INTERACTION BETWEEN HUMANS AND CAR SEATS

Studies of occupant seat adjustment, posture, position, and real world neck injuries in rear-end impacts

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Umeå 2008

ABSTRACT

Background: Neck injuries in rear-end collisions are still a major problem both for the injured and, in terms of cost, for society. The latest generation of rear-end whiplash protection systems, as found in the WHIPS Volvo and SAHR Saab, have reduced injury rates by almost 50% in comparison with the previous generation of seat/head restraint systems. Occupant behaviour, such as seated posture and seat adjustment settings, may affect the injury risk.

Method: Five studies were conducted. Study I was an injury outcome study based on insurance data. Studies II-IV investigated seat adjustment, occupant backset, and cervical retraction for drivers and occupants in different postures and positions in the car, during stationary and driving conditions. Finally, study V compared the occupant data from studies II and III with a commonly-used vehicle testing tool, the BioRID dummy, using the protocols of the International Standardization Organisation (ISO), the Research Council for Automobile Repairs (RCAR), and the RCAR International Insurance Whiplash Prevention Group (RCAR-IIWPG).

Results: Female drivers and passengers had a threefold increased risk for medically-impairing neck injury in rear-end impacts, compared with males. Driver position had a double risk compared with front passenger seat position. Female drivers adjusted the driver seat differently to male drivers; they sat higher and closer to the steering wheel and with more upright back rest. The volunteers also adjusted their car seat differently to the ISO, RCAR, and RCAR-IIWPG protocol settings; males sat 61 mm and females 20 mm further away from the steering wheel, and seat back angle was 1˚ more upright in males and 4˚ more upright in females than in the protocols. In stationary cars, backset was highest in the rear seat position and lowest in the front passenger seat position. Males had a larger backset than females. Resting the hands on the upper part of the steering wheel increased the backset by 26 mm in females and 37 mm in males, in comparison with having the hands in the lap. Cervical retraction decreased and backset increased for both sexes when posture changed from a self-selected posture to a slouched posture. Backset was 41 mm greater in females and 43 mm greater in males during driving, in comparison to stationary conditions. The BioRID II dummy was found to represent a 35th–45th percentile male in stature, a 35th percentile male in weight, a 96th percentile female in stature, and a 69th percentile female in weight in the volunteer group.

Conclusion: Risks in car rear-end impacts differ by sex and seated position. Seated posture affects backset size and cervical retraction capacity, and hence the risk for end-range loading of cervical joints. The current BioRID II dummy does not represent the female population very well; and the ISO, RCAR, and RCAR-IIWPG testing protocols do not take sex and seated position differences into account. This thesis indicates the need for a 50th percentile female BioRID dummy and re-evaluation of the ISO, RCAR, and RCAR-IIWPG protocols, and further developments of new safety systems to protect occupants in rear-end impacts.

LIST OF PAPERS

This thesis is based on the following papers:

I.   Jonsson, B., Tingvall, C., Krafft, M., Björnstig, U., The Risk of Whiplash-Induced Medical Impairment in Rear-End Impacts for Males and Females in Driver Seat Compared to Front Passenger Seat. *Traffic Injury Prevention,* (submitted).

II.   Jonsson, B., Stenlund, H., Svensson, M.Y., Björnstig, U. (2008) Seat adjustment – capacity and repeatability among occupants in a modern car. *Ergonomics,* Vol. 51, No. 2, pp. 232-241.

III.   Jonsson, B., Stenlund, H., Svensson, M.Y., Björnstig, U. (2007) Backset and Cervical Retraction Capacity among Occupants in a Modern Car. *Traffic Injury Prevention,* Vol. 8, No. 1, pp. 87-93.

IV.   Jonsson, B.**,** Stenlund, H., Björnstig, U. Backset — stationary and during car driving. *Traffic Injury Prevention,* (submitted).

V.   Jonsson, B., Svensson, M.Y., Linder, A., Björnstig, U. BioRID II Manikin and Human Seating Position in Relation to Car Head Restraint. *International Journal of Crashworthiness,* (accepted 08/04/2008).

LIST OF ABBREVIATIONS AND MEDICAL TERMS

AIS 1	Abbreviated Injury Scale. Range 1-6. AIS 1 indicates a minor injury, e.g. whiplash injury
Backset	Horizontal distance between the back of occupant's head and the vertical line through a fixed zero-point on the frontal aspect of the seam of the fabric on top of the head restraint
BioRID	Biofidelity Rear Impact Dummy (crash dummy)
DHA	Diagnostic Host Application
ECU	Electronic Control Units
Extension	Is a position or movement that is made possible by the joint angle increasing.
Flexion	Is a position or movement that is made possible by the joint angle decreasing.
IBGE	Instituto Brasileiro de Geografia e Estatística
ICC	Intraclass Correlation
IIHS	Insurance Institute of Highway Safety
ISO	International Organization for Standardization
Lordosis	Inward curvature of a portion of the vertebral column
Occipital protuberance	The bony ridge at the back of the skull
Protraction	Horizontal forward translation of the head relative to the torso
RCAR	Research Council for Automobile Repairs
RCAR-IIWPG	Research Council for Automobile Repairs — International Insurance Whiplash Prevention Group
Retraction	Horizontal rearward translation of the head relative to the torso
ROM	Range of motion
SAE	Society of Automotive Engineers
Sagittal plane	The plane dividing a person's body into left and right halves
SCB	Statistiska centralbyrån (Statistics Sweden)

SIKA	Statens Institut för Kommunikationsanalys (Swedish Institute for Transport and Communications Analysis)
Spondylosis	Spinal degeneration and deformity of the joint(s) of two or more vertebrae
VAS	Visual Analogue Scale. Range 0-100. 0 = No pain, 100 = As bad as it could be.
WAD	Whiplash Associated Disorders. Range 0-4. Classification of acute injuries.
QTF	Québec Task Force

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INTRODUCTION

The ergonomic chair

The word "ergonomics" describes both the scientific discipline concerned with the understanding of interactions among humans and other elements of a system, and the profession that applies theory, principles, data, and methods to design in order to optimise human well-being and overall system performance (IEA, 2007). Drury and Coury (1982) identified five requirements that a seat (in this case an office chair) must fulfil to be regarded as ergonomic: 1) it must be safe; 2) it must be adaptable to meet the anthropometric needs of a wide range of users; 3) it must be comfortable; 4) it must fit a wide range of body curves and shapes; and 5) it must be practical and solid, so that it is reliable and easy to adjust. All of these criteria also apply to a car seat. In addition, a car seat should offer the driver good conditions for manoeuvring the steering wheel, foot pedals, and other actuators; and, finally, it should contribute to good vision. This means that the seated posture of an occupant in a car seat will be greatly influenced by the driving task and personal preferences of the individual user such as, seat adjustability and as well as geometrical design.

Safety in rear-end impacts

Neck complaints secondary to automotive impacts constitute a problem for the victims, the relatives, insurance companies, and society as a whole. The neck movement known as "whiplash" was first described by the American doctor H. E. Crowe (Crowe, 1928). When J. R. Gray and K. H. Abbott published their 1953 article with the word "whiplash" in the title, and then later described the related symptoms that followed after rear end impacts, the medical term "whiplash injury" was established. This term was later partly replaced by the term "Whiplash Associated Disorders" (WAD), following the 1995 report of the Québec Task Force (QTF) (Spitzer et al., 1995).

The QTF definition was:
"Whiplash is an acceleration-deceleration mechanism of energy transfer to the neck.
It may result from rear-end or side-impact motor vehicle collisions, but can also occur during diving or other mishaps. The impact may result in bony or soft-tissue injuries (whiplash injury), which in turn can lead to a variety of clinical manifestations".

The QTF also made specific recommendations on prevention, diagnosis and treatment of WAD. An updated review of the QTF report was published in 1998 (Freeman et al., 1998).

The annual incidence for whiplash injury in the US, Australia, Canada, Sweden, and ranges from 1.0 to 6.0 per 1000 inhabitants (Barancik et al., 1989; Barnsley et al., 1994; Cassidy et al., 2000; Sterner et al., 2003; Quinlan et al., 2004). In Sweden, 30 000 neck complaints following automotive crashes are reported annually to the insurance companies, at a total cost of 4 billion SEK (645 million USD) (Whiplashkommissionen, 2005). The corresponding annual cost in the US is 29 billion USD (Spitzer et al., 1995). Most of the injured parties recover with or without rehabilitation, but permanent medical disability (>10%) is the outcome for 1500 Swedes annually. The costs of these neck injuries are mainly due to lack of future income from work, as has been shown in Sweden (Whiplashkommissionen, 2005).

Much research effort has been expended on identifying the anatomic structures that are involved in WAD, but as yet no clear and simple picture has emerged. A number of researchers have proposed that the zygapophysial (facet) joints and their surrounding joint ligaments and capsules could be a source of injury or symptoms (Barnsley et al., 1995; Lord et al., 1996; Yang & Begeman, 1996; Ono et al., 1997; Kaneoka et al., 1999; Deng et al., 2000; Cusick et al., 2001; Yang & King, 2003; Yoganandan et al., 2001; Yoganandan et al., 2002; Stemper et al., 2004). Others have suggested the disc (Pettersson et al., 1997; Panjabi et al., 2004). A long-term follow-up study of whiplash patients demonstrated that cervical spondylosis was six times more frequent in these patients than in sex- and age-matched controls (Hohl, 1974). Muscle injury during lengthening contraction in rear-end impacts has also been suggested (Brault et al., 2000). Finally, another possibility is injuries to nerve structures (Aldman, 1986; Örtengren et al., 1996; Svensson et al., 2000). Knowledge of the structures which may have been injured is, of course, of crucial importance in medical treatment and rehabilitation of whiplash injuries.

