaments. However, ISL has not received much attention with regard to being a possible cause of WADs. It can be reasonably assumed that intervertebral flexion would not be affected much by impact severity and that ISL elongation would not reach a harmful level. Further detailed investigation would be needed to establish a relationship between ISL elongation and any WAD injury mechanisms. In addition, in comparison to other cervical ligaments less elongation was observed in the LF and PLL. Whether LF and PLL play a major role in WAD injury risk remains unknown due to lack of information in the literature.

Previous studies, conducting experiments with PMHS specimens, have demonstrated that variations in cervical spinal alignment influenced the severity of neck injuries (Liu et al. 1989, Maiman et al. 1983 and 2002, Pintar et al. 1995, Stemper et al. 2005, Yoganandan et al. 1986 and 1999). Stemper et al. (2005) investigated the influence of cervical spinal alignment on CL elongation in rear impact simulations, using a male head-neck numerical model with lordotic, straight, and kyphotic cervical spinal alignment. This is due to damage to the CL being one likely cause of WAD (Bogduk 2011). CL elongation was increased, particularly at C5/C6, for kyphotic cervical spinal alignment, compared to lordotic and straight cervical spinal alignment. Stemper et al. (2005) concluded that kyphotic cervical spinal alignment could contribute to an increased risk of WAD. These findings support results obtained in this thesis.

5.6 Implications of actual whiplash injuries

None of the seats used in this thesis were equipped with head restraints. In previous rear impact sled tests with an automotive seat at an impact level similar to in this thesis, the head-to-head restraint contact time was 91 ms for female subjects and 100 ms for male subjects (Carlsson et al. 2010), and 95 ms for male subjects (Pramudita et al. 2007). In the second sled test series in Paper I, the cervical spine was exposed to the maximum cervical S-shape at a time between 90 ms and 100ms for both genders. The cervical S-shape was more pronounced for the female subjects than the male subjects, and exceeded the range of maximum voluntary retraction motion for female subjects, as described in Paper II. In the reconstruction simulations of the sled test in Paper V, the maximum cervical S-shape occurred at a time around 70 ~ 80 ms for all spinal alignment patterns. The cervical S-shape was more pronounced for a slightly kyphotic or almost straight cervical spine and less-kyphotic thoracic spine including the average female spinal alignment pattern, compared to a lordotic cervical and more pronounced kyphotic thoracic spine including the average male spinal alignment pattern.

Head-to-head restraint contact time depends on several factors; foam stiffness, seat back recliner stiffness, and the initial gap between the head and head restraint. However, based on findings in this thesis and the head-to-head restraint contact timings reported in previous papers (Pramudita et al. 2007, Carlsson et al. 2010), it has been found that in real-world rear impact cases at the same impact level as adopted in this thesis, the maximum S-shape of the cervical spine might occur around the head-to-head restraint contact for both men and women with various spinal alignment patterns. Hence, women who display a similar spinal alignment to the average female spinal alignment pattern, would potentially be exposed to a more pronounced cervical S-shape than men who have a similar spinal alignment to the average male spinal alignment pattern, beyond the range of maximum voluntary retraction. At around the observed head-to-head restraint contact timings, vertebral displacement and elongation of the cervical ligaments are already larger for the average female spinal alignment pattern, compared to the

average male spinal alignment pattern. The above findings in this thesis may play a part in understanding gender differences in the injury mechanisms and risk of sustaining WADs.

Considering more severe and injurious real-world accidents, it is to be expected that the vertebral kinematic responses would follow the trends observed in the second sled test series in Paper I. However, they exceed the voluntary range of motion to an even greater extent and thus cause damage to cervical soft tissues. The female subjects in the second sled test series in Paper I and the occupant FE model, with the average female spinal alignment pattern in Paper V, were exposed to a more pronounced cervical S-shape than male subjects or the occupant FE model with the average male spinal alignment pattern. Similarly, in more severe and injurious real-world accidents, it is expected that women whose spinal alignment is similar to the average female spinal alignment pattern, would be exposed to an even more pronounced cervical S-shape than men who have a similar spinal alignment to the average male spinal alignment pattern. However, to avoid subjecting the volunteers to injuries in the rear impact sled tests, this thesis did not address the higher impact levels observed in real-world accidents. Consequently, future analysis at real-world accident impact levels would be conducted with whole-body occupant FE models for investigating gender differences in dynamic cervical vertebral kinematics at higher impact levels.

Investigations into the prevalence of neck pain at the cervical zygapophysial joint, sustained in rear end accidents, found that the chronic pain the majority of patients experience occurred at C2/C3 or C5/C6 (Barnsley et al. 1995, Lord et al. 1996, Liliang et al. 2008, Bogduk 2011). The study of a rear impact sled test series with PMHSs reported that slight damage of cervical soft tissues was found at the C5/C6 and C6/C7 level during the autopsy (White et al. 2009). In the volunteer rear impact sled tests in Paper I, most forward vertebral translational displacement relative to the lower adjacent vertebra was observed at C2/C3 in the female subject. At C5/C6 and C6/C7, vertebral angular displacement in extension and rearward displacement relative to the lower adjacent vertebra was observed beyond the voluntary muscle-induced vertebral kinematics range, especially in the female subjects. In Paper V, the rear impact reconstruction simulations with the whole-body occupant FE model demonstrated that elongation of the CL was greater, especially at C3/C4 with intervertebral flexion and C5/C6 and C6/C7 with facet joint posterior shear and intervertebral extension. These CL elongations were greater for a slightly kyphotic or almost straight cervical spine and less-kyphotic thoracic spine including the average female spinal alignment, compared to a lordotic cervical and more pronounced kyphotic thoracic spine including the average male spinal alignment. Such findings in this thesis indicate similar vertebral levels as reported in clinical studies for the prevalence of neck pain and in the autopsy report of the PMHS sled tests. In the original report of the second sled test series in Paper I (Ono et al. 2006), three male subjects suffered neck or shoulder muscular pain/discomfort, or shoulder discomfort. The rear impact sled tests were conducted under relaxed conditions as well as with the muscles tensed. Tensing the muscles may induce symptoms of muscular pain/discomfort post sled tests and it was difficult to identify the aetiology of the subjects' complaints. The other subjects, including female subjects, had no complaints following the rear impact sled tests.

5.7 Laboratory seat design

All seats used in the investigations of cervical vertebral kinematics and spinal alignment in this thesis were laboratory seats, consisting of two stiff flat plates without a head restraint. The seats were designed to exclude the influence of seat properties (foam, frame stiffness and its distribution, etc.) and the external shape of the seat back and seat pan. This design was neutral to body size differences between individuals and gender, and ensured a uniform seated posture in contrast to a regular car seat. Thus, the seated height against the seat was not a factor explaining individual differences in vertebral kinematics and spinal alignment in this thesis, since the flatness of the seating surface made the set-up insensitive to seated height. Consequently, it was easier to assign differences in cervical vertebral kinematics and spinal alignment to gender, and resulted in such gender differences as have been observed in this thesis.

A similar analysis on cervical spines in an automotive seated posture, conducted by the principal component analysis, demonstrated that stature and the ratio of seated height to stature had a significant influence on cervical spine geometry including cervical spinal alignment (Reed & Jones 2017). This might be attributed in part to the effect of the external shape of the seat back used in their investigation. This finding might imply that results in this thesis were limited in a population of men and women with the same stature should a regular car seat have been used.

To assess vertebral kinematics and spinal alignment in more realistic situations in future studies, men and women of different body sizes should be tested in a variety of commercially available car seats. In addition, other vehicle interior elements that might affect seated posture should also be included, such as different types of vehicles, variations to the seat position such as seat height and positioning of the steering wheel and mirrors, etc. Lastly, reclining seats are commonly expected for highly automated vehicles in the future. Hence, seat back angle variations would be an important issue to take into account.

5.8 Volunteers

The subjects in Paper I and II were in the 20-30 year group. They were selected based on the average Japanese body size for women and men. The subjects scanned by the upright open MRI system were in the 20–40 year age group. All subjects were recruited in Europe and Japan. The selection was based on the crash test dummy family sizes (Schneider et al. 1983) for European subjects and the average height and weight of the Japanese population aged between 20-40 for Japanese subjects (Ministry of Education, Culture, Sports, Science and Technology, Japan 2013). All subjects were close to the average body sizes. In both the sled tests and the MRI scans, a limited number of subjects participated due to the cost and time.

Previous studies have reported that the risk of sustaining WADs is associated with age as well as gender (Jakobsson et al. 2004a, Eis et al. 2005). The risk of sustaining WADs decreases with increasing age. Numerous studies have shown that age affects the whole spinal alignment in a standing posture (see for instance Boyle et al. 2002, Erkan et al. 2010, Yukawa et al. 2012, Park et al. 2013, Lee et al. 2014, Been et al. 2017). The age-related change in the whole spinal alignment in a standing posture is different for women and men (Oe et al. 2015). Beside the effect of age, overall body size affects the cervical spine geometry including the cervical spinal alignment in a seated posture (Reed & Jones 2017).

To generalise spinal alignment patterns and their effect on vertebral kinematics for a wider age range, gender differences through all ages, body sizes and other factors, future studies would need to include a larger number of subjects.

5.9 Towards WAD countermeasures for both men and women

According to epidemiological studies (Narragon 1965, Kihlberg 1969, O'Neill et al. 1972, Thomas et al. 1982, Otremski et al. 1989, Maag et al. 1990, Morris and Thomas 1996, Dolinis 1997, Temming & Zobel 1998, Chapline et al. 2000, Richter et al. 2000, Krafft et al. 2003, Jakobsson et al. 2004b, Storvik et al. 2009, Carlsson et al. 2010, Kullgren et al. 2010 and 2013, Carstensten et al. 2012), women are more likely to be vulnerable to WADs than men.

In the current test protocols prescribed in UN regulations and consumer crash test programmes such as Euro NCAP, JNCAP, etc., only the physical crash test dummy BioRID II, representing a 50th percentile male, is used to evaluate the WAD protection performances of front seats under low severity rear impact loading. However, the recently developed 50th percentile female crash test dummy FE model, EvaRID, and a prototype physical crash test dummy of a 50th percentile female have demonstrated different dynamic responses from the BioRID II (Schmitt et al. 2012, Linder et al. 2015 and 2018, Sato et al. 2017). Differences in overall body size and joint stiffness affected the interaction with the seat back and the head restraint. Accordingly, different levels of WAD protection system performance may benefit male and female occupants when seated in the same seat design. To develop better WAD countermeasures for both men and women, it is important to also take the female population into consideration.

In the last decade or so, experimental studies comprising volunteers and PMHSs demonstrated gender differences in dynamic kinematic responses of occupants during rear impacts (Szabo et al. 1994, Siegmund et al. 1997, van den Kroonenberg et al. 1998, Hell et al. 1999, Yoganandan et al. 2000, Welcher et al. 2001, Croft et al. 2002, Stemper et al. 2003 and 2004a, Ono et al. 2006, Pramudita et al. 2007, Dehner et al. 2008, Linder et al. 2008, Schick et al. 2008, Carlsson et al. 2010 and 2012). In particular, Paper I and II in this thesis highlight the gender differences

of inertia-induced cervical vertebral kinematics during a rear impact, by reanalysing previous rear impact sled tests with female and male volunteers. The analysis revealed that female volunteers exhibited greater intervertebral kinematics in the cervical spine with a more pronounced cervical S-shape, compared to the male volunteers. Thereafter, Paper III and IV focused on whole spinal alignment in an automotive seated posture as one of the possible causes of the observed gender difference in inertia-induced cervical vertebral kinematics. The average gender specific spinal alignments include almost straight cervical and less-kyphotic thoracic spine for the female subjects, and lordotic cervical and more pronounced kyphotic thoracic spine for the male subjects. With findings in Paper III and IV, Paper V illustrated the effect of different whole spinal alignment patterns on cervical vertebral kinematics in a series of rear impact reconstruction simulations. The average female spinal alignment pattern demonstrated greater intervertebral kinematics in the cervical spine with a more pronounced cervical S-shape, compared to the average male spinal alignment pattern. Larger elongation of the cervical ligaments likely appeared at intervertebral levels where larger intervertebral displacements were found. This may contribute partially to the understanding of the elevated injury risk of sustaining WADs for women. Consequently, in order to improve and assess WAD protection systems, gender differences in cervical vertebral kinematics and whole spinal alignment patterns identified in this thesis, should be taken into consideration when establishing WAD injury criteria, thresholds and injury mechanisms for both men and women.