However, in injury prevention strategies other data is also important; sex differences, for example, as females are more vulnerable to neck injury compared to men (Kihlberg, 1969; O'Neill et al., 1972; Huelke & Marsh, 1974; Thomas et al., 1982; Dolinis, 1997; Chapline et al., 2000; Krafft, 2002; Krafft et al., 2003; Jakobsson, 2005). Females and males differ in stature and weight. Males are heavier than females, and they are exposed to 30% lower neck acceleration relative to the torso and a later-occurring neck displacement during rear impacts (Viano, 2003). Neck acceleration is proportional to torso mass and seat stiffness, meaning that females will accelerate faster than males in rear impacts (Siegmund et al., 1997). Low mean acceleration with no distinct peaks will probably reduce the risk of neck injury (Kullgren, 1998; Eriksson & Boström, 1999; Krafft et al., 2002).

Shear loading has been described as one risk factor in rear-end impacts (Yang & Begeman, 1996; Deng et al., 2000; Panjabi et al., 2004). Deng et al., (2000) performed tests on human cadavers in 0° and 20° seatback inclinations. In the 20° inclination, there was less initial cervical lordosis, more upward ramping of the thoracic spine, and more relative rotation of each cervical motion segment in comparison with the 0° seatback tests. Relative to the Th1 vertebra, the head went from flexion to extension at 20° inclination, but stayed in extension at 0° inclination (Deng et al., 2000), indicating that the joint mechanics in the neck can behave differently depending on seat adjustments. This is an important reason to study occupant seating preferences.

Another reason to study seating preferences is that vertebral joint mechanics are affected by seated posture. The curvature in the sagittal plane of the spine is basically governed by the pelvic position. A rearward tilted pelvis increases flexion in both lumbar and thoracic spine, giving a slouched seated posture, whereas a forward rotated pelvis gives the opposite effect, an erect seated posture (see Figure 1).

Figure 1. Neck postures in lateral x-rays due to different seated postures. A line is drawn parallel to the facet joint plane of C5-6.

The position of the neck is also determined by the task of the seated occupant. The most important task in driving is vision, and so vision demands govern head position to a high degree. Another factor is arm and hand position, as the driver must keep at least one hand on the steering wheel; this may be one reason why drivers have an increased injury risk compared to front seat passengers (Berglund et al., 2003; Krafft et al., 2003). Increased extension in the lumbar spine, as a result of lumbar support/forward rotating pelvis, is associated with increased extension and decreased flexion ROM in the cervical spine, and vice-versa (Bergqvist & Geurts, 2005). Finally, an x-ray study by Banks et al. (2000) showed that the lumbar posture in driving position was close to the fully voluntarily flexed lumbar spine posture; however, the weakness of this study is that it was only performed in one volunteer.

Anthropometric adaptation to the occupant

Today, every new car seat has fore- and aft adjustment as well as adjustable seat back inclination; together, these two adjustments are regarded as the most important adjustments for obtaining an acceptable occupant position in a car. Most cars also have a seat tilt function, or a separate adjustment of the height of the front and rear parts of the seat cushion so as to provide the capacity to raise or lower the whole seat. In addition, most cars also have adjustable lumbar supports, and luxury seat constructions also allow seat cushion depth adjustments. In most cars, the actuators are handled manually, but more and more seats are being built with between two and six electric motors to handle adjustments. The purpose of these different adjustments is of course to fit as large a range of the population as possible. Normally, the ranges of adjustments in a car seat are aimed at matching the anthropometric range of a 5th percentile female up to a 95th percentile male. The mean anthropometric data are different between males and females, but there are also differences within the sexes between different parts of the world. Mean female stature varies between different countries; the mean stature of females in ten European countries is 163.7 cm (Cavelaars et al., 2000), that of Chinese females is 154.5 cm (Bell, 2002), and that of Brazilian females is 160.3 cm (IBGE,

2006). As another example, Swedish males are 14 cm taller than Swedish females (SCB, 2005). Similar data can be found for weight. These size differences mean that different people adjust car seats differently; females sit closer to the steering wheel and with three degrees more upright back rest as compared to males (Jonsson et al., 2008). This difference in back rest inclination probably also increases shear loading in the neck for females in rear impacts.

Comfort and adaptation to body shape

Good seated comfort is important, as it helps to reduce driver fatigue and musculoskeletal discomfort and disorders (Bellina, 1994). Seated comfort depends on several factors, such as pressure distribution (Park et al., 1998; Ebe & Griffin, 2001), thermal comfort (ISO 7730, 1994), vibration (ISO 2631-1, 1997), seat shape, upholstery characteristics, covering materials, head rest support, arm rests, seat cushion height, seat cushion tilt, seat back angle, back support, side contours, and finally lumbar support (Akioka et al., 1994). All these factors are of importance because the exposure time for drivers in cars is fairly high. In Sweden, the average annual distance covered per car in 2006 was 14 390 km (SIKA, 2007). With a mean speed between 50-70 km/h, this implies about 200-300 hours of driving per car each year. Most of the driving time is for shorter distances, meaning that the need for seated comfort is fulfilled in most production seats. However, this is not always the case for professional drivers such as taxi or outdoor sales personnel, who may have 3-4 times more driving time. Driving is a rather static activity, since at least one hand and one foot of the driver are occupied at all times, and almost constant eye contact with the road is also necessary. All these factors mean that good comfort is required if car driving is to be enjoyable. However there are possible conflicts between comfort and safety demands in seat geometric design; one example is the need to allow space for hats and pony-tails between the occupant's head and the head restraint, which conflicts with the safety-related need for proximity between head and head restraint (i.e., a low backset). Most researchers consider low backset distance to be one factor which reduces the risk of whiplash injury in rear-end impacts (Olsson et al., 1990; Farmer et al., 1999; Chapline et al., 2000; Eriksson, 2004; Jakobsson, 2005). It is thus necessary for seat manufacturers and car makers to determine the optimum safety and ergonomic position for the head restraint relative to the seat back. This is one reason why some of the studies in this thesis were performed with no head restraint in place.

Practicality and solidity

Seat adjustment actuators must be simple to operate, regardless of whether the actuator is mechanical or electrical, since otherwise there is the risk that the occupant will fail to make use of the seat adjustment capacity. The power seat adjustment actuator often has the shape of a "mini seat", which makes the adjustments easy to understand. The second advantage of this approach is that all adjustments are controlled using the same device, which favours more accurate and more frequent adjustments. A car seat must withstand large forces in crash situations and must therefore be solid, but as light as possible, to contribute to low total vehicle weight and thereby low fuel consumption.

AIMS OF THE THESIS

The overall objective of this thesis was to study human and car seat interaction in pre-crash conditions for a car with a high safety rating and medical impairment data from rear-end impacts. The specific aims of the individual studies are described below.

The aims of studies I–V were to measure or analyse:

I. Risk differences in relation to sex and seating position in rear-end impacts in which there was an occupant in both front seats, and at least one front seat occupant sustained a whiplash injury with resulting permanent medical impairment.

II. The repeatability and ICC of seat adjustments in the driver's position, in a car with a high safety rating.

III. (i) Capacity to perform cervical retraction, (ii) backset, and (iii) vertical distance from the occipital protuberance (bone ridge) at the back of the head to the top of the head restraint, in three postures (self-selected, slouched, and erect) and in three occupant positions (driver, front passenger, and rear passenger).

IV. Stationary backset in the driver's position and backset during driving in and outside a small urban town, in a car with high safety rating.

V. How well the BioRID II, when positioned according to the ISO, RCAR, and RCAR-IIWPG protocols, corresponds in size and backset to data from a randomly selected population of Swedish female and male volunteers, sitting as drivers (hands on the steering wheel) and as front and rear seat passengers (hands in the lap).

METHODS AND MATERIALS

General overview

Study I is a retrospective study of an insurance company's data set of whiplash injuries, using the double comparison technique described by Evans (1986). Studies II, III, and IV are cross-sectional studies, while study V compares the BioRID II with the data from humans gathered in studies II and III. The five studies are shown schematically in Figure 2 and described further below.

Studies II, III, and IV provide data on occupants during both stationary and driving conditions. Together, they describe the interactions between seat adjustment preferences, backset, vertical position of head relative to the top of the head restraint, and cervical retraction capacity. All these variables are influenced by occupant behaviour and the geometrical design of the seat. The studies were conducted in a car with a high safety rating; a Volvo V70, year models 2003 and 2007 (IIHS, 2007). Study I provides an analysis of outcome data from real world rear-end impacts, taking into account the sex and seated position of the injured occupant. Study V concerns the current final validation tool that is used within the automotive business, the BioRID II, positioned according to the ISO, RCAR, and RCAR-IIWPG protocols plus an extra routine for the rear seat used internally by Volvo Cars. These data are compared to human data from studies II and III. Finally, this thesis provides conclusions, and recommendations for future action.
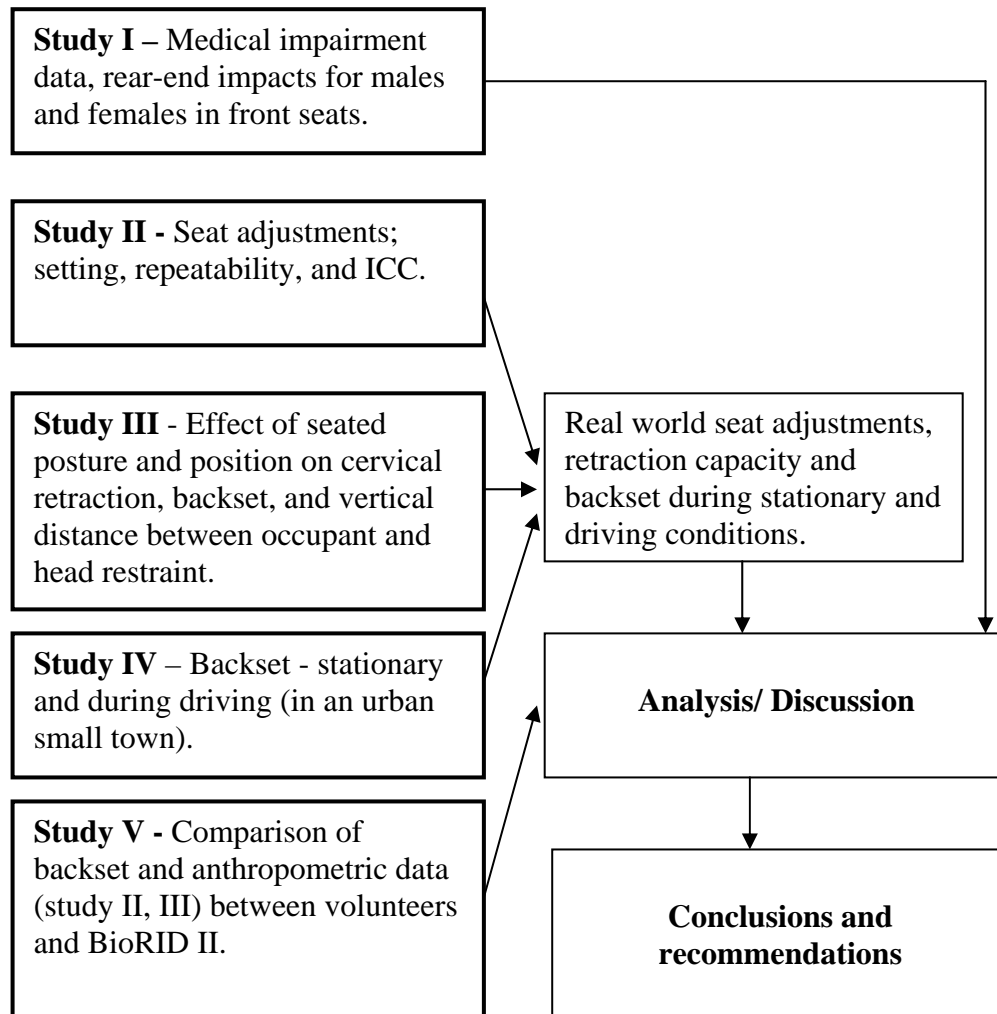
Figure 2. Flow chart showing studies I-V and their interactions.

Overview of study design

All volunteers in studies II-V were recruited in Örnsköldsvik, a small city with 28 000 inhabitants. The insurance dataset from the medical impaired occupants in study I, was from the entire country. In the following text, some methodological aspects of the studies are clarified and explained in detail.

Study I

This retrospective outcome study used a data set provided by Folksam (a Swedish insurance company) to compare whiplash injuries between males and females in the two front seat positions, using a double comparison technique (Evans, 1986). This method makes it possible to control for the level of rear-end impact violence, which is a factor known to influence injury outcome. The study data were based on crash insurance data reported to the company between 1990 and 1999. The data were collected by Folksam in 2002.

The inclusion criteria for the study were: ≥ 18 years for the driver, and ≥ 16 years or ≥ 150 cm stature or ≥ 50 kg in weight for the front seat passenger. The authors consider that most people are of adult stature by the age of 16 years; however, there is always a possibility that big (≥ 150 cm stature or ≥ 50 kg) but young (<16 years) children in the front passenger seat will be compared to adults under these selection criteria. The response rate was 81%. A follow-up investigation of the injured non-responders showed that they did not differ from the responders in age, weight, or stature. One weakness of this study is that data on the co-occupants were lacking in the non-responding group (19%), and the time lag between incident and data collection. Some data may have been hard to remember, for example the co-occupant's age, weight, and stature at the moment of impact, and even the injured person's own weight at the time of injury.

Study II

Is this cross-sectional study, a randomly selected group of females (n=74) and males (n=76) performed three adjustments of a Volvo V 70 electrically manoeuvred seat. . At the beginning of the study, a pilot group of fifteen volunteers (not participating in study II or III) made ten seat adjustments. A statistical analysis was performed, and ten adjustments showed no difference compared to the chosen three adjustments. Hence, for statistical and time consumption reasons, three repetitions of seat adjustments were chosen for studies II and III. The selection was stratified with regard to age and sex, but was otherwise random. Sweden had 4.5 million passenger cars in traffic during year 2006. Of these, 3.8 million were owned by individuals and the remaining 0.7 million by corporations (SIKA, 2007). At the same time point, the total size of the Swedish population aged 18 or over was 7.2 million (SCB, 2008), meaning that approximately half of the Swedish population (aged ≥ 18 years) owned a private car, and even higher numbers had access to a car. In Sweden, 5.8 million individuals hold a valid driver licence (class B) for cars (Vägverket 2008). In Sweden, all cars are inspected once after three years of use, and then annually after five years of use (Bilprovningen, 2008).The summons for inspection is based on the last digit of the car's registration number, which is randomly assigned by a computer at the Swedish Vehicle Inspection Company. The other random factor for selection in this study was when the test leader approached a person and asked if they were interested in participating. Approximately 80% of those asked declined to participate in the studies; the three most commonly-cited reasons were lack of time, ongoing pain in the upper body, or simply not wanting to participate.

The measuring equipment in study II was a commercial product known as the VCT 2000, which works like a "translator" between the car's electronic computing unit (ECU) and the laptop. The Volvo DHA software is then used on the laptop to transform binary code to numerical data. Both of these tools have been used by the ergonomics department of Volvo Cars for several years, and have been internally validated.

Study III

The volunteers in study III were the same as in study II.
Cervical retraction, backset, and vertical distance were measured in relation to a zero-reference point located to the sewing rim on front/top of the imaginary head restraint. The measuring device consisted of two grade scales and two metal rods attached to each other and inserted into the mounting place of the head restraint; see Figure 3.

Figure 3. Volunteer in driver position, with measuring equipment.

The measuring equipment and mathematical equation were developed and validated in consultation with Autoliv Research Sweden. A revalidation was performed by the authors by hanging a plummet from the ceiling in front of the head restraint on two randomly selected places in the sagittal plane of the seat. The seat adjustment was altered between the two measurements. A 1.5 metre water-level device was used to ensure a correct horizontal alignment from the zero-reference point on the head restraint. Manual measurement was made in vertical and horizontal directions and compared to the data from the measuring device/computer data. The results showed a maximum difference of 2 mm in both vertical and horizontal directions. The car was parked in an indoor garage with a horizontal floor during the revalidation.

The second methodological consideration was fixation at the Th1 level during cervical retraction. A fixation device was made and tested in the group of fifteen volunteers in the pilot group. Different shapes and minor padding were tested, but none was found to function properly. In terms of ROM of cervical retraction, the pilot group preferred manual fixation of the Th1 level; when mechanical fixation was used, several volunteers indicated discomfort and found it difficult to perform maximal retraction due to contact pressure at the Th1 level of the spine. The problem is that the human configuration in the sagittal plane is very different in this region; some people are flat, while others have a hump. In our outcome data, the cervical retraction variable seemed to be fairly normally distributed, and the mean results were comparable to previously presented data (Brault et al., 1998; Edmondston et al., 2005). However, this is a possible source of measurement inaccuracy in this study.

Study IV

This cross-sectional study included 65 volunteers; 35 males and 30 females. The same measuring technique was used for stationary backset as described in study III, but both the measuring device and the equation were adapted for the new seat in the 2007 model Volvo V70. The validation process with the plummet was repeated, yielding the same results as in study III; a maximum of $\pm$ 2 mm difference. The recruitment process in this study was different to that of studies II and III in that a non-random selection was employed due to the length of time required for the tests; it was the authors' experience from the earlier studies that few volunteers would have the required 1.5 hours available without forward planning. Advertisements for volunteers were posted in the local newspaper and on two company intranets. All of the volunteers who fulfilled the inclusion criteria participated in the study.

A video camera was used to record backset during driving, specifically a Panasonic NV-GS500 with a Panasonic VW-LW4307ME wide conversion lens. Measuring backset on taller occupants increases the risk for parallax error, especially when using wide lens optics, and the readouts from the video recording also carry the possibility of measurement errors. To investigate this, five individuals, independent of the study, made readouts from the Dartfish Connect software, version 4.0.9.0 available at (www.dartfish.com). The measuring error of backset during video-recorded driving in comparison to manual control measurements was found to have a maximum of $\pm$ 5 mm. The seat was tested in its most forward and most rearward longitudinal positions, but was not otherwise adjusted. The measurement accuracy was higher if the occupant had the seat in the forward position and less accurate with the seat in the rearward position, indicating that the chosen technique does give parallax errors.