In addition, morphological literature with size matched male and female volunteers indicate that women have more slender necks and less muscle volume with smaller vertebral bodies than men (DeRosia 2008, Stemper et al. 2008, 2009 and 2011, Vasavada et al. 2008). John et al. (2018) have demonstrated that gender differences on the geometrical variations of the cervical vertebrae affect vertebral kinematic responses in a C5/C6 segment FE model. The findings in the literature may also partially contribute to the understanding of why women are exposed to a higher injury risk of sustaining WADs, which should be taken into consideration when designing enhanced WAD protection systems based on male and female WAD injury mechanisms.

When accounting for the gender specific morphological characteristic, human body FE models are essential and useful tools for developing better WAD countermeasures for both men and women. In accordance to findings in this thesis as well as previous studies described above, female human body FE models should not be scaled down from the male human body FE models. Female human body FE models must be developed directly based on female anthropometrical and geometrical dimensions, and designed with an anatomically detailed cervical spine model to evaluate and assess the WAD protection seat performances. However, a number of human body FE models have been released based primarily on the average male dimensions. It is evident from this thesis and previous studies that this type of occupant FE models are not suitable for enhancing WAD protection performances with the female population in focus. For this reason, a 50th percentile female occupant FE model based on an existing 5th percentile female occupant FE model, rather than an existing 50th percentile male occupant FE model, was developed in this thesis.

In future studies, according to previous morphological studies (DeRosia 2008, Stemper et al. 2008, 2009 and 2011, Vasavada et al. 2008), this thesis recommends to use size matched male and female occupant FE models based on neck length or seated height for deeper investigation on gender dependence. This could distinguish the effect of gender from size, and would provide better knowledge of gender differences on WAD injury mechanisms and suggestions for future WAD countermeasures for both men and women. Furthermore, since the Euro NCAP has pointed out an advantage of introducing virtual testing to complement current consumer crash test programmes with physical crash test dummies (van Ratingen MR, 2016, Linder et al. 2018), anatomically detailed human body FE models would also be suitable for evaluating WAD protection performance, based on gender differences in WAD injury mechanisms.

6 Conclusions

Reanalysis of previous volunteer test data provided dynamic characteristics of inertia-induced cervical vertebral kinematics and quasi-static characteristics of muscle-induced cervical vertebral kinematics for women and men. This reanalysis specified trends in the gender differences of inertia-induced cervical vertebral kinematics during a rear impact.

MDS analyses on spinal alignments obtained by an upright open MRI system portrayed variations and typical patterns of spinal alignment in an automotive seated posture. The estimated average gender specific spinal alignment patterns illustrated gender differences of the whole spinal alignment.

Rear impact reconstruction simulations with a whole body occupant FE model demonstrated the effect of spinal alignment patterns on cervical vertebral kinematics and ligament stretches. These FE simulations indicate a potential impact of gender differences in whole spinal alignment on cervical vertebral kinematics and ligament stretches.

The gender differences found in this thesis support previous studies. The findings may also contribute to the understanding of the elevated injury risk of sustaining WADs for women. In addition, the findings highlight the importance of the whole spinal alignment when developing female models to study and assess WAD countermeasures, and may thus improve occupant protection for women as well as men.

The main findings on dynamic characteristics of inertia-induced cervical kinematics responses for women and men in rear impact are listed as follows:

- The dynamic inertia-induced vertebral kinematics showed a peak S-shape at a time between 90 ms and 100 ms, and the transition from the peak S-shape to extension phase for both genders.
- The vertebral angular displacements in dynamic inertia-induced cervical vertebral kinematics were larger for the female subjects than the male subjects at all spinal segments virtually throughout the whole sled test duration, producing a more pronounced cervical S-shape for the female subjects.
- In the quasi-static muscle-induced vertebral kinematics, all vertebrae rotated in extension and the S-shape deformation was not observed in voluntary neck extension.
- C4/C5 through C6/C7 showed larger extension angles in the peak S-shape beyond the range observed in maximum voluntary retraction for the female subjects. In contrast, the peak S-shape for the male subjects appeared within the range of maximum voluntary retraction.

The main findings on whole spinal alignment patterns in an automotive seated posture are listed as follows:

- The largest variations in spinal alignment due to individual differences indicate a prominent relationship showing that cervical lordosis occur together with pronounced thoracic kyphosis. Subjects with lordotic cervical spinal alignment tended to have a more pronounced kyphotic thoracic spine, with a peak of the thoracic kyphosis at a lower vertebral level. Subjects with kyphotic cervical spinal alignment tended to have a less-kyphotic thoracic spine, with a peak of the thoracic kyphosis at a higher vertebral level.
- The prominent relationship was reflected in the differences between the estimated average gender specific spinal alignment patterns. The average female spinal alignment was a slight kyphotic, or almost straight cervical and less-kyphotic thoracic spine. The average male spinal alignment was a lordotic cervical and more pronounced kyphotic thoracic spine.
- A slight gender difference was seen in the lumbar spinal alignment due to the seat design used in this thesis.
- When altering the seat back angle from 20° to 25°, the most prominent influence of the seat back inclination on the spinal alignment was shown in the thoracic kyphosis.

The main findings on the effect of the whole spinal alignment pattern on vertebral kinematics are listed as follows:

- For a slightly kyphotic or almost straight cervical spine with a less-kyphotic thoracic spine, including the average female spinal alignment pattern, intervertebral angular displacements and facet joint displacements were concentrated from the lower cervical spine to the upper thoracic spine at the time of the maximum cervical S-shape.
- On the other hand, for a lordotic cervical spine with a more pronounced kyphotic thoracic spine, including the average male spinal alignment pattern, the displacements were more concentrated from the lower thoracic spine to the lumbar spine.
- When looking at the cervical region at the time of the maximum cervical S-shape, for a slightly kyphotic or almost straight cervical spine with a less-kyphotic thoracic spine, including the average female spinal alignment pattern, intervertebral angular displacements and facet joint displacements at the lower cervical vertebral levels were greater, when compared to a lordotic cervical spine with a more pronounced kyphotic thoracic spine including the average male spinal alignment pattern.
- Larger elongation of the spinal ligaments likely appeared at intervertebral levels where larger vertebral displacements were found.

7 References

- Ames, C.P., Blondel, B., Scheer, J.K., Schwab, F.J., Le Huec, J.C., Massicotte, E.M., Patel, A.A., Traynelis, V.C., Kim, H.J., Shaffrey, C.I., Smith, J.S. & Lafage, V. (2013) Cervical radiographical alignment: Comprehensive assessment techniques and potential importance in cervical myelopathy. *Spine*, 38(22S), S149-S160.
- Anderson, S.E., Boesch, C., Zimmermann, H., Busato, A., Hodler, J., Bingisser, R., Ulbrich, E.J., Nidecker, A., Buitrago-Téllez, C.H., Bonel, H.M., Heini, P., Schaeren, S. & Sturzenegger M. (2012) Are there cervical spine findings at MR imaging that are specific to acute symptomatic whiplash injury? A prospective controlled study with four experienced blinded readers. *Radiology*, 262(2), 567-575.
- Aldman, B. (1986) An analytical approach to the impact biomechanics of head and neck injury. In: *Association for Advancement of Automotive Medicine*, Montreal, Canada, 446-454.
- Armijo-Olivo, S., Jara, X., Castillo, N., Alfonso, L., Schilling, A., Valenzuela, E., Frugone, R. & Magee, D.A. (2006) Comparison of the head and cervical posture between the self-balanced position and the Frankfurt method, *Journal of Oral Rehabilitation*, 33, 194-201.
- Barnsley, L., Lord S.M., Wallis B.J. & Bogduk, N. (1995) The prevalence of chronic cervical zygapophysial joint pain after whiplash. *Spine*, 20(1), 20-25.
- Been, E., Shefi, S. & Soudack, M. (2017) Cervical lordosis: the effect of age and gender. *The Spine Journal*, 17, 880-888.
- Berthonnaud, E., Dimmet, J. & Roussouly, P. (2005) Analysis of the sagittal balance of the spine and pelvis using shape and orientation parameters. *Journal of Spinal Disorders & Techniques*, 18(1), 40-47.
- Binder, A. (2007) The diagnosis and treatment of nonspecific neck pain and whiplash. *EURA Medicophysics*, 43(1), 79-89.
- Bogduk, N. (2011) On cervical zygapophysial joint pain. *Spine*, 36 (25S), S194-S199.
- Borg, I. & Groenen, P.J.F. (2005) Modern multidimensional scaling. 2nd Ed. New York: Springer.
- Boström, O., Svensson, M.Y., Aldman, B., Hansson, H.A., Håland, Y., Lövsund, P., Seeman, T., Suneson, A., Säljö, A. & Örtengren, T. (1996) A new neck injury criterion candidate - based on injury findings in the cervical spinal ganglia after experimental neck extension trauma. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Dublin, Ireland.

References

- Boyle, J., Singer, K. & Milne, N. (1996) Morphological survey of the cervicothoracic junctional region. *Spine*, 21(5), 544-548.
- Brolin, K. & Halldin, P. (2004) Development of a finite element model of the upper cervical spine and a parameter study of ligament characteristics. *Spine*, 29(4), 376-385.
- Brolin, K., Halldin, P. & Leijonhufvud, I. (2005) The effect of muscle activation on neck response. *Traffic Injury Prevention*, 6(1), 67-76.
- Brolin, K., Östh, J., Svensson, M.Y., Sato, F., Ono, K., Linder, A. & Kullgren A. (2015) Aiming for an average female virtual human body model for seat performance assessment in rear-end impacts. In: *Enhanced Safety of Vehicles Conference*, Gothenburg, Sweden.
- Carlsson, A., Siegmund, G.P., Linder, A. & Svensson, M.Y. (2010) Motion of the head and neck of female and male volunteers in rear impact car-to-car tests at 4 and 8 km/h. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Hanover, Germany.
- Carlsson, A., Linder, A., Davidsson, J., Hell, W., Schick, S. & Svensson M.Y. (2011) Dynamic kinematic responses of female volunteers in rear impacts and comparison to previous male volunteer tests. *Traffic Injury Prevention*, 12, 347–357.
- Carlsson, A., Siegmund, G.P., Linder, A. & Svensson M.Y. (2012) Motion of the head and neck of female and male volunteers in rear impact car-to-car impacts. *Traffic Injury Prevention*, 13, 378–387.
- Carlsson, A., Chang, F., Lemmen, P., Kullgren, A., Schmitt, K.-U., Linder, A. & 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), 855–865.
- Carroll, L.J., Holm, L.W., Hogg-Johnson, S., Côté, P., Cassidy, J.D., Haldeman, S., Nordin, M., Hurwitz, E.L., Carragee, E.J., van der Velde, G., Peloso, P.M. & Guzman, J. (2008) Course and prognostic factors for neck pain in whiplash-associated disorders (WAD). Results of the bone and joint decade 2000–2010 task force on neck pain and its associated disorders. *European Spine Journal*, 17(Suppl 1), 83–92.
- Carstensen, T.B., Frostholm, L., Oernboel, E., Kongsted, A., Kasch, H., & Jensen T.S. (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.
- Cassidy, J.D., Carroll, L.J. & Cote, P. (2000) Effect of eliminating compensation for pain and suffering on the outcome of insurance claims for whiplash injury. *The New England Journal of Medicine*, 342(16), 1179–86.
- Chabert, L., Ghannouchi, S., & Cavallero, C. (1998) Geometrical characterisation of a seated occupant. In: *Enhanced Safety of Vehicles Conference*, Ontario, Canada.