Study V

This study compared the human backset and anthropometric data collected in studies II and III to the corresponding variables for the BioRID II. The tests were performed in the same Volvo seats and with the same measuring equipment as in studies II and III. The BioRID II settings and measurements followed the ISO, RCAR, and RCAR-IIWPG protocols, and were conducted by the Volvo cars specialist responsible for Volvo's own testing. The ISO protocol seat adjustment requirements are different to the RCAR and RCAR-IIWPG protocols. In all protocols the seat length adjustment are the same, the ISO protocol has no required settings for the other seat settings, they recommend the manufacture's design positions. Volvo cars design positions follows the same settings as in the RCAR-IIWPG-protocols. Other car manufactures can have other setting routines using the ISO-protocol. The possible errors described previously in the context of collecting human data in studies II and III may of course also have affected the results of study V. This study did not include validation of the ISO, RCAR, and RCAR-IIWPG protocols.

RESULTS

The investigation began with an analysis of neck injury outcome data from rear-end impacts, using a dataset provided by Folksam. The focus was on the differences between the sexes and the front seat positions in the risk of sustaining a medically-impairing neck injury (n=444 injured in total).

Study I

Study I produced the following relative risk (RR) estimates for medically-impairing whiplash injury for the different sexes and seated positions:

- Driver Male (DM) / Passenger Female (PF)   0.51   n=218
- Driver Male (DM) / Passenger Male (PM)   1.38   n=057
- Driver Female (DF) / Passenger Female (PF)   2.52   n=102
- Driver Female (DF) / Passenger Male (PM)   4.58   n=067

Overall, females had a risk which was threefold that of males. In addition, the driver position had an almost doubled risk compared to the front passenger position (RR for males: 1.38; RR for females: 2.52).

The next step in the attempt to understand more of the interaction between the occupant and the seat was to study seat adjustments.

Study II

The variables investigated in study II were length adjustment (LA), back angle (BA), height of rear seat cushion (HRS), and height of front seat cushion (HFS). In comparison to males, females sat 41 mm closer to the steering wheel, with the back rest 3° more upright, with the front cushion 4 mm higher, and with the rear cushion 3 mm higher. All these results reflect stature differences between the genders. The study also measured repeatability and ICC of seat adjustments of the driver's seat, performed by 154 volunteers. The repeatability values (Table 1) represent an upper bound below which the difference between two repetitions is expected with probability 0.95.

Table 1. Repeatability values based on two repetitions/participant.

| Seat Adjustment		LA (mm)	BA (degree)	HRS (mm)	HFS (mm)
Total		49	9	22	15
Sex	Male	52	10	22	15
	Female	44	7	21	14
Age (years)	≤39	42	7	20	13
	40-59	55	8	23	15
	≥60	48	12	25	17
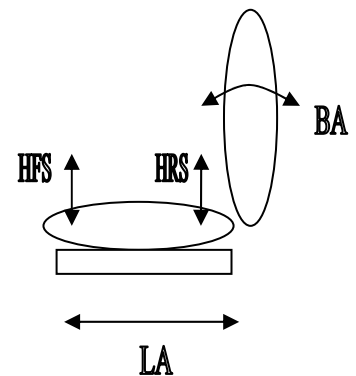
As shown in Table 1, females were more accurate than men in adjusting the seat. With one exception, younger people were also more accurate than older people. The maximum possible values of the adjustment variables were 280 mm for LA, 61.6° for BA, 41 mm for HRS, and 30 mm for HFS; thus, relative to these maximum possible adjustments, BA and LA were the most accurately accomplished seat adjustments, while HFS and HRS were less accurately adjusted.

Overall ICCs ranged from 0.57 to 0.92; a higher value indicates a larger variation between the individual volunteers relative to the total variation in the group. The highest ICCs were found for LA, where almost all ICCs were very high. The ICCs for BA, HRS, and HFS were fairly equal, but with one exception were all below 0.80. Females and younger people had slightly higher ICCs (Table 2).

Table 2. Intraclass correlation coefficient values based on two repetitions per volunteer.

Seat Adjustment		LA	BA	HRS	HFS
Total		0.87	0.74	0.67	0.69
Sex	Male	0.82	0.69	0.62	0.67
	Female	0.88	0.79	0.70	0.70
Age (years)	≤39	0.92	0.81	0.72	0.79
	40-59	0.79	0.68	0.62	0.65
	≥60	0.90	0.72	0.63	0.57
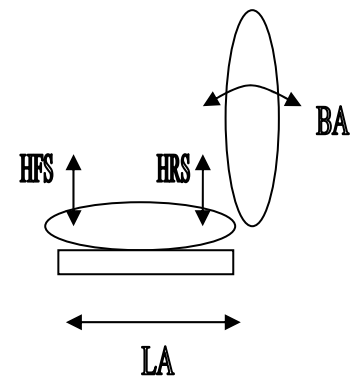
Study III

Study III examined backset and vertical distance from a defined point on the back of the occupant's head to a zero-reference point located on the frontal aspect of the sewn rim of the head restraint. Maximal retraction was measured with the same method. Measurements were taken in three different postures; self-selected, slouched, and erect, and in three different positions within the car; driver's seat, front passenger seat, and rear passenger seat. The results are shown in Figure 4.
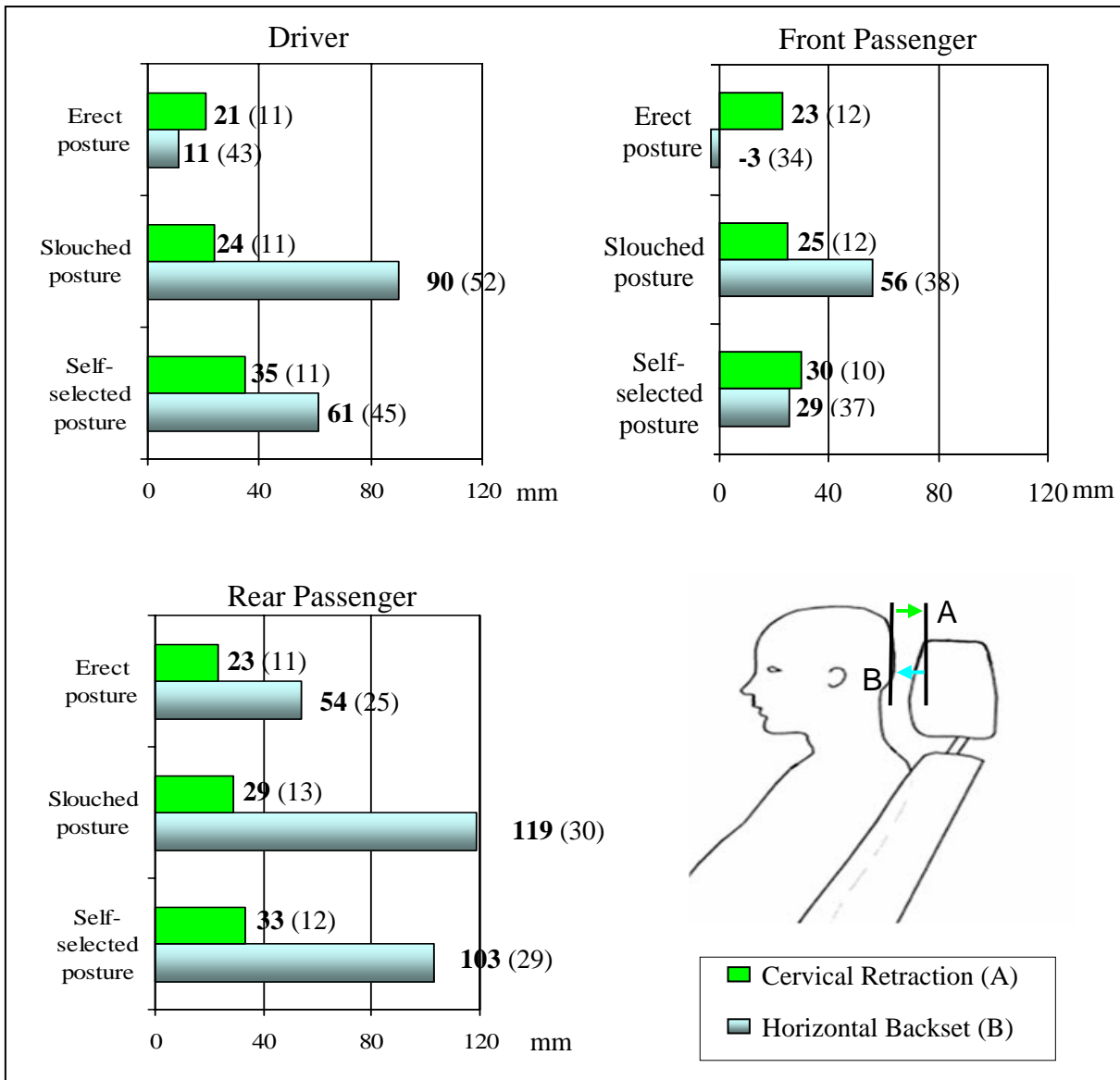
Figure 4. Mean cervical retraction and backset for both genders in driver's seat, front passenger seat, and rear passenger seat (standard deviation within brackets).

The main finding was that backset was largest in the rear seat. The front passenger seat had lower values than the driver's position. Cervical retraction was largest in the self-selected posture and smallest in the erect posture. In the ideal situation, it seems best for the cervical retraction capacity to be larger than the backset; this would decrease the risk of end-range loading of the cervical spine in rear-end impacts. This situation was only observed in certain combinations of posture and position; both front seats in the erect posture and the front passenger seat in the self-selected posture.

The conclusions of study III were as follows:

1. Females had lower mean backset than males, particularly in the self-selected driving position. Mean backset was largest for rear passengers (103 mm) and lowest for front passengers (29 mm), with drivers falling in between (61 mm).

2. Among males, increased backset was significantly associated with increased body height in all positions and postures.

3. In the driving position, backset decreased significantly with increasing age for both females and males.

4. In the self-selected posture, the drivers, who were instructed to keep their hands on the steering wheel, had greater backset than the front passengers (an increase of 27 mm in females and 37 mm in males).

5. In the self-selected posture, the mean vertical distance was 43 mm greater for drivers than for front passengers. For the driver's position, a postural change from self-selected to slouching increased the vertical distance by 16 mm.

6. When subjects changed posture from self-selected to slouching, not only did backset and vertical distance increase, but the mean range of cervical retraction capacity decreased by 4–11 mm, making the slouched posture the most vulnerable posture in all positions in the car.

Study IV

Rear-end impact can occur both on stationary cars and during driving. It is therefore important to compare stationary driving backset with driving backset.

Study IV found that mean backset during driving was larger than stationary backset for both sexes; 43 mm larger for males and 41 mm larger for females. Backset during driving was 44 mm larger for males than for females, a similar finding to the mean stationary backset difference between the sexes (42 mm). Among males, driving backset was moderately correlated (0.37–0.43) to stature, seated height, and seat back angle, while among females, driving backset was moderately correlated (0.44-0.52) to hip width, waist circumference, and weight. The overall ICC of driving backset was 0.81 (CI: 0.75-0.86). The median driving backset and variability for both sexes was largest during driving in urban traffic (route 3) compared to more rural areas (routes 1, 2, and 4).

Study V

Finally, the stature, weight, and backset volunteer data gathered in studies II and III was compared to the BioRID II manikin data when seated in the same car seat according to the ISO, RCAR, and RCAR-IIWPG protocols.

The BioRID II, which is designed to represent a 50th percentile male, was found to correspond approximately to a 35th–45th percentile male in stature (-2 cm), a 35th percentile male in weight (-7 kg), a 96th percentile female in stature (+11 cm), and a 69th percentile female in weight (+8 kg). BioRID II backset was 73 mm in the driver's seat, 76 mm in the front passenger seat, and 94 mm in the rear passenger seat. The corresponding mean data for the volunteers were 81 mm (male) and 39 mm (female) in the driver's seat, 44 mm (male) and 13 mm (female) in the front passenger seat, and 109 mm (male) and 98 mm (female) in the rear passenger seat. The volunteers also adjusted their car seat differently to the ISO, RCAR, and RCAR-IIWPG protocol settings; males sat 61 mm and females 20 mm further away from the steering wheel, and seat back angle was 1° more upright in males and 4° more upright in females than in the protocols.

DISCUSSION

Impact outcome

Dolinis (1997) studied drivers in Australia and found an odds ratio = 4.5 for a history of previous neck injury and whiplash injury after rear-end impacts. Jakobsson (2005) found in a Swedish dataset an increased risk of AIS 1 neck injury among adult in front seats, that had a history of neck problems before the rear-end impact. Ongoing neck problem has been studied in populations worldwide. In a review study of prevalence of neck pain in the world, Fejer et al. (2006) found the point prevalence for the adult population (15-74 years) to range between 5.9-22.2%, with a mean of 7.6%. Females reported more neck pain compared to males in 83% of the studies. It is a clinical medical experience that ongoing pain decreases range of motion in the neck, and the joints are more pain sensitive in end-range loading. Berglund et al. (2006) found in their 2–year follow up study of a Swedish whiplash injuries dataset a correlation between neck pain intensity and disability ranging from 0.70 to 0.76. Moderate (VAS 31-54) and severe (VAS 55-100) initial neck pain at impact had an odds ratio of 3.9 and 8.4 to neck pain intensity at the end of the period. VAS 0-30 pain score at impact was set to 1.0. Females scored slightly higher pain (VAS +5) compared to males. This study shows the connection between pain generating trauma and long term consequences.

Study I showed that females are more prone to neck injury compared to males, and occupants in the driver's seat have a higher risk compared to front seat passengers. This is in line with previous studies (Jakobsson et al., 2000; Berglund et al., 2003; Krafft et al., 2003). The double comparison technique described by Evans (1986) was used to control for crash violence. An interesting result emerged from examining the combination of the two parameters, sex and position. The relative risk was lowest for male drivers in comparison to female front seat passengers (RR: 0.5), and highest for female drivers in comparison to male front seat passengers (RR: 4.6). The study also showed an overall increased female relative risk of three times that of males, and a doubled risk for the driver position compared to the front seat passenger position independently of sex. This raises the question of why such large differences exist, and whether some of the studies in this thesis can give a clue as to the reasons behind these results.

Backset/cervical retraction

Many researchers have indicated an increased risk for neck injury in rear-end impacts if the head restraints are inadequately positioned, if the backset is large, and/or the head restraint is low (Olsson et al., 1990; Farmer et al., 1999; Chapline et al., 2000; Eriksson, 2004; Jakobsson, 2005). This provides a background for the geometric tests of seats and head restraints performed by car manufacturers and safety organisations such as IIHS. The aim is to keep proximity between the head and the head restraint, with the ideal situation being zero backset and the top of the head being level with the head restraint top. Eriksson (2004) showed that risk reduction was larger for a decrease in backset than for a decreased head-to-head restraint height. The results in study III regarding stationary backset support this conclusion, drivers had larger backset than front seat passengers. However, the same study showed that backset was clearly largest in the rear seat; the most likely reasons for this result are that rear seat occupants sit often higher compared to front seats and have fixed back rests with a more reclined angle compared to front seat occupants (see studies II and V). Berglund et al. (2003) have reported lower relative risks in rear seats compared to the driver's seat,

while Lövsund et al. (1988) and Otremski et al. (1989) found the same result in comparison to front seats. Jakobsson et al. (2000) reported increased driver risk compared to all other seat positions. One study (Krafft et al., 2003) showed increased risk for female rear seat passengers compared to male drivers. The results regarding backset size correlated to injury risk seem partially contradictory.

The females in studies III (stationary) and IV (driving) had lower backset than males; but in real world crashes, females suffer higher risks (Lövsund et al., 1988; Dolinis, 1997; Temming & Zobel, 1998; Farmer et al., 1999; Chapline et al., 2000; Krafft et al., 2003). This is a confusing result. Some other causes of the increased female risk have been suggested, such as different anatomy. Males have stronger neck muscles, as indicated by the ratio between head volume and neck cross-sectional area (Temming, 1998; Vasavada et al., 2008). Females have longer necks and larger heads relative to their own body weight than males (Temming, 1998). Neke circumference correlates well with peak head x-acceleration (Hell et al., 2002). Females generally have smaller values for neck circumference suggesting this may be a risk factor. They are also subjected to higher acceleration than males, due to their lower body mass (Viano, 2003). Other findings in the present thesis can add more information to the sex risk differences.

As demonstrated in study II, females sit differently to males; they sit higher and closer to the steering wheel, and their back rest angle is more upright. This means that females will have a slightly higher horizontal shear stress component to the spine in rear-end impacts compared to males. Female seat proximity to the steering wheel and foot pedals is in line with previous findings by other researchers (Parkin et al., 1995; Cullen et al., 1996; McFadden et al., 2000; Porter & Porter, 2001; Welsh et al., 2003). Study III demonstrates that when an occupant sits in a more slouched posture, backset will increase and cervical retraction capacity will decrease in comparison to the self-selected posture. In the same study, mean backset difference between driver and front seat passenger was shown to be 32 mm (males 37 mm, females 27 mm). This finding was solely dependent on the difference between holding the hands on the steering wheel ("10 minutes to 2" position) compared to holding the hands in the lap.

Study IV was a comparison of stationary backset (study III) for drivers and a study of backset during driving. The results in both studies showed the same pattern for stationary backset; self-selected posture had the highest retraction ROM values and erected posture the lowest. However, the mean stationary backset in study IV was 2-4 mm higher than in study III. Study IV showed mean female driving backset to be 73 mm (sd=23 mm) and male 117 mm (sd=41 mm). This sex difference is similar to that found during stationary measurements; in comparison to females, males had a 42 mm larger backset under stationary conditions and a 44 mm larger backset when driving. The difference seems to be sex related, rather than due to the task of driving. The study also showed that driving backset was 44 mm larger for males compared to females. The difference between stationary and driving conditions is probably due to vision needs during driving; this assumption is supported by the fact that route 3 (driving in an urban area) had the highest mean values for both sexes. Stationary backset in slouched seated posture was 112 mm for males (sd=44 mm) and 63 mm for females (sd=31 mm). Anthropometric data in females; like hip width, waist circumference and weight was correlated to backset (r = 0.44-0.52). The result might indicate that the pelvis and lumbar spine lack seat back support. Slouched stationary backset was smaller than driving backset. The design of study IV does not automatically prove that driving backset corresponds to a slouched posture, but this could be an interesting topic for future studies. In order to more

accurately determine the occupant posture during driving, it is necessary to develop a measuring technique that can log both vertical and horizontal (backset) data simultaneously.