- Chapline, J.F., Ferguson, S.A., Lillis, R.P., Lund, A.K. & Williams, A.F. (2000) Neck pain and head restraint position relative to the driver's head in rear-end collisions. *Accident Analysis and Prevention*, 32(2), 287–297.
- Cholewicki, J., Panjabi, M.M., Nibu, K., Babat, L.B., Grauer, J.N. & Dvorak, J. (1998) Head kinematics during in vitro whiplash simulation. *Accident Analysis and Prevention*, 30(4), 469–479.
- Combest, J.C. (2016) Current status and future plans of the GHBMC. In: *6th Symposium Human Modeling and Simulation in Automotive Engineering*, Heidelberg, Germany.
- Cox, T.F. & Cox, M.A.A. (2000) *Multidimensional Scaling*. 2nd Ed. Chapman and Hall/CRC.
- Croft, A.C., Haneline, M.T. & Freeman, M.D. (2002) Differential occupant kinematics and forces between frontal and rear automobile impacts at low speed: evidence for a differential injury risk. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Munich, Germany.
- Cronin, D., Fice, J., DeWit, J. & Moulton, J. (2012) Upper cervical spine kinematic response and injury prediction. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Dublin, Ireland.
- Cusick, J.F., Pintar, F.A. & Yoganandan, N. (2001) Whiplash syndrome. Kinematic factors influencing pain patterns. *Spine*, 26(1), 1252–1258.
- Davidsson, J., Deutscher, C., Hell, W., Svensson, M.Y., Linder, A. & Lövsund, P. (1998) Human volunteer kinematics in rear-end sled collisions. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Gothenburg, Sweden.
- Davidsson, J., Lövsund, P., Ono, K., Svensson, M.Y. & Inami, S. (1999) A comparison between volunteer, BioRID P3 and Hybrid III performance in rear impacts. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Sitges, Spain.
- Davis, M.L., Koya, B., Schap, J.M. & Gayzik, F.S. (2016) Development and full body validation of a 5th percentile female finite element model. *Stapp Car Crash Journal*, 60, 509-544.
- Davis, S., Teresi, L., Bradley, W., Ziemba, M. & Bloze A. (1991) Cervical spine hyperextension injuries: MR findings. *Radiology*, 180(1), 245–51.
- Deans, G.T., Magalliard, J.N., Kerr, M. & Rutherford, W.H. (1987) Neck sprain - a major cause of disability following car accidents. *Injury*, 18(1), 10-12.
- Dehner, C., Schick, S., Arand, M., Elbel, M., Hell, W. & Kramer, M. (2008) Influence of anthropometry on the kinematics of the cervical spine and the risk of injury in sled tests in female volunteers. *Accident Analysis and Prevention*, 40, 1305-1312.
- Deng, B., Begeman, P.C., Yang, K.H., Tashman, S. & King, A.I. (2000) Kinematics of human cadaver cervical spine during low speed rear-end impacts. *Stapp Car Crash Journal*, 44, 171-188.

- Deng, B., Luan, F., Begeman, P.C., Yang, K.H., King, A.I. & Tashman, S. (2000) Testing shear hypothesis of whiplash injury using experimental and analytical approaches. In: Yoganandan, N., and Pinter, F.A. (eds) *Frontiers in whiplash trauma*. IOS Press, Amsterdam, The Netherlands, 491–509.
- DeRosia, J. (2008) *Role of gender and size in biomechanics of rear impact*. Marquette University, Texas, USA. Doctoral Dissertation, Number: 3357947.
- Dolinis, J. (1997) Risk factors for “Whiplash” in drivers: a cohort study of rear-end traffic crashes. *Injury*, 28(3), 173–179.
- Dullerud, R., Gjertsen, O. & Server A. (2010) Magnetic resonance imaging of ligaments and membranes in the craniocervical junction in whiplash-associated injury and in healthy control subjects. *Acta Radiologica*, 51(2), 207–212.
- Eichberger, A., Darok, M., Steffan, H., Leinzinger, P.E., Boström, O. & Svensson, M.Y. (2000) Pressure measurements in the spinal canal of post-mortem human subjects during rear-end impact and correlation of results to the neck injury criterion. *Accident Analysis and Prevention*, 32(2), 251–260.
- Eis, V., Sferco, R. & Fay, P. (2005) A detailed analysis of the characteristics of European rear impacts. In: *Enhanced Safety of Vehicles Conference*, Washington D.C., US.
- Elliott, J., Jull, G., Noteboom, J.T., Darnell, R., Galloway, G. & Gibbon, W.W. (2006) Fatty infiltration in the cervical extensor muscles in persistent whiplash-associated disorders: a magnetic resonance imaging analysis. *Spine*, 31(22), 847–855.
- Elliott, J., Jull, G., Noteboom, J.T. & Galloway, G. (2008) MRI study of the cross-sectional area for the cervical extensor musculature in patients with persistent whiplash associated disorders (WAD). *Manual Therapy*, 13(3), 258–265.
- Elliott, J.M. & Cherry, J. (2008) Upper cervical ligamentous disruption in a patient with persistent whiplash associated disorders. *The Journal of Orthopaedic and Sports Physical Therapy*, 38(6), 377.
- Endo, K., Suzuki, H., Nishimura, H., Tanaka, H., Shishido, T. & Yamamoto, K. (2014) Characteristics of sagittal spino-pelvic alignment in Japanese young adults. *Asian Spine Journal*, 8(5), 599–604.
- Endo, K., Suzuki, H., Sawaji, Y., Nishimura, H., Yorifuji, M., Murata, K., Tanaka, H., Shishido, T. & Yamamoto, K. (2016) Relationship among cervical, thoracic, and lumbopelvic sagittal alignment in healthy adults. *Journal of Orthopaedic Surgery*, 24(1), 92–96.
- Erkan, S., Yercan, H.S., Okcu, G. & Özalp R.T. (2010) The influence of sagittal cervical profile, gender and age on the thoracic kyphosis. *Acta Orthopaedica Belgica*, 76(5), 675–80.
- Euro NCAP (2018) <https://www.euroncap.com>. Accessed: November 1, 2018.
- Evans, R.W. (1992) Some Observations on Whiplash Injuries. *Neurologic Clinics*, 10(4) 975–997.

- Foret-Bruno, J.Y., Dauvilliers, F. & Tarriere, C. (1991) Influence of the seat and head rest stiffness on the risk of cervical injuries in rear impact. In: *Enhanced Safety of Vehicles Conference*, Paris, France.
- Frobin, W., Leivseth, G., Biggemann, M. & Brinckmann, P. (2002) Vertebral height, disc height, posteroanterior displacement and dens-atlas gap in the cervical spine: precision measurement protocol and normal data. *Clinical Biomechanics*, 17(6), 423- 431.
- Grauer, J.N., Panjabi, M.M., Cholewicki, J., Nibu, K. & Dvorak, J. (1997) Whiplash produces an S-shaped curvature of the neck with hyperextension at lower levels. *Spine*, 22(21), 2489-2494.
- Gonzales-Carcedo, M. & Brolin, K. (2012) Generation of numerical human models based on medical imaging. *Chalmers University of Technology, Gothenburg, Sweden, Technical report*, No. 2012:01.
- Gore, D.R., Sepic, S.B. & Gardner, G.M. (1986) Roentgenographic findings of the cervical spine in asymptomatic people. *Spine*, 11(6), 521-524.
- Gayzik, F.S., Hamilton, C.A., Tan, J.C., McNally, C., Duma, S.M., Klinich, K.D. & Stitzel, J.D. (2009) A multi-modality image data collection protocol for full body finite element model development. *SAE Technical Paper*, No. 2009-01-2261.
- Gayzik, F.S., Moreno, D.P., Geer, C.P., Wuertzer, S.D., Martin, R.S. & Stitzel, J.D. (2011) Development of a full body CAD dataset for computational modeling: A multi-modality approach. *Annals of Biomedical Engineering*, 39 (10), 2568–2583.
- Halldin, P., Brolin, K., Kleiven, S., von Holst, H., Jakobsson, L. & Palmertz, C. (2000) Investigation of conditions that affect neck compression-flexion injuries using numerical techniques. *Stapp Car Crash Journal*, 44, Paper No. 2000-01-SC10.
- Hardacker, J.W., Shuford, R.F., Capicoto, P.N. & Pryor, P.W. (1997) Radiographic standing cervical segmental alignment in adult volunteers without neck symptoms. *Spine*, 22(13), 1472-1480.
- Hanten, W.P., Olson, S.L., Russell, J.L., Lucio, R.M. & Campbell, A.H. (2000) Total head excursion and resting head posture: normal and patient comparisons. *Archives Physical Medicine and Rehabilitation*, 81(1) 62–66.
- Harder, S., Veilleux, M. & Suissa, S. (1998) The effect of socio-demographic and crash-related factors on the prognosis of whiplash. *Journal of Clinical Epidemiology*, 51(5), 377–384.
- Harrison, D.E., Harrison, D.D., Cailliet, R., Troyanovich & S.J., Holland, B. (2000) Cobb Method or Harrison Posterior Tangent Method. *Spine*, 25(16), 2072-2078.
- Harty, J., Quinlan, J., Kennedy, J., Walsh, M. & O'Byrne, J. (2004) Anthropometrical analysis of cervical spine injuries. *Injury*, 35(3), 249-252.

- Hell, W., Langwieder, K. & Walz, F. (1998) Reported soft tissue neck injuries after rear-end car collision. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Gothenburg, Sweden.
- Helliwel, P.S., Evans, P.F. & Wright, V. (1994) The Straight cervical spine: does it indicate muscle spasm? *The Journal of Bone & Joint Surgery*, 76(1), 103-106.
- Holm, L.W., Carroll L.J., Cassidy, J.D., Hogg-Johnson, S., Côté, P., Guzman, J, Peloso, P., Nordin, M., Hurwitz, E., van der Velde, G., Carragee, E. & Haldeman S. (2008) The burden and determinants of neck pain in whiplash-associated disorders after traffic collisions. Results of the bone and joint decade 2000–2010 task force on neck pain and its associated disorders. *European Spine Journal*, 17(Suppl 1), 52-59.
- Hukuda, S. & Kojima, Y. (2002) Sex discrepancy in the canal/body ratio of the cervical spine implicating the prevalence of cervical myelopathy in men. *Spine*, 27(3), 250-253.
- Ichihara, D., Okada, E., Chiba, K., Toyama, Y., Fujiwara, H., Momoshima, S., Nishiwaki, Y., Hashimoto, T., Ogawa, J., Watanabe, M., Takahata, T. & Matsumoto, M. (2009) Longitudinal magnetic resonance imaging study on whiplash injury patients: minimum 10-year follow-up. *Journal of Orthopaedic Science*, 14(5), 602–610.
- Ivancic, P.C., Pearson, A.M., Panjabi, M.M. & Ito, S. (2004) Injury of the anterior longitudinal ligament during whiplash simulation. *European Spine Journal*, 13(1), 61–68.
- Ivancic, P.C., Ito, S., Tominaga, Y., Rubin, W., Coe, M.P., Ndu, A.B., Carlson, E.J. & Panjabi, M.M. (2008) Whiplash causes increased laxity of cervical capsular ligament. *Clinical Biomechanic*, 23(2), 159–165.
- Iwamoto, M., Kisanuki, Y., Watanabe, I., Furuu, K., Miki, K. & Hasegawa, J. (2002) Development of a finite element model of the total human model for safety (THUMS) and application to injury reconstruction. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Munich, Germany.
- Iwamoto, M. & 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.
- Jakobsson, L. (1998) Automobile design and whiplash prevention. In: Gunzburg, R., Szpalski, M. (eds) *Whiplash injuries: Current concepts in prevention, diagnosis and treatment of the cervical whiplash syndrome*. Lippincott-Raven, Philadelphia, 299–306.
- Jakobsson, L. (2004a) Field analysis of AIS1 neck injuries in rear-end car impacts injury reducing effect of the WHIPS seat. *Journal of Whiplash and Related Disorders*, 3(2), 37–54.
- Jakobsson, L., Norin, H. & Svensson, M.Y. (2004b) Parameters influencing AIS1 neck injury outcome in frontal impacts. *Traffic Injury Prevention*, 5(2), 156–163.