Finally, there are possible conflicts in seat and head restraint design between the head restraint and occupant posterior head proximity. Some females have pony-tails, larger hair-styles or hats (also males) that can interfere with the head restraint position. This is demonstrated in study V, for a subgroup of shorter occupants of both sexes. For these subgroups of occupants there is a possibility that the head is forced forward into a non-selected head resting position, which might increase static muscular tension in the neck region. This observation might be an explanation to the larger backset values during driving (head restraint in place) compared to stationary backset (head restraint removed).

Validation tools

Study V showed that the backset difference among the volunteers between driver and front passenger seat position (study III) was not reflected in the ISO, RCAR, and RCAR-IIWPG protocols. The differences in seating adjustments between males and females found in study II were also not reflected in the test protocols. The BioRID II sits with 4° more reclined back rest compared to the female volunteers. Seat back angle difference might be of particular importance because it probably affects backset size and cervical posture in humans.

There was low agreement between the BioRID II and the female volunteers in terms of stature; the BioRID II corresponded to a 96th percentile female in the volunteer group. The situation for weight was better, with the BioRID II representing a 69th percentile female. The BioRID II was also a better match for male values, representing a 35-45th percentile male in terms of stature and a 35th percentile male in terms of weight. The study results indicate the need for both a review of the test protocols and a global review of stature and weight for the next update of a male 50th percentile BioRID manikin. The most important findings of study V are the need for a female 50th percentile BioRID manikin and a re-evaluation of the ISO, RCAR, and RCAR-IIWPG protocols. In addition, study III showed that seated posture affects backset and cervical range of motion. Cervical joint mobility in humans is a combination of angular movement and sliding of the joint surfaces, while the BioRID II has capacity for only angular movement. This should be taken into consideration in future BioRID designs.

Analysis: End-range loading of joints

Both a slouched seated posture and having one's hands on the top of the steering wheel result in increased risk for end-range loading of the cervical spine segments.

This risk might dependent on two posture-related factors:

1) The degree of forward inclination of the upper thoracic spine (Th1-7). Contributing factors are:
   a. Hands on steering wheel
   b. Back rest angle
2) The occupant's visual needs and thereby head positioning

In rear-end impacts, the lower cervical segments may be loaded in extension and the upper in flexion as a result of passive cervical retraction. Full flexion of the upper spine (C0-2) can only be achieved during cervical retraction (Ordway et al., 1999). In their x-ray study they

demonstrated the C6-7 segment to be in a mid extension position and C5-6 in its midrange position during full cervical retraction. However, the seated posture of the subjects was with a lumbar roll support and with scapula contact to the chair back, i.e. in comparison the studied posture is more similar to a self-selected or erected posture in this thesis. If the x-rays would have been taken in a slouched posture, the lower cervical segments would be expected to be in a more extended position during cervical retraction.

The inclination of the upper thoracic spine depends on the pelvic/lumbar position. Banks et al. (2000) x-rayed a seated 50th percentile male for pelvic, lumbar, and lower thoracic spine while sitting in a comfortable driving position with his hands on the steering wheel. The lumbar position was compared to the fully flexed and extended lumbar movement. The authors reported that the pelvis was rotated rearward and the lumbar spine was close to full flexion while seated in a production car. Lumbar posture affects ROM in the neck, as shown by Bergqvist and Geurts (2005), who found that a flexed lumbar spine in a sitting (slouching) position was correlated to decreased cervical extension and increased flexion ROM. Increased lumbar lordosis showed the opposite results. No correlation was found between lumbar posture and retraction and protraction ROM. In another study, Black et al. (1996) found that lumbar flexion (slouched posture) resulted in extension in both lower and upper cervical spine. Extension in lumbar spine gave the opposite result. The self-selected posture in this study can be compared to the sitting head resting position described by Hanten et al. (2000). They studied differences in standing and sitting head resting position on 13 healthy males and 29 females. Males had a - 27 mm difference, and females 43 mm. Females had 39 mm higher horizontal distances in sitting head resting position compared to male. These findings in this study indicate that females might sit in a more slouched posture compared to males. Persson et al. (2007) reported data from fourteen healthy female test subjects. The results were; 60% of the total protrusion-retraction ROM took place in the neck down to C7, and 40% from Th1 down to Th12. Their study shows that the thoracic segmental mobility affects cervical total protrusion-retraction ROM. The thoracic spine is in a flexed position when an occupant assumes a slouched posture, and thereby reducing retraction ROM in the cervical spine as found in study III. Holding the hands high on the steering wheel, gives higher backset and probably contributes to a slouched posture of the upper thoracic spine, thus decreasing cervical ROM in retraction. The findings of study III show that decreased retraction and increased backset both imply increased risk for end-range loading of cervical joints.

As shown in Figure 5, facet orientation is strongly affected by seated posture. Deng et al. (2000) reported that facet joint planes that was more horizontally orientated were more prone to sheer loading in rear-end impact. This horizontal orientation is the case in slouched posture for the lower segments of the neck. Slouched posture is a result of the centre of gravity is located forward to the lumbar and thoracic vertebras. In Figures 5A and 5B, the C5-6 segment is closer to maximal extension; then to the erect posture shown in Figures 5C and 5D.

A more forward-inclining upper thoracic spine will increase vertical compression of the cervical spine compared to a more erect spine in rear-end impacts, according to the results of Matsushita et al. (1994). Vertical compression of the neck and horizontal shear loading together with extension of the lower cervical spine in rear-end impacts has been demonstrated by several researchers using a number of different study techniques (Kaneoka et al., 1997; Grauer et al., 1997; Yoganandan et al., 1998; Kaneoka et al., 1999; Deng et al., 2000; Luan et al., 2000; Cusick et al., 2001; Yoganandan et al., 2002; Stemper et al., 2004).

5A

5B

5C

5D

Figure 5. X-rays of a seated subject with hands held on a steering wheel. 5A and 5B are in a slouched posture, and 5C and 5D in an erect posture. 5A and 5C are in neutral or resting position, and 5B and 5D in a maximal retracted position. The line is drawn parallel with the facet joint planes of C5-6.

Figure 6A shows the same seated subject as in Figure 5 performing a maximal cervical extension by sitting with maximal lordosis and extended thoracic spine, while Figure 6B shows the same subject seated in maximal flexion of the cervical, thoracic and lumbar spine. The C5-6 facet plane orientation in Figure 6B resembles best that in Figures 5A, while that in Figure 6A resembles that in Figures 5C. This demonstrates that facet plane orientation in the lower neck is governed mainly by pelvic/lumbar and thoracic posture. The facet plane orientation at C5-6 is less affected by the retraction movement, both in slouched (5A and B) and erected posture (5C and D). The position of the upper cervical segments in the cervical spine is also affected by visual needs.

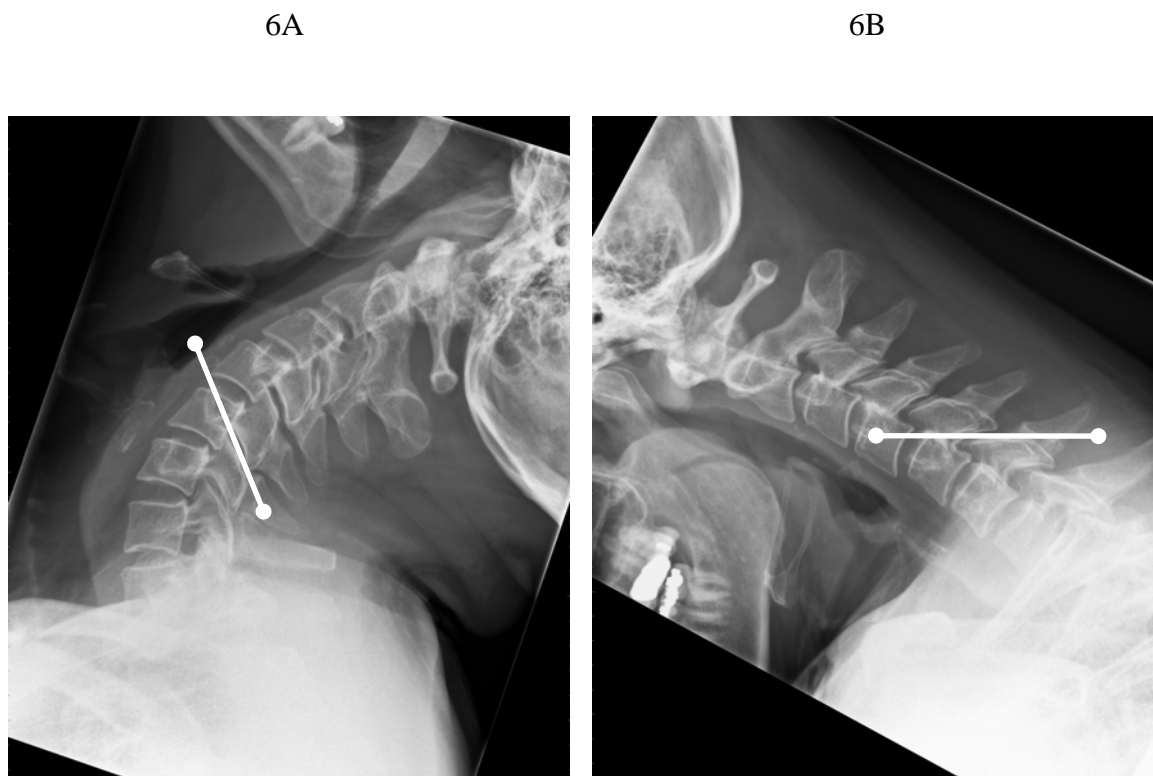6A   6B

Figure 6. Maximal extension (6A) and maximal flexion (6B) of the cervical spine. The line is drawn parallel with the facet joint planes of C5-6.