References

- Janssen, M.M., Drevelle, X., Humbert, L., Skalli, W. & Castelein, R.M. (2009) Differences in male and female spino-pelvic alignment in asymptomatic young adults and its relation to spinal deformities – a three-dimensional analysis using upright low-dose digital biplanar X-rays. *Spine*, 34(23), E826-832.
- JNCAP (2018) <http://www.nasva.go.jp/mamoru/en/index.html>. Accessed: November 1, 2018.
- John, J.D., Yoganandan, N., Arun, M.W.J. & Kumar, G.S. (2018) Influence of morphological variations on cervical spine segmental responses from inertial loading. *Traffic Injury Prevention*, 19(S1), S29-S36.
- Jósson, H., Cesarini, K., Sahlstedt, B. & Rauschnig, W. (1994) Findings and outcome in whiplash-type neck distortions. *Spine*, 19(24), 2733–2743.
- Jun, H.S., Chang, I.B., Song, J.H., Kim, T.H., Park, M.S., Kim, S.W. & Oh, J.K. (2014) Is it possible to evaluate the parameters of cervical sagittal alignment on cervical computed tomographic scans? *Spine*, 39(10), E630-636.
- Kaale, B.R., Krakenes, J., Alberktsen, G. & Wester, K. (2005) Whiplash-associated disorders impairment rating: neck disability index score according to severity of MRI findings of ligaments and membranes in the upper cervical spine. *Journal of Neurotrauma*, 22(4), 466-475.
- Kaale, B.R., Krakenes, J., Alberktsen, G. & Wester, K. (2005) Head position and impact direction in whiplash injuries: associations with MRI-verified lesions of ligaments and membranes in the upper cervical spine. *Journal of Neurotrauma*, 22(11), 1294-1302.
- Kaneoka, K., Ono, K., Inami, S. & Hayashi, K. (1999) Motion analysis of cervical vertebrae during whiplash loading. *Spine*, 24(8), 763-770.
- Kaneoka, K., Ono, K., Inami, S., Ochiai, N. & Hayashi, K. (2002) The human cervical spine motion during rear impact collisions: a proposed cervical facet injury mechanism during whiplash trauma. *Journal of Whiplash and Related Disorders*, 1(1), 85-97.
- Kasai, T., Ikata, T., Katoh, S., Miyake, R. & Tsubo, M. (1996) Growth of the cervical spine with special reference to its lordosis and mobility. *Spine*, 21(18), 2067-2073.
- Katz, P.R., Reynolds, H.M., Foust, D.R. & Baum, J.K. (1975) Mid-sagittal dimensions of cervical vertebral bodies. *American Journal of Physical Anthropology*, 43(3), 319–326.
- Kihlberg, J.K. (1969) Flexion-torsion neck injury in rear impacts. In: *Association for the Advancement of Automobile Medicine*, Minneapolis, USA.
- Kitagawa, Y., Yasuki, T. & Hasegawa, J. (2008) Research study on neck injury lessening with active head restraint using human body FE model. *Traffic Injury Prevention*, 9(6), 574-582.
- Kitagawa, Y., Yamada, K., Motojima, H. & Yasuki, T. (2015) Consideration on gender difference of whiplash associated disorder in low speed rear impact. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Lyon, France.

- Klinich, K.D., Ebert, S.M., Van Ee C.A., Flannagan, C.A.C., Prasad, M., Reed, M.P. & Schneider, L.W. (2004) Cervical spine geometry in the automotive seated posture: variations with age, stature, and gender. *Stapp Car Crash Journal*, 48, 301-330.
- Knott, P.T., Mardjetko, S.M. & Techy, F. (2010) The use of the T1 sagittal angle in predicting overall sagittal balance of the spine. *The Spine Journal*, 10, 994-998.
- Krafft, M. (2002) When do AIS1 neck injuries result in long-term consequences - Vehicle and human factors. *Traffic Injury Prevention*, 3(2), 89-97.
- Krafft, M., Kullgren, A., Lie, A. & 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), 136-140.
- Krakenes, J., Kaale, B., Moen, G., Nordli, H., Gilhus, N. & Rorvik, J. (2002) MRI assessment of the alar ligaments in the late stage of whiplash injury—a study of structural abnormalities and observer agreement. *Neuroradiology*, 44(7), 617-624.
- Krakenes, J., Kaale, B., Moen, G., Nordli, H., Gilhus, N. & Rorvik, J. (2003) MRI of the tectorial and posterior atlanto-occipital membranes in the late stage of whiplash injury. *Neuroradiology*, 45(9), 585-591.
- Krakenes, J., Kaale, B.R., Nordli, H., Moen, G., Rorvik, J. & Gilhus, N.E. (2003) MR analysis of the transverse ligament in the late stage of whiplash injury. *Acta Radiologica*, 44(6), 637-644.
- Krakenes, J. & Kaale, B.R. (2006) Magnetic resonance imaging assessment of craniovertebral ligaments and membranes after whiplash trauma. *Spine*, 31(24), 2820-2826.
- Kullgren, A. & Krafft, M. (2010) Gender analysis on whiplash seat effectiveness: results from real-world crashes. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Hanover, Germany.
- Kullgren, A., Stigson, H. & Krafft, M. (2013) Development of whiplash associated disorders for male and female car occupants in cars launched since the 80s in different impact directions. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, 2013, Gothenburg, Sweden.
- Lee, J.H., Park, Y.K. & Kim, J.H. (2014) Chronic neck pain in young adults: perspectives on anatomic differences. *The Spine Journal*, 14(11), 2628-2638.
- Lee, S.H., Son, E.S., Seo, E.M., Suk, K.S. & Ki, K.T. (2015) Factors determining cervical spine sagittal balance in asymptomatic adults: correlation with spinopelvic balance and thoracic inlet alignment. *The Spine Journal*, 15, 705-712.
- Li, Q., Shen, H. & Li, M. (2013) Magnetic resonance imaging signal changes of alar and transverse ligaments not correlated with whiplash-associated disorders. *European Spine Journal*, 22(1), 14-20.
- Liguoro, D., Vandermeersch, B. & Guerin, J. (1994) Dimensions of cervical vertebral bodies according to age and sex. *Surgical Radiologic Anatomy*, 16(2), 149-155.

- Lind, B., Sihlbom, H., Nordwall, A. & Malchau, H. (1989) Normal Range of Motion of the Cervical Spine. *Archives of Physical Medicine and Rehabilitation*, 70(9), 692–695.
- Lindgren, K.A., Kettunen, J.A., Paatelma, M. & Mikkonen, R.H. (2009) Dynamic kinematic resonance imaging in whiplash patients and in age- and sex-matched controls. *Pain Research and Management*, 14(6), 427–432.
- Liliang, P.C., Lu, K., Hsieh, C-H., Kao, C.Y., Wang, K.W. & Chen H.J. (2008) Pulsed radiofrequency of cervical medial branches for treatment of whiplash-related cervical zygapophysial joint pain. *Surgical Neurology*, 70(Suppl), 50-55.
- Linder, A., Carlsson, A., Svensson, M.Y. & Siegmund, G.P. (2008) Dynamic responses of female and male volunteers in rear impacts. *Traffic Injury Prevention*, 9(6), 592–599.
- Linder, A., Schick, S., Hell, W., Svensson, M., Carlsson, A., Lemmen, P., Schmitt, K.-U., Gutsche, A. & Tomasch, E. (2013) ADSEAT - Adaptive seat to reduce neck injuries for female and male occupants. *Accident Analysis and Prevention*, 60, 334-343.
- Linder, A., Holmqvist, K. & Svensson, M.Y. (2015) Low severity rear impact simulations with average male and female dummy models in Euro NCAP test configuration. In: *The Australasian Road Safety Conference*, Gold Coast, Australia.
- Linder, A., Holmqvist, K. & Svensson, M.Y. (2018) Average male and female virtual dummy model (BioRID and EvaRID) simulations with two seat concepts in the Euro NCAP low severity rear impact test configuration. *Accident Analysis and Prevention*, 114, 62-70.
- Linder, A., Östh, J., Brodin, K. & Svensson, M.Y. (2018) Open source human body models and virtual testing of low severity vehicle safety: the ViVA model and the VIRTUAL project. In: *Society of Automotive Engineers of Japan (JSAE) Annual Congress (Spring)*, Yokohama, Japan.
- Liu, Y.K. & Dai, Q.G. (1989) The second stiffest axis of a beam-column: implications for cervical spine trauma. *Journal of Biomechanical Engineering*, 111(2), 122-127.
- Lord, S.M., Barnsley, L., Wallis, B.J., McDonald, G.J. & Bogduk, N. (1996) Precutaneous radiofrequency neurotomy for chronic cervical zygapophysial joint pain. *The New England Journal of Medicine*, 335(23), 1721-1726.
- Luan, F., Yang, K.H., Deng, B., Begeman, P.C., Tashman, S. & King, A.I. (2000) Qualitative analysis of neck kinematics during low-speed rear-end impact. *Clinical Biomechanics*, 15(9), 649-657.
- Lundell, B., Jakobson, L., Alfredsson, B., Lindstrom, M. & Simonsson, L. (1998) The WHIPS Seat – A car seat for improved protection against neck injuries in rear end impacts. In: *Enhanced Safety of Vehicles Conference*, Windsor, Canada.
- Maag, U., Desjardins, D., Bourbeau, R. & Laberge-Nadeau, C. (1990) Seat belts and neck injuries. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Bron, France.

- MacNab, I. (1964) Acceleration injuries of the cervical spine. *Journal of Bone and Joint Surgery*, 46, 1797-1799.
- Mac-Thiong, J.M., Labelle, H., Berthounaud, E., Betz, R.R. & Roussouly, P. (2007) Sagittal spinopelvic balance in normal children and adolescents. *European Spine Journal*, 16(2), 227-234.
- Maiman, D.J., Sances, A. Jr., Myklebust, J.B., Larson, S.J., Houterman, C., Chilbert, M. & El-Ghatit, A.Z. (1983) Compression injury of the cervical spine. *Neurosurgery*, 13(3), 254-260.
- Maiman, D.J., Yoganandan, N. & Pintar, F.A. (2002) Preinjury cervical alignment affecting spinal trauma. *Journal of Neurosurgery*, 97(1 Suppl), 57-62.
- Matsumoto, M., Fujimura, Y., Suzuki, N., Toyama, Y. & Shiga, H. (1998) Cervical curvature in acute whiplash injuries: prospective comparative study with asymptomatic subjects. *Injury*, 29(10), 775-778.
- Matsushita, T., Sato, T., Hirabayashi, K. & Fujimura, S. (1994) X-ray study of the human neck motion due to head inertia loading. *SAE Technical Paper*, No. 942208, 55-64.
- Mattucci, S.F.E. & Cronin, D.S. (2015) A method to characterize average cervical spine ligament response based on raw data sets for implementation into injury biomechanics models. *Journal of the Mechanical Behavior of Biomedical Materials*, 41, 251-260.
- Milne, N. (1991) The role of zygapophysial joint orientation and uncinated processes in controlling motion in the cervical spine. *Journal of Anatomy*, 178, 189-201.
- Ministry of Education, Culture, Sports, Science and Technology. *Japan: Annual Report of Anthropometry Data by Age in 2012*. October 15, 2013. Available at: <http://www.e-stat.go.jp/SG1/estat/List.do?bid=000001077241&cyclo=0>. Accessed: February 1, 2015.
- Miyazaki, Y., Ujihashi, S., Mochimaru, M. & Kouchi, M. (2005) Influence of the head shape variation on brain damage under impact. In: *SAE Digital Human Modeling for Design and Engineering Symposium*, Iowa City, USA.
- Mochimaru, M. & Kouchi, M. (2000) Statistics for 3D human body forms. In: *SAE Digital Human Modeling for Design and Engineering Conference and Exposition*, Dearborn, USA.
- Mordaka, J. (2004) *Finite element analysis of whiplash injury for women*. Nottingham Trent University, Nottingham, UK. Doctoral Dissertation.
- Morimoto, Y., Shigematsu, H., Iwata, E., Tanaka, M., Okuda, A., Masuda, K., Yamamoto, Y., Takeshima, T., Nakagawa, Y. & Tanaka, Y. (2018) Evaluating cervical sagittal alignment in cervical myelopathy: are sitting cervical radiographs and standing whole-spine radiographs equally useful? *Global Spine Journal*, <https://doi.org/10.1177/2192568218811841>.

- Morris, A.P., & Thomas, P.D. (1996) Neck injuries in the UK co-operative crash injury study. *SAE Technical Paper*, No.962433, 317-329.
- Mutafy, T., El-Rich, M., Mesfar, M. & Moglo, K. (2014) Investigation of impact loading rate effects on the ligamentous cervical spine load-partitioning using finite element model of functional unit C2-C3. *Journal of Biomechanics*, 47, 2891–2903.
- Myklebust, J.B., Pinter, F., Yoganandan, N., Cusick, J.F., Maiman, D., Myers, T.J. & Sances, A. (1988) Tensile strength of spinal ligaments. *Spine*, 13(5), 526-531.
- Myran, R., Kvistad, K.A., Nygaard, O.P., Andresen, H., Folvik, M. & Zwart, J.A. (2008) Magnetic resonance imaging assessment of the alar ligaments in whiplash injuries: a case–control study. *Spine*, 33(18), 2012–2016.
- Narragon, E.A. (1965) *Sex comparisons in automobile crash injury*. CAL Report No.VJ-1823-R15.
- Newell, R.S. (2014) Are inversion, posture, motion and muscle effects important to spinal alignment? University of British Columbia, Vancouver, Canada. Doctoral Dissertation.
- Newell, R.S., Siegmund, G.P., Blouin, J.S., Street, J. & Cripton, P.A. (2014) Cervical vertebral realignment when voluntarily adopting a protective neck posture. *Spine*, 39(15), E885-893.
- Newell, R.S., Blouin, J.S., Street, J., Cripton, P.A. & Siegmund, G.P. (2018) The neutral posture of the cervical spine is not unique in human subjects. *Journal of Biomechanics*, 80, 53-62.
- Nibu, K., Cholewicki, J., Panjabi, M.M., Babat, L.B., Grauer, J.N., Kothe, R. & Dvorak, J. (1997) Dynamic elongation of the vertebral artery during an in vitro whiplash simulation. *European Spine Journal*, 6(4), 286-289.
- Nightingale, R.W., Sganga, J., Cutcliffe, H. & Bass, C.R. (2016) Impact response of the cervical spine: a computational study of the effect of muscle activity, torso constraint, and pre-flexion. *Journal of Biomechanics*, 49, 558–564.
- Nygren, Å., Gustafsson, H. & Tingvall, C. (1985) Effects of different types of headrests in rear-end collisions. *International Conference on Experimental Safety Vehicles*, No. 856023, Oxford, UK
- Ommaya, A.K., Faas, F. & Yarnell, P. (1968) Whiplash injury and brain damage: an experimental study. *Journal of American Medical Association*, 204(4), 285-289.
- O’Neill, B., Haddon, W., Kelley, A.B. & Sorenson, W.W. (1972) Automobile head restraints—frequency of neck injury claims in relation to the presence of head restraints. *American Journal of Public Health*, 62(3), 399–406.
- Ono, K., Kaneoka, K., Wittek, A. & Kajzer, J. (1997) Cervical injury mechanism based on the analysis of human cervical vertebral motion and head-neck-torso kinematics during low speed rear impacts. *SAE Technical Paper*, No. 973340, 339-356.

- Ono, K., Inami, S., Kaneoka, K., Gotou, T., Kisanuki, T., Sakuma, S. & Miki, K. (1999) Relationship between localized spine deformation and cervical vertebral motions for low speed rear impacts using human volunteers. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Barcelona, Spain.
- Ono, K., Ejima, S., Suzuki, Y., Kaneoka, K., Fukushima, M. & Ujihshi, S. (2006) Prediction of neck injury risk based on the analysis of localized cervical vertebral motion of human volunteers during low-speed rear impacts. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Madrid, Spain.
- Örtengren, T., Hansson, H.A., Lövsund, P., Svensson, M.Y., Suneson, A. & Saljo, A. (1996) Membrane leakage in spinal ganglion nerve cells induced by experimental whiplash extension motion: a study in pigs. *Journal of Neurotrauma*, 13(3), 171–180.
- Östh, J., Brodin, K., Svensson, M.Y. & Linder, A. (2016a) A female ligamentous cervical spine finite element model validated for physiological loading. *Journal of Biomechanical Engineering*, 138 (6).
- Östh, J., Mendoza-Vazquez, M., Svensson, M.Y., Linder A. & Brodin, K. (2016b) Development of a 50th percentile female human body model. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Malaga, Spain.
- Östh, J., Mendoza-Vazquez, M., Sato, F., Svensson, M.Y., Linder A. & Brodin, K. (2017) A female head-neck model for rear impact simulations. *Journal of Biomechanics*, 51, 49–56.
- Otremski, I., Marsh, J.L., Wilde, B.R., McLardy Smith, P.D. & Newman R.J. (1989) Soft tissue cervical injuries in motor vehicle accidents. *Injury*, 20(6), 349–351.
- Panjabi, M.M., Nibu, K. & Cholewicki, J. (1998a) Whiplash injuries and the potential for mechanical instability. *European Spine Journal*, 7(6), 484–492.
- Panjabi, M.M., Cholewicki, J., Nibu, K., Grauer, J., Babat, L.B. & Dvorak, J. (1998b) Critical load of the human cervical spine: an in vitro experimental study. *Clinical Biomechanics*, 13(1), 239-49.
- Panjabi, M.M., Cholewicki, J., Nibu, K., Babat, L.B. & Dvorak, J. (1998c) Simulation of whiplash trauma using whole cervical spine specimens. *Spine*, 23(1), 17-24.
- Panjabi, M.M., Cholewicki, J., Nibu, K., Grauer, J. & Vahldiek, M. (1998d) Capsular ligament stretches during in vitro whiplash simulations. *Journal of Spine Disorders*, 11(3), 227-232.
- Panjabi, M.M., Wang, J.L. & Delson, N. (1999) Neck injury criterion based on intervertebral motions and its evaluation using an instrumented neck dummy. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Sitges, Spain.
- Panjabi, M.M., Pearson, A.M., Ito, S. & Ivancic, P.C. (2004a) Cervical spine curvature during simulated whiplash. *Clinical Biomechanics*, 19, 1–9.

References

- Panjabi, M.M., Ito, S., Pearson, A.M. & Ivancic, P.C. (2004b) Injury mechanisms of the cervical intervertebral disc during simulated whiplash. *Spine*, 29(11), 1217–1225.
- Panzer, M. & Cronin, D. (2009) C4-C5 segment finite element model development, validation, and load-sharing investigation. *Journal of Biomechanics*, 42, 480-490.
- Panzer, M., Fice, J. and Cronin, D. (2011) Cervical spine response in frontal crash. *Medical Engineering & Physics*, 33(9), 1147-1159.
- Parenteau, C.S., Zuby, D., Brolin, K.B., Svensson, M.Y., Palmertz, C. & Wang, S.C. (2013) Restrained male and female occupants in frontal crashes: Are we different? In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Gothenburg, Sweden.
- Parenteau, C.S., Zhang, P., Holcombe, S. & Wang, S. (2014) Characterization of vertebral angle and torso depth by gender and age groups with a focus on occupant safety. *Traffic Injury Prevention*, 15(1), 66-72.
- Park, G., Kim, T., Crandall, J.R., Arregui-Dalmases, C. & Luzon-Narro, J. (2013) Comparison of kinematics of GHBMC to PMHS on the side impact condition. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Gothenburg, Sweden.
- Park, M.S., Moon, S.H., Lee H.M., Kim S.W., Kim T.H., Lee, S.Y. & Riew, K.D. (2013) The effect of age on cervical sagittal alignment. *Spine*, 38(8), E458-E463.
- Park, S.M., Song, K.S., Park, S.H., Kang, H., Riew, K.D. (2015) Does whole-spine lateral radiograph with clavicle positioning reflect the correct cervical sagittal alignments? *European Spine Journal*, 24(1), 57-62.
- Parkin, S., Mackay, G.M., Hassan, A.M. & Graham, R. (1995) Rear end collisions and seat performance - to yield or not to yield. In: *Association for Advancement of Automotive Medicine*, Chicago, IL, 231-244.
- Pearson, A.M., Ivancic, P.C., Ito, S. & Panjabi, M.M. (2004) Facet joint kinematics and injury mechanisms during simulated whiplash. *Spine*, 29(4), 390–397.
- Pettersson, K., Hildingsson, C., Toolanen, G., Fagerlund, M., & Bjornebrink, J. (1994) MRI and neurology in acute whiplash trauma. *Acta Orthopaedica Scandinavica*, 65(5), 525–8.
- Pintar, F., Yoganandan, N., Voo, L., Cusick, J.F., Maiman, D.J. & Sances, A. Jr. (1995) Dynamic characteristics of the human cervical spine. *SAE Technical Paper*, No. 952722, 195-202.
- Pramudita, J.A., Ono, K., Ejima, S., Kaneoka, K., Shiina, I. & Ujihashi, S. (2007) Head/neck/torso behavior and cervical vertebral motion of human volunteers during low speed rear impact: mini-sled tests with mass production car seat. In: *International Research Council on Biomechanics of Research Conference*, Maastricht, The Netherlands.