Does all this make sense? Imagine an occupant seated in a slouched posture in the front seat with an upright back rest, with all the postural effects described above (i.e. Figure 5A). The occupant is looking horizontally and directly ahead out of the car. If the seat back rest is reclined by 5°, the lower cervical spine moves from a close to end-range extension position to a more mid-joint position, and the upper cervical joints move in the same direction; however, the backset increases due to the forward-fixed eye point direction. This is supported by the work of Deng et al. (2000), who tested six cadavers in rear-end impacts in different seat back inclinations. They reported less lordotic cervical curvature, a more upward ramping of the thoracic spine, and a more relative rotation of each cervical segment C1-2 to C5-6 when seat back angle changed from 0° to 20° inclination. Lordosis was 20° higher in the 0° seat back inclination than in the 20°s inclination, and the 0° position resembled the slouched posture shown in Figure 5A. They also found that the relative rotation between each vertebral

segment was lower in the 0˚ inclination than in the 20˚ inclination; this result was echoed in study III (slouched and self-selected posture) of the present thesis. This might be an important explanation for why rear seat occupants in most studies have lower injury rates than front seat occupants, and males have lower injury rates than females. It may be the case that segmental joint end-range loading risk is just as important as backset size. These conclusions are supported by the results of studies I-III.

These findings indicates the need for further studies of seated posture and injury risk, and the development of better test methods and in the long run better protective systems in rear-end impacts.

CONCLUSIONS

The main conclusions of this thesis are:

1. Females have a threefold risk for a medically-impairing neck injury in rear-end impacts, in comparison to males.
2. Occupants in the driver's position have a doubled risk for a medically-impairing neck injury in rear-end impacts, in comparison to front seat passengers.
3. In comparison to males, females sit higher, closer to the steering wheel, and with more upright seat back rest.
4. Males have larger stationary backset than females in all postures and positions in the car.
5. The rear seat position results in the largest stationary backset, and the front passenger position the lowest.
6. Stationary backset is 32 mm greater in drivers than in front seat passengers (37 mm in males, 27 mm in females), due to hand/arm positioning on the steering wheel.
7. As posture changes from a self-selected posture to a slouched posture, stationary backset increases and cervical retraction capacity decreases.
8. Driving backset is greater than stationary backset (43 mm greater in males, 41 mm greater in females).
9. Driving backset in males is 44 mm greater than in females.
10. The BioRID II reflects a 96th percentile female in stature and a 69th percentile female in weight in the female volunteer group in this thesis. The BioRID II also sits with 4° more reclined back rest compared to the female volunteers.

Recommendations

- More high quality research focusing on seated posture and joint mechanism in seated ergonomics and rear-end impacts.
- Assessment and re-evaluation of the ISO, RCAR, and RCAR-IIWPG protocols.
- Development of a new 50th percentile female BioRID manikin.
- Developments of new automotive protection systems for rear-end impacts.

SWEDISH SUMMARY

Bakgrund: Nackskador som ett resultat av påkörningskrascher bakifrån är fortfarande ett stort problem för de drabbade och kostnadsmässigt för samhället. Den sista generationen av skyddssystem mot nackskador vid påkörning bakifrån, som t.ex. Volvos WHIPS och Saabs SAHR system har resulterat i nästan en 50 % förbättring jämfört med föregående generation av stols/huvudskydd. De åkandes beteende, som t.ex. sittande hållning och justering av stolen, kan påverka skaderisken.

Metod: Fem studier har genomförts. Studie I var en utfallsstudie av nackskador från ett försäkringsmaterial. Studie II-IV undersökte stolsjustering, de åkandes backset, cervikal retraktionsförmåga för förare och passagerare i olika sittande hållning och positioner i bilen, med bilen stillastående samt under körning. Slutligen, i studie V jämfördes resultaten från studie II och III med verktyg för fordonsprovning såsom BioRID dockan, samt protokoll från Internationella Standardiserings Organisationen (ISO), Research Council for Automobile Repairs (RCAR) och International Whiplash Prevention Group (RCAR-IIWPG).

Resultat: Kvinnliga förare och passagerare har en trefaldig risk jämfört med män att få en medicinsk funktionsnedsättning i nacken vid påkörningskrascher bakifrån. Förarpositionen hade dubbel risk jämfört med passagerarplatsen fram. Kvinnliga förare justerar förarstolen annorlunda jämfört med manliga förare; kvinnor sitter högre och närmare mot ratten och med mera upprättade ryggstöd. Försökspersonerna justerade förarstolen annorlunda än inställningarna i ISO, RCAR och RCAR-IIWPG protokollen; Män satt 61 mm och kvinnor 20 mm längre bort från ratten, och byggstödets vinkel var 1° mera upprättad hos män och 4° mera hos kvinnor jämfört med protokollen. I stillastående bil var backset högst i baksätet och lägst i passagerarplatsen fram. Män hade högre backset jämfört med kvinnor. Om föraren höll händerna på rattens övre del ökade backset med 26 mm för kvinnor och 37 mm för män jämfört om den åkande höll händerna i knät. Cervikal retraktionsförmåga minskade och backset ökade för båda könen då hållningen ändrades från självvald till hopsjunken hållning. Backset under körning var 41 mm större för kvinnor och 43 mm för män jämfört med backset i stillastående bil. BioRID II dockan motsvarade en 35-45 percentil man i kroppslängd och en 35 percentil man i vikt, en 96 percentil kvinna i kroppslängd och 69 percentil kvinna i vikt i försöksgruppen.

Konklusion: Skaderisken vid påkörningskrascher bakifrån skiljer mellan könen och olika positioner i bilen. Sittande hållning påverkar backset storlek och halsryggens retraktionsförmåga, och därmed risken för ytterlägesbelastning av halsryggens leder. Den nuvarande BioRID II dockan representerar inte den kvinnliga befolkningen storleksmässigt särskilt väl. ISO-, RCAR- och RCAR-IIWPG test protokollen tar inte hänsyn till könsskillnaderna. Detta avhandlingsarbete indikerar behovet av utvecklingen av en 50 percentil kvinnlig BioRID docka och en uppgradering av ISO-, RCAR- och RCAR-IIWPG test protokollen, samt fortsatt utveckling av nya säkerhetssystem vid påkörnings krascher bakifrån.

Nyckelord: bilstol, hållning, backset, cervikal retraktion, RCAR, BioRID, whiplash

ACKNOWLEDGEMENTS

This thesis would not have been possible without the support of several companies and organisations. I hereby express my deepest gratitude for the financial support that I have received from the Swedish Road Administration, Folksam Insurance Company, Volvo Cars, Autoliv Research, and finally my home department, the section of surgery within the Department of Surgical and Perioperative Sciences at Umeå University.

Money means a lot, but when it comes to the bottom line there are also many warm, friendly, supportive, and intelligent professionals to thank:

- Prof. Ulf Björnstig, for your great heart and mind that have helped me understand the processes of science and research in a way that would never otherwise have been possible.
- Associate Prof. Hans Stenlund, for making statistics into a helpful scientific tool.
- Prof. M Y Svensson, for good advice and constant support.
- Dr. Maria Krafft, for believing in my research ideas from an early stage, and providing support thereafter.
- Dr. Lotta Jakobsson, for valuable support and thoughts during the workflow process.
- Dr. Astrid Linder, for constructive and helpful support all the way.
- Prof. Claes Tingvall, for moral and statistical support.
- Dr. Per-Olof Bylund, for your critical reading of my drafts.
- Dr. Jan Petzäll for friendly support and help with my project finances.
- Kenneth Håkansson at the Swedish Motor Vehicle Inspection Company, for your cooperation in the studies.
- Magnus Björklund at Volvo Cars, for your constant help.
- Lennart Liedberg at Volvo Cars for ergonomic guidance and help.
- Johanna Björnstig, at AKMC for help with layout and graphic design.
- Lars Degerfeldt, PT, for reviewing the dissertation draft

And all my good friends back home;

Lars Håkan and Birgitta, Hans-Erik and Siv, Robban 1 and 2, Annica, Roger, Stefan and Helena, Leif and Carina, Bosse, and Evert and Cissa.

Finally, my family ; Annica, Filip, Martin, Marcella, and Magdalena,

who from time to time have not seen much of me .

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REFERENCES

Akioka, T., Harada, H., Katsuura, T., Kikuchi, Y. (1994) Ergonomic evaluation of automobile driver's seat. *Proceeding of Internal Congress on Physiological Anthropology* Kiel, Germany.

Aldman, B. (1986) An analytical approach to the impact biomechanics of the head and neck injury. *Proceeding of the 30th Annual AAAM Conf*erence, October 6-8, Montreal, Quebec, Canada, pp. 439-454.

Banks, R., Martini, J., Smith, H., Bowles, A., McNish, T., Howard, R. (2000) Alignment of the lumbar vertebra in driving posture. *Journal of Crash Prevention and Injury Control,* Vol. 2, No. 2, pp. 123-130.

Barancik, J.L., Kramer, C.F., Thode, H.C. (1989*) Epidemiology of motor vehicle injuries in Suffolk County, New York before enactment of the New York State seatbelt law.* Washington, DC: US Department of transportation, National Highway Traffic Safety. June 1989; DOT HS 807 638.

Barnsley, L., Lord, S., Bogduk N. (1994) Whiplash injury: Clinical review. *Pain,* Vol. 58, No. 3, pp. 283-307.

Barnsley, L., Lord, S., Wallis, B.J., Bogduk, N. (1995) The prevalence of chronic cervical zygapophysial joint pain after whiplash, *Spine,* Vol. 20, No. 1, pp. 20-25.

Bell, C., Adair, L., Popkin, B. (2002) Ethnic differences in the association between body mass index and hypertension, *American Journal of Epidemiology*, Vol. 155, No. 4, pp. 346–353.

Bellina, G. (1994) Evolution of the car seat as a system. *Proceedings of 4th International ATA Conference.* New design frontiers for more efficient, reliable, and ecological vehicles, Mars 16-18, Florence, Italy, pp. 16-18.

Berglund, A., Alfredsson, L., Jensen, I., Bodin, L., Nygren, Å. (2003) Occupant- and crash related factors associated with risk of whiplash injury. *Annals of Epidemiology,* Vol. 13, No. 1, pp. 66-72.

Berglund, A., Bodin, L., Jensen I., Wiklund, A., Alfredsson, L. (2006) The influence of prognostic factors on neck pain intensity, disability, anxiety and depression over a 2-year period in subjects with acute whiplash injury. *Pain,* Vol. 125, No. 3, pp. 244-256.

Bergqvist, M., Geurts, J. (2005) *Influence of lumbar spine posture on the neck range of motion and the change in lumbar spine posture in frontal impact – a volunteer study.* Master thesis 2005:44, Department of Applied Mechanics, Chalmers University of Technology, Gothenburg, Sweden.

Bilprovningen AB. (2008) (Swedish motor vehicle inspection company). http://www.bilprovningen.se/externt/en/bpweb.nsf/va_LookupWeb/4896C2F980A094D4C12 572200042A8DB!opendocument&m=1 [Accessed Mars 10 2008].

Black, K.M., McClure, P., Polansky, M. (1996) The influence of different sitting positions on cervical and lumbar posture. *Spine,* Vol. 21, No. 1, pp. 65-70.

Brault, J.R., Siegmund, G.P, Wheeler, J.B. (2000) Cervical muscle response during whiplash: Evidence of a lenghtening muscle contraction. *Clinical Biomechanics,* Vol. 15, No. 6, pp. 426-435.

Brault, J.R., Wheeler, J.B., Siegmund, G.P, Brault, E.J. (1998) Clinical response of human subjects to rear-end automobile collisions. *Archives of Physical Medicine and Rehabilitation*, Vol. 79, No. 1, pp. 72–80.

Cassidy, J.D., Carrol, L.J., Côté, P., Lemstra, M., Berglund, A., Nygren, Å. (2000) Effect of eliminating compensation for pain and suffering on the outcome of insurance claims for whiplash injury. *New England Journal Medicine,* Vol. 342, No. 16, pp. 1179-1186.

Cavelaars, A.E.J.M., Kunst, A.E., Geurts, J.J.M., Crialesi, R., Grötvedt, L., Helmert, U., Lahelma, E., Lundberg, O., Mielck, A., Rasmussen, N.K.R., Regidor, E., Sphuler, T.H., Mackenbach, J.P. (2000) Persistent variation in average height between countries and between socio-economic groups: An overview of 10 European countries. *Annals of Human Biology,* Vol. 27, No. 4, pp. 407-421.

Chapline, J., 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*, Vol. 32, No. 2, pp. 287–297.

Crowe, H.E. (1928) Injuries to the cervical spine. Paper presented at the meeting of the Western Orthopaedic Association, San Francisco, USA.

Cullen, E., Stabler, K.M., Mackay, G.M., Parkin, S. (1996) How people sit in cars: Implications for driver and passenger safety in frontal collisions – The case for smart restraints. *Proceedings of the 40th Conference of AAAM,* October 9–11, Vancouver, Canada, pp. 77-93.

Cusick, J.F., Pintar, F.A., Yoganandan, N. (2001) Whiplash syndrome: kinematic factors influencing pain patterns. *Spine,* Vol. 26, No. 11, pp. 1252–1258.

Deng, B., Begeman, P.C., Yang, K.H., Tashman, S. and King A.I. (2000) Kinematics of human cadaver cervical spine during low speed rear-end impacts. *Proceedings of the 44th Stapp Car Crash Conference*, November 6-8, Atlanta, United States. Paper No. 2000-01-SC13. Society of Automotive Engineers, Warrendale, United States, pp. 171-188.

Dolinis, J. (1997) Risk factors for whiplash in drivers: A cohort study of rear-end traffic crashes. *Injury*, Vol. 28, No. 3, pp. 173-179.

Drury, C.G., Coury, B.G. (1982) A methodology for chair evaluation. *Applied Ergonomics*, Vol. 13, No. 3, pp. 195–202.

Ebe, K., Griffin, M.J. (2001) Factors effecting static and seat cushion comfort, *Ergonomics*, Vol. 44, No. 10, pp. 901–921.

Edmondston, S., Henne, S.E., Loh, W., Ostvold, E. (2005) Influence of cranio-cervical posture on three-dimensional motion of the cervical spine. *Manual Therapy*, Vol. 10, No. 1, pp. 44–51.

Eriksson, L. (2004) *Influence of Head Restraint Position on Long-Term AIS 1 Neck Injury Risk.* Ph.D. dissertation, department of machine and vehicle systems, Chalmers University of Technology, Gothenburg, Sweden.

Eriksson, L., Boström, O. (1999) Assessing the influence of crash pulse, seat force characteristics, and head restraint position on NICmax in rear-end crashes using a mathematical BioRID dummy. *Proceeding of IRCOBI International Conference on the Biomechanics of Impacts,* September 23-24, Barcelona, Spain, pp. 213-223.

Evans, L. (1986) Double paired comparison – A new method to determine how occupant characteristics affect fatality risk in traffic crashes. *Accident Analysis and Prevention,* Vol. 18, No. 3, pp. 217-227.

Farmer, C.M., Wells, J.K., Werner, J.V. (1999) Relationship of head restraint positioning to driver neck injury in rear-end crashes. *Accident Analysis and Prevention*, Vol. 31, No. 6, pp. 719–728.

Fejer, R., Ohm Kyvik, K., Hartvigsen, J. (2006) The prevalence of neck pain in the world population: a systematic critical review of the literature. *European Spine Journal,* Vol. 15, No. 6, pp. 834-848.

Freeman, M.D., Croft, A.C., Rossignol, A.M. (1998) ""Whiplash associated disorders: redefining whiplash and its management" by the Quebec Task Force. A critical evaluation". *Spine,* Vol. 23, No. 9, pp. 1043–1049.

Grauer, J.N., Panjabi, M.M., Cholewicki, J., Nibu, K., Dvorak, J. (1997) Whiplash produces an S-shaped curve of the neck with hyperextension at lower levels. *Spine*, Vol. 21, No. 22, pp. 2489-2494.

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 of Physical Medicine and Rehabilitation,* Vol. 81, No. 1, pp. 62-66.

Hell, W., Schick, S., Langwieder, K., Zellmer, H. (2002) Biomechanics of cervical spine injuries in rear end car impacts: Influence of car seats and possible evaluation criteria. *Traffic Injury Prevention,* Vol. 3, No. 2, pp. 127-140.

Hohl, M. (1974) Soft tissue injuries of the neck in automobile accidents: factors influencing prognosis. *Journal of Bone and Joint Surgery,* Vol. 56A, No. 8, pp. 1675-1682.

Huelke, D.F., Marsh, J.C. (1974) Analysis of rear-end accident factors and injury patterns. *Proceedings of 18th Association for the Advancement of Automotive Medicine Conference AAAM* Toronto, Ontario, Canada, pp. 174-199.

IBGE, Instituto Brasileiro de Geografia e Estatística (Brazilian Institute of Geography and Statistics). (2006) *Pesquisa de orçamentos familiares 2002-2003*, Rio de Janeiro, Brazil.

Available in Portuguese at: http://www.ibge.gov.br/home/estatistica/populacao/condicaodevida/pof/2003medidas/pof2003medidas.pdf [Accessed 10 Mars 2008].

IEA, International Ergonomics Association. (2007) *Definition of Ergonomics*. Available at: http://www.iea.cc [Accessed 10 Mars 2008].

IIHS, Insurance Institute for Highway Safety. (2007) *Head restraints*: Volvo, Available at: http://www.iihs.org/ratings/head_restraints/headrestraints.aspx?volvo [Accessed 10 Mars 2008].

ISO 7730. (1994) Moderate thermal environments—determination of the PMV and PPD indices and specification of the conditions for thermal comfort. *International Standards Organisation*, Geneva, Switzerland.

ISO 2631-1. (1997) Mechanical vibration and shock—evaluation of human exposure to whole-body vibration—Part 1: General requirements. *International Standards Organisation,* Geneva, Switzerland.

Jakobsson, L. (2005) Field analysis of AIS 1 neck injuries in rear-end car impacts—injury reducing effect of the WHIPS seat. *Journal of Whiplash Related Disorders,* Vol. 3, No. 2, pp. 37–53.

Jakobsson, L., Lundell, B., Norin, H., Isaksson-Hellman, I. (2000) WHIPS - Volvo's whiplash protection study. *Accident Analysis and Prevention,* Vol. 32, No. 2, pp. 307-319.

Jonsson, B., Stenlund, H., Svensson, M.Y., Björnstig, U. (2008) Seat adjustment