- Quinn, K.P. & Winkelstein, B.A. (2007) Cervical facet capsular ligament yield defines the threshold for injury and persistent joint-mediated neck pain. *Journal of Biomechanics*, 40, 2299-2306.
- Radanov, B.P., Sturzenegger, M. & Di Stefano, G. (1995) Long-term outcome after whiplash injury. A 2-year follow-up considering features of injury mechanism and somatic, radiologic, and psychosocial findings. *Medicine*, 74(5), 281–297.
- Richter, M., Otte, D., Pohlemann, T., Krettek, C. & Blauth, M. (2000) Whiplash-type neck distortion in restrained car drivers: frequency, causes and long-term results. *European Spine Journal*, 9(2), 109–117.
- Rocabado, M. (1983) Biomechanical relationship of the cranial, cervical, and hyoid regions. *The Journal of Craniomandibular Practice*, 1(3), 61-66.
- Ronnen, H.R., de Korte, P.J., Brink, P.R., van der Bijl, H.J., Tonino, A.J. & Franke, C.L. (1996) Acute whiplash injury: is there a role for MR imaging? A prospective study of 100 patients. *Radiology*, 201(1), 93-96.
- Roussouly, P., Gollogly, S., Berthonnaud, E. & Dimnet, J. (2005) Classification of the normal variation in the sagittal alignment of the human lumbar spine and pelvis in the standing position. *Spine*, 30(3), 346-353.
- Roussouly, P. & Pinheiro-Franco, J.L. (2011) Sagittal parameters of the spine: biomechanical approach. *European Spine Journal*, 20 (Suppl 5), S578-S585.
- Sato, F., Antona, J., Ejima, S. & Ono, K. (2010) Influence on cervical vertebral motion of the interaction between occupant and head restraint/seat, based on the reconstruction of rear-end collision using finite element human model. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Hanover, Germany.
- Sato, F., Odani, M., Endo, Y., Tada, M., Miyazaki, Y., Nakajima, T., Ono, K., Morikawa, S. & Svensson, M.Y. (2016) Analysis of the alignment of whole spine in automotive seated and supine postures using an upright open MRI system. *International Journal of Automotive Engineering*, 7, 29-35.
- Sato, F., Holmqvist, K., Linder, A., Svensson, M., Kullgren, A., Tanabe, J. & Yamazaki, K. (2017) Average-sized male and female rear-impact dummy models in simulations of realworld cases addressing sensitivity in whiplash associated disorder assessment. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Antwerp, Belgium.
- Schick, S., Horion, S., Thorsteinsdottir, K. & Hell, W. (2008) Differences and commons in kinetic parameters of male and female volunteers in low speed rear end impact. In: *TÜV SÜD, Whiplash-Neck Pain in Car Crashes, 2nd International Conference*, Erding, Germany.
- Schonstrom, N., Twomey, L. & Taylor, J. (1993) The lateral atlanto-axial joints and their synovial folds: an in vitro study of soft tissue injuries and fractures. *The Journal of Trauma*, 35(6), 886-892.

- Sekizuka, M. (1998) Seat designs for whiplash injury lessening. In: *Enhanced Safety of Vehicles Conference*, Windsor, Canada.
- Schneider, L.W., Robbins, D.H., Pflüg, M.A. & Snyder, R.G. (1983) *Development of anthropometrically based design specifications for an advanced adult anthropomorphic dummy family*. Ann Arbor, MI, USA: University of Michigan Transportation Research Institute; Final Report, UMTRI-83-53-1.
- Schmitt, K.-U., Weber, T., Svensson, M.Y., Davidsson, J., Carlsson, A., Björklund, M. & Linder, A. (2012) Seat testing to investigate the female neck injury risk - preliminary results using a new female dummy prototype. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Dublin, Ireland.
- Siegmund, G.P., King, D.J. & Lawrence, J.M. (1997) Head/neck kinematic response of human subjects in low-speed rear-end collisions. *SAE Technical Paper*, No. 973341.
- Siegmund, G.P., Myers, B.S., Davis, M.B., Bohnet, H.F. & Winkelstein, B.A. (2001) Mechanical evidence of cervical facet capsule injury during whiplash: a cadaveric study using combined shear, compression and extension loading. *Spine*, 26(19), 2095–2101.
- Siegmund, G.P., Davis, M.B., Quinn, K.P., Hines, E., Myers B.S., Ejima, S., Ono K., Kamiji, K., Yasuki, T. & Winkelstein, B.A. (2008) Head-turned postures increase the risk of cervical facet capsule injury during whiplash. *Spine*, 33(15), 1643–1649.
- Siegmund, G.P., Winkelstein, B.A., Ivancic, P.C., Svensson, M.Y. & Vasavada, A. (2009) The anatomy and biomechanics of acute and chronic whiplash injury. *Traffic Injury Prevention*, 10(2), 101-112.
- Spitzer, W.O., Skovron, M.L., Salmi, L.R., Cassidy, J.D., Duranceau, J., Suissa, S. & Zeiss, E. (1995) Scientific monograph of the Quebec task force on Whiplash-Associated Disorders: redefining "whiplash" and its management. *Spine*, 20(8 Suppl), 1-73.
- Stemper, B.D., Yoganandan, N. & Pintar, F.A. (2003) Gender dependent cervical spine segmental kinematics during whiplash. *Journal of Biomechanics*, 36(9), 1281–1289.
- Stemper, B.D., Yoganandan, N. & Pintar, F.A. (2004a) Gender- and region-dependent local facet joint kinematics in rear impact. *Spine*, 29(16), 1764–1771.
- Stemper, B.D., Yoganandan, N. & Pintar, F.A. (2004b) Response corridors of the human head-neck complex in rear impact. In: *48th Annual Conference of the Association for the Advancement of Automotive Medicine*, Miami, US.
- Stemper, B.D., Yoganandan, N. & Pintar, F.A. (2005) Effects of abnormal posture on capsular ligament elongations in a computational model subjected to whiplash loading. *Journal of Biomechanics*, 38(6), 1313–1323.
- Stemper, B.D., Yoganandan, N., Pintar, F.A., Maiman, D.J., Meyer, M.A, DeRosia, J., Shender, B.S. & Paskoff, G. (2008) Anatomical gender differences in cervical vertebrae of size-matched volunteers. *Spine*, 33(2), E44–E49.

References

- Stemper, B.D., DeRosia, J., Yogananan, N., Pintar, F., Shender, B. & Paskoff, G. (2009) Gender dependent cervical spine anatomical differences in size-matched volunteers. *Biomedical Sciences Instrumentation*, 45, 149-154.
- Stemper, B.D., Pintar, F.A. & Rao, R.D. (2011) The influence of morphology on cervical injury characteristics. *Spine*, 36(25S), S180–S186.
- Stemper, B.D. & Corner, B.D. (2016) Whiplash-associated disorders: occupant kinematics and neck morphology. *Journal of Orthopaedic & Sports Physical Therapy*, 46(10), 834-844.
- Sterling, M. (2004) A proposed new classification system for whiplash associated disorders—implications for assessment and management. *Manual Therapy*, 9(2), 60–70.
- Sterner, Y. & Gerdle, B. (2004) Acute and chronic whiplash disorders—a review. *Journal of Rehabilitation Medicine*, 36(5), 193–209.
- Stigson, H., Gustafsson, M., Sunnevång, C., Krafft, M. & Kullgren, A. (2015) Differences in long-term medical consequences depending on impact direction involving passenger cars. *Traffic Injury Prevention*, 16, S133–S139.
- Storvik, S.G., Stemper, B.D., Yoganandan, N. & Pintar, F.A. (2009) Population-based estimates of whiplash injury using NASS CDS data—biomed 2009. *Biomedical Sciences Instrumentation*, 45, 244–249.
- Sturzenegger, M., Radanov, P.B. & Di Stefano, G. (1995) The effect of accident mechanisms and initial findings on the long-term course of whiplash. *Journal of Neurology*, 242(7), 443-449.
- Svensson, M.Y., Aldman, B., Hansson, H.A., Lövsund, P., Seeman, T., Suneson, A. & Örtengren, T. (1993) Pressure effects in the spinal canal during whiplash extension motion: a possible cause of injury to the cervical spinal ganglia. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Eindhoven, Netherlands.
- Svensson, M.Y., Lövsund, P., Håland, Y. & Larsson, S. (1993) Rear-end collisions—A study of the influence of backrest properties on head-neck motion using a new dummy neck. *SAE Technical Paper*, No. 930343.
- Szabo, T.J., Welcher, J.B., Anderson, R.D. & Rice, M. (1994) Human occupant kinematic response to low-speed rear end impacts. *SAE Technical Paper*, No. 940432, 23-35.
- Takeshima, T., Omokawa, S., Takaoka, T., Araki, M., Ueda, Y. & Takakura, Y. (2002) Sagittal alignment of cervical flexion and extension. *Spine*, 27(15), E348–E355.
- Taylor, J.R. & Twomey, L.T. (1993) Acute injuries to cervical joints. An autopsy study of neck sprain. *Spine*, 18(9), 1115–1122.
- Taylor, J.R. & Taylor, M. (1996) Cervical spinal injuries: an autopsy study of 109 blunt injuries. *Journal of Musculoskeletal Pain*, 4(4), 61–80.

- Temming, J. & Zobel, R. (1998) Frequency and risk of cervical spine distortion injuries in passenger car accidents: significance of human factors data. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, 1998, Gothenburg, Sweden.
- Thomas, C., Faverjon, G., Hartemann, F., Tarriere, C., Patel, A. & Got, C. (1982) Protection against rear-end accidents. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Cologne, Germany.
- Toyota Motor Corporation. (2011) *Documentation - Total Human Model for Safety (THUMS) - AF50 occupant model: Version 4.0_211103*, Nagakute, Japan.
- Uhrenholt, L., Grunnet-Nilsson, N. & Hartvigsen, J. (2002) Cervical spine lesions after road traffic accidents. A systematic review. *Spine*, 27(17), 1934–1941.
- UNECE. (2018) <http://www.unece.org/trans/main/welcwp29.html>. Accessed: November 1, 2018.
- Valkeinen, H., Ylinen, J., Malkia, E., Alen, M. & Hakkinen, K. (2002) Maximal force, force/time and activation/coactivation characteristics of the neck muscles in extension and flexion in healthy men and women at different ages. *European Journal of Applied Physiology*, 88(3), 247–254.
- van Ratigen, M.R. (2016) Saving lives with safer cars: the past, present, and future of consumer safety ratings. In: *International Research Council on Biomechanics of Injury Conference (IRCOBI)*, Malaga, Spain.
- ven den Kroonenberg, A., Philippens, M., Cappon, H., Wismans, J., Hell, W. & Langwieder, K. (1998) Human head-neck response during low-speed rear end impacts. *Stapp Car Crash Journal*, 42, 207-221.
- Vasavada, A., Li, S. & Delp. S. (2001) Three-dimensional isometric strength of neck muscles in humans. *Spine*. 26(17), 1904-1909.
- Vasavada, A.N., Danaraj, J. & Siegmund, G.P. (2008) Head and neck anthropometry, vertebral geometry and neck strength in height-matched men and women. *Journal of Biomechanics*, 41(1), 114–121.
- Vavalle, N.A. (2012) Validation of the Global Human Body Models Consortium mid-sized male model in lateral impacts and sled tests. *Wake Forest University, ProQuest Dissertations Publishing*, No. 1518875.
- Vavalle, N.A., Schoell, S.L., Weaver, A.A., Stitzel, J.D. & Gayzik, F.S. (2014) Application of radial basis function methods in the development of a 95th percentile male seated FEA model. *Stapp Car Crash Journal*, 58, 361-384.
- Vetti, N., Krakenes, J., Damsgaard, E., Rorvik, J., Gilhus, N.E. & Espeland, A. (2011) Magnetic resonance imaging of the alar and transverse ligaments in acute whiplash-associated disorders 1 and 2: a cross-sectional controlled study. *Spine*, 36(6), E434–E440.

References

- Viano, D.C. (2003a) Energy transfer to an occupant in rear crashes: effect of stiff, and yielding seats. *SAE Technical Paper*, No. 2003-01-1351.
- Viano, D.C. (2003b) Seat influences on female neck responses in rear crashes: a reason why women have higher whiplash rates. *Traffic Injury Prevention*, 4(3), 228-239.
- Viano, D.C. (2003c) Seat properties affecting neck responses in rear crashes: a reason why whiplash has increased. *Traffic Injury Prevention*, 4(3), 214-27.
- Viano, D.C. (2008) Seat design principles to reduce neck injuries in rear impacts. *Traffic Injury Prevention*, 9(6), 552-560.
- Watanabe, R., Katsuhara, T., Miyazaki, H., Kitagawa, Y. & Yasuki, T. (2012) Research of the relationship of pedestrian injury to collision speed, car-type, impact location and pedestrian sizes using human FE model (THUMS Version 4). *Stapp Car Crash Journal*, 56, 269-321.
- Watanabe, Y., Ichikawa, H., Kayama, O., Ono, K., Kaneoka, K. & Inami, S. (2000) Influence of seat characteristics on occupant motion in low-velocity rear-end impacts. *Accident Analysis and Prevention*, 32(2), 243-250.
- Watkinson, A., Gargan, M.F. & Bannister, G.C. (1991) Prognostic factors in soft tissue injuries of the cervical spine. *Injury*, 22(4), 307-309.
- Welsh, R. & Lenard, J. (2001) Male and female car drivers – Differences in collision and injury risks. In: *Association for Advancement of Automotive Medicine (45th AAAM)*, Texas, USA.
- Welcher, J.B. and Szabo, J.S. (2001) Relationships between seat properties and human subject kinematics in rear impact tests. *Accident Analysis and Prevention*, 33(3), 289-304.
- White, N.A., Begeman, P.C., Hardy, W.N., Yang, K.H., Ono, K., Sato, F., Kamiji, K., Yasuki, T. & 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*, No. 2009-01-0387.
- Wiklund K. & Larsson, H. (1997) SAAB active head restraint (SAHR) – seat design to reduce the risk of neck injuries in rear impacts. *SAE Technical Paper*, No. 980297.
- Wilmink J.T. & Patijn, J. (2001) MR imaging of alar ligament in whiplash-associated disorders: an observer study. *Neuroradiology*, 43(10), 859–863
- Winkelstein, B.A., Nightingale, R.W., Richardson, W.J. & Myers, B.S. (2000) The cervical facet capsule and its role in whiplash injury: a biomechanical investigation. *Spine*, 25(10), 1238– 1246.
- Yang, K., Zhu, F., Luan, F., Zhao, L. & Begeman, P. (1998) Development of a finite element model of the human neck. *Stapp Car Crash Journal*, 42, No. 983157.

References

- Yang, K.H. & King, A.I. (2003) Neck kinematics in rear-end impacts. *Pain Research and Management*, 8(2), 79–85.
- Yao, H.D., Svensson, M.Y. & Nilsson, H. (2016) Transient pressure changes in the vertebral canal during whiplash motion –a hydrodynamic modelling approach. *Journal of Biomechanics*, 49(3), 416-422.
- Yoganandan, N., Sances, A. Jr., Maiman, D.J., Myklebust, J.B., Pech, P. & Larson, S.J. (1986) Experimental spinal injuries with vertical impact. *Spine*, 11(9), 855–860.
- Yoganandan, N., Pintar, F.A., Gennarelli, T.A., Eppinger, R.H. & Voo, L.M. (1999) Geometrical effects on the mechanism of cervical spine injury due to head impact. In: *International Research Council of Biomechanics of Injury Conference*, Sitges, Spain.
- Yoganandan, N., Pintar, F.A., Stemper, B.D. & Schlick, M.B. (2000) Biomechanics of human occupants in simulated rear crashes: Documentation of neck injuries and comparison of injury criteria. *Stapp Car Crash Journal*, 44, 189-204.
- Yoganandan, N., Cusick, J.F., Pinter, F.A., Rao, R.D. (2001) Whiplash injury determination with conventional spine imaging and cryomicrotomy. *Spine*, 26(22), 2443–2448.
- Yoganandan, N., Pinter, F.A., Cusick, J.F. (2002) Biomechanical analyses of whiplash injuries using an experimental model. *Accident Analysis and Prevention*, 34(5), 663–671.
- Yoganandan, N., Knowles, S., Maiman, D.J. & Pinter, F. (2003) Anatomic study of the morphology of human cervical facet joint. *Spine*, 28(20), 2317-2323.
- Youdas, J.W., Garrett, T., Suman, V.J., Bogard, C.L., Hallman, H.O. & Carey, J.R. (1992) Normal range of motion of the cervical spine: an initial goniometric study. *Physical Therapy*, 72(11), 770–80.
- Yukawa, Y., Kato, F., Suda, K., Yamagata, M. & Ueta, T. (2012) Age-related changes in osseous anatomy, alignment, and range of motion of the cervical spine. Part I: radiographic data from over 1,200 asymptomatic subjects. *European Spine Journal*, 21(8), 1492–1498.
- Zheng, L. (2011) Sex differences in human neck musculoskeletal biomechanics and modelling. Washington State University, Seattle, USA. Doctoral Dissertation.

8 Appendix

Based on WAD injury mechanism hypotheses, as described in Chapter 2, WADs are considered related to damage of the cervical soft tissues. Greater cervical vertebral kinematics caused during the rapid deformation of the cervical S-shape, might induce harmful local deformation in the cervical soft tissues. Different theories of the injury mechanisms involved, such as the transient pressure gradient in the spinal canal, the compression of the facet joints, the stretch of cervical ligaments, and so on circulate (see for instance Aldman et al. 1986, Kaneoka et al. 1999, Luan et al. 2000). From aspects of clinical findings and experimental studies, sub-catastrophic failure of the capsular ligament (CL) by stretching has gained attention as a major potential cause of WAD (Siegmund et al. 2009, Bogduk 2011).

In Paper V, through rear impact reconstruction simulations including six different spinal alignment patterns, intervertebral angular displacement was seen in the investigation of effects of spinal alignment on vertebral kinematics. In the context of the above hypotheses, to investigate a potential impact of spinal alignment on the risk of sustaining WADs, the response of the facet joint and the cervical ligaments were further analysed with the results of the rear impact reconstruction simulations.

Methods

Rear impact reconstruction simulations: Reconstruction simulation of the second sled test series in Paper I were conducted with a whole-body occupant FE model in Paper V, implementing six different spinal alignment patterns obtained in Paper III. These simulation results were used in this additional analysis. The complete description of the methods applied in the sled test reconstruction simulation are provided in Paper V. The definitions of the spinal alignments in the Appendix follows the description in Paper V.

Facet joint kinematics: To observe the response of the facet joint during a rear impact, facet joint displacement, shear and distraction, were extracted from the occupant model at the time of the maximum cervical S-shape. This moment is defined as the instant when the C2/C3 showed the largest flexion (Stemper et al. 2003). Facet joint shear has been defined as translation of the superior facet along the inferior facet plane. Facet joint distraction has been defined as the increase in the relative distance between the inferior and superior nodes on the anterior and posterior end of the facets, in accordance with Stemper et al. (2004a) and Östh et al. (2017).

Elongation of the cervical ligaments: The elongation of the cervical ligaments was analysed on the Anterior longitudinal ligament (ALL), Capsular ligament (CL), Interspinous ligament (ISL), Ligamentum flavum (LF) and the Posterior longitudinal ligament (PLL). The maximum elongation of the cervical ligaments at each intervertebral level was normalised to tensile failure data given in the literature (Brolin et al. 2005, Myklebust et al. 1988, Mattucci et al. 2015). The catastrophic tensile failure elongation of the cervical ligaments at each intervertebral level was

obtained from Myklebust et al. (1988). For the sub-catastrophic tensile failure data, the elongation at the transition point to the traumatic region at a strain rate of 20/s (Mattucci et al. 2015) were used. Strain rates of the cervical ligaments were up to approximately 11/s in the rear impact reconstruction simulations.

Results

Facet joint kinematics: Facet joint displacements at the time of the maximum cervical S-shape has been summarised in Figure A1b-d with intervertebral angular displacements, Figure A1a. Intervertebral angular displacements and facet joint displacements were concentrated from the lower cervical spine to the upper thoracic spine, for a slightly kyphotic or almost straight cervical spine and less-kyphotic thoracic spine ('1^{st-}' and the average female). On the other hand, these displacements were more concentrated from the lower thoracic spine to the lumbar spine, for a lordotic cervical and more pronounced kyphotic thoracic spine ('1^{st+}' and the average male).

When looking at the cervical spine, the lower cervical spine from C4/C5 to C7/T1 exhibited intervertebral flexion with facet joint posterior shear, while C2/C3 and C3/C4 exhibited extension, for all spinal alignment patterns. The intervertebral flexion and facet posterior shear in the lower cervical spine were greater, for a slightly kyphotic or almost straight cervical spine and less-kyphotic thoracic spine ('1^{st-}' and the average female).

Elongation of the cervical ligaments: The normalised maximum elongations are summarised in Figure A2 and Figure A3. The maximum elongation of the cervical ligaments occurred at around the time of the maximum cervical S-shape. Overall, the normalised maximum elongations of the spinal ligaments tended to be greater for a slightly kyphotic or almost straight cervical spine and less-kyphotic thoracic spine ('1^{st-}' and the average female), when compared to a lordotic cervical and more pronounced kyphotic thoracic spine ('1^{st+}' and the average male).

Larger elongation likely appeared at intervertebral levels where larger vertebral displacements (intervertebral angular displacements and facet joint displacements in Figure A1) were found, when compared to the cervical ligament elongation among intervertebral levels. The normalised maximum elongation was greater at C4/C5 and C5/C6 for the ALL, at C3/C4, C5/C6 and C6/C7 for the CL, at C2/C3, C3/C4 and C4/C5 for the ISL, LF and PLL. The elongation of the LF and PLL was relatively less. The ISL, LF and PLL are located in the posterior region of the cervical spine, and may be affected by flexion of the upper cervical spine. On the other hand, the ALL and CL are located in the relatively anterior region of the cervical spine. They may be affected by the extension with backward shear, observed in the lower cervical spine.

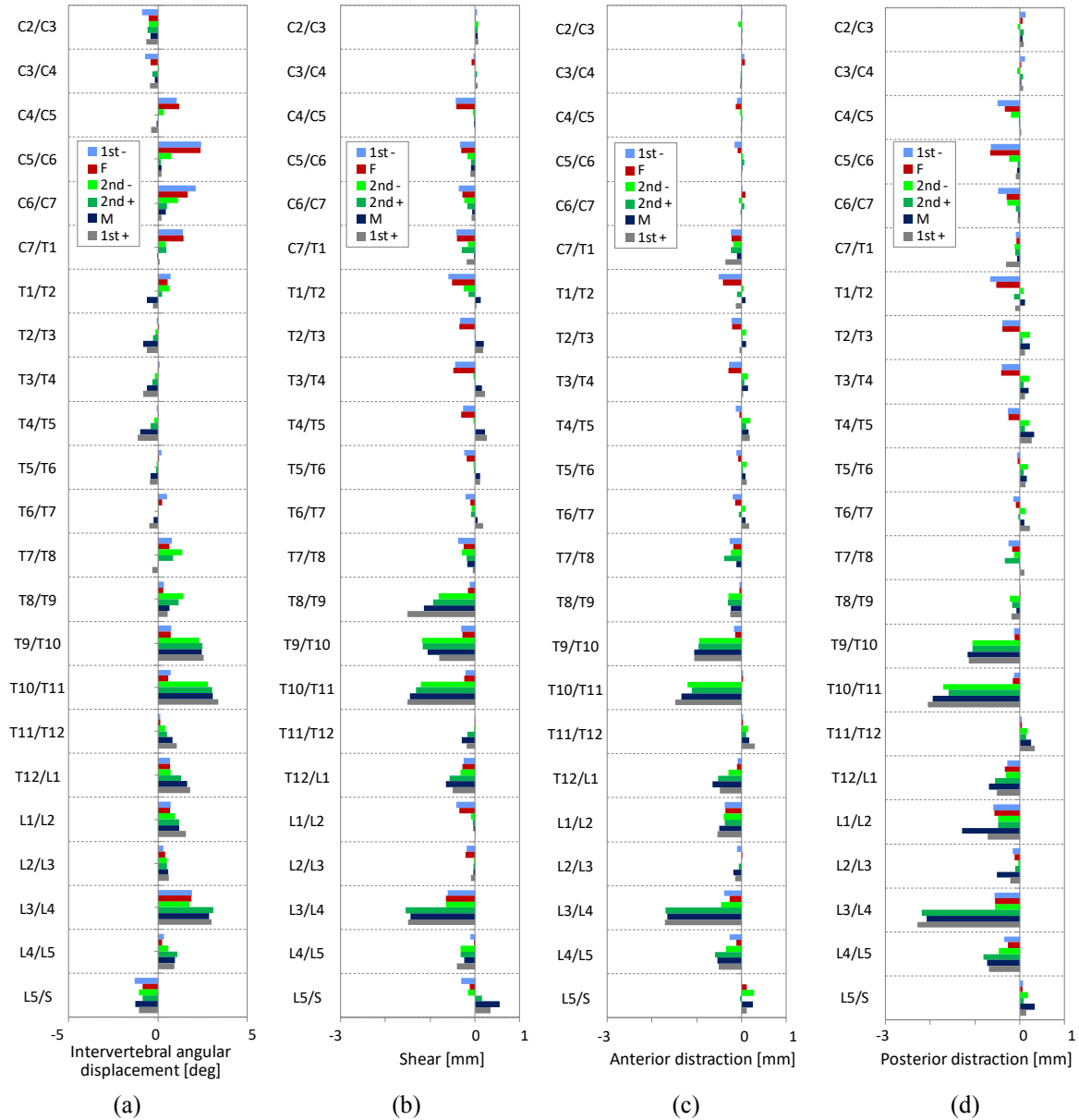


Figure A1. Intervertebral angular displacements (a) from Paper V and facet joint displacements (shear (b), anterior distraction (c) and posterior distraction (d)) at the time of the maximum cervical S shape. For the intervertebral angular displacements, the positive side is extension and negative flexion relative to the lower adjacent vertebra. ‘1st-’ and ‘1st+’ indicate the representative spinal alignment patterns estimated at the intersections of the 50% probability ellipse and the axes of the 1st MDS dimension in the negative and positive region of the 1st MDS dimension, respectively. The ‘2nd-’ and ‘2nd+’ indicate the representative spinal alignment patterns estimated at the intersections of the 50% probability ellipse and the axes of the 2nd MDS dimension in the negative and positive region of the 2nd MDS dimension, respectively. The ‘F’ and ‘M’ indicate spinal alignments estimated at the average MDS score for females and males, respectively. The maximum cervical S-shape occurred at around 70 - 80 ms in each spinal alignment pattern.

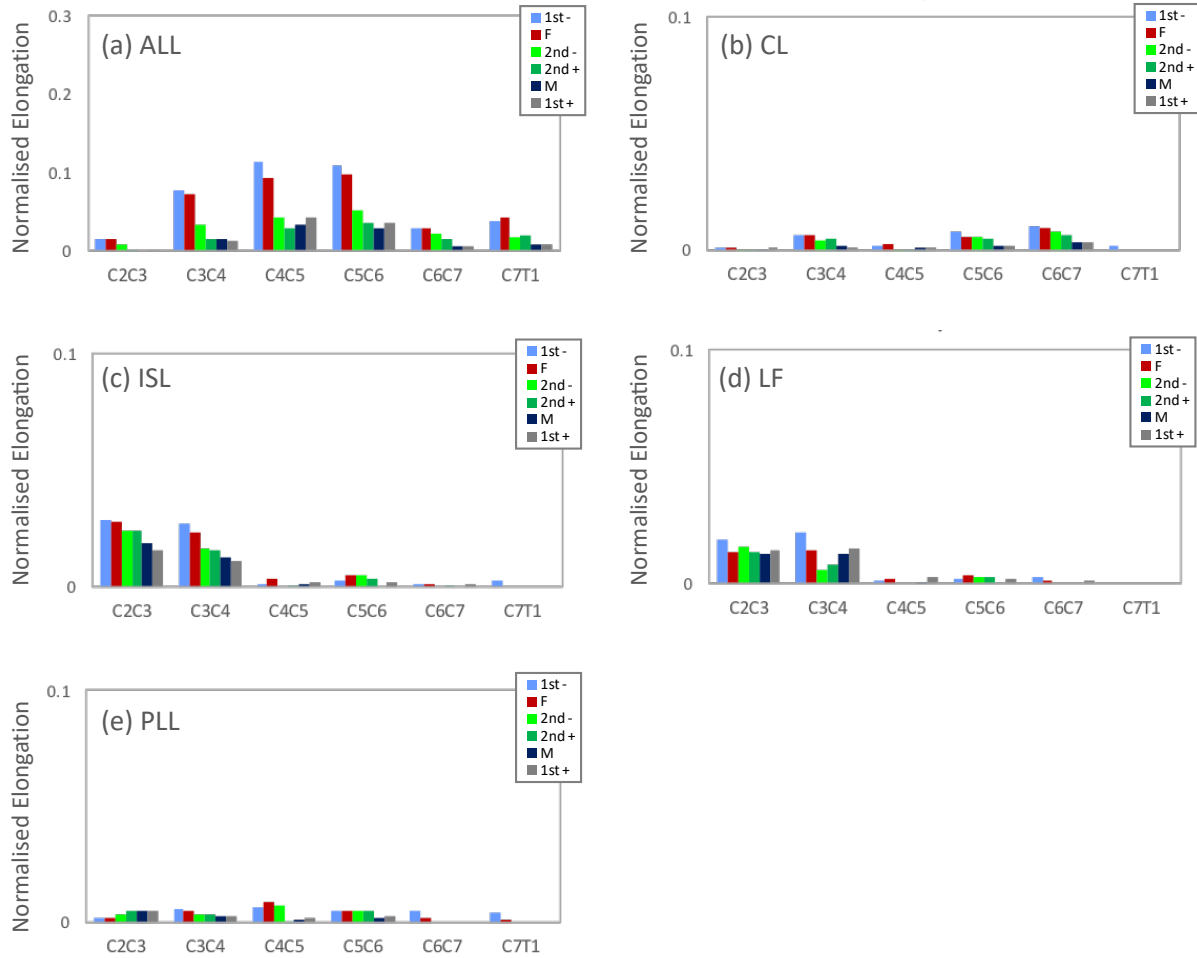


Figure A2. Maximum cervical ligament elongations normalised by the catastrophic failure elongation at each intervertebral level (Myklebust et al. 1988), ALL (a), CL (b), ISL (c), LF(d) and PLL (e). The ‘1st-’ and ‘1st+’ indicate the representative spinal alignment patterns estimated at the intersections of the 50% probability ellipse and the axes of the 1st MDS dimension in the negative and positive region of the 1st MDS dimension, respectively. The ‘2nd-’ and ‘2nd+’ indicate the representative spinal alignment patterns estimated at the intersections of the 50% probability ellipse and the axes of the 2nd MDS dimension in the negative and positive region of the 2nd MDS dimension, respectively. The ‘F’ and ‘M’ indicate spinal alignments estimated at the average MDS score for females and males, respectively.

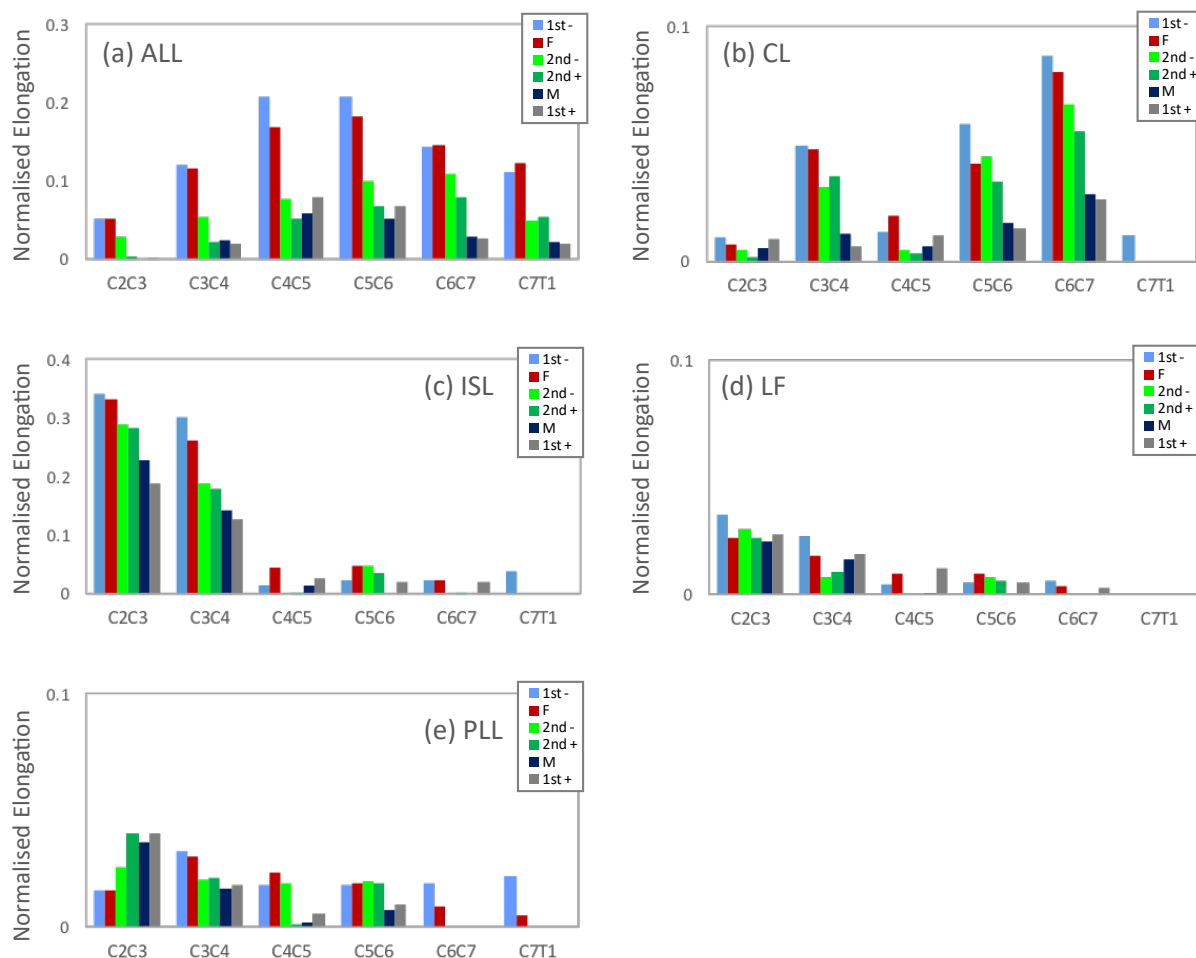


Figure A3. Maximum cervical ligament elongations normalised by the sub-catastrophic failure elongation at each intervertebral level (Mattucci et al. 2015), ALL (a), CL (b), ISL (c), LF(d) and PLL (e). The ‘1st-’ and ‘1st+’ indicate the representative spinal alignment patterns estimated at the intersections of the 50% probability ellipse and the axes of the 1st MDS dimension in the negative and positive region of the 1st MDS dimension, respectively. The ‘2nd-’ and ‘2nd+’ indicate the representative spinal alignment patterns estimated at the intersections of the 50% probability ellipse and the axes of the 2nd MDS dimension in the negative and positive region of the 2nd MDS dimension, respectively. The ‘F’ and ‘M’ indicate spinal alignments estimated at the average MDS score for females and males, respectively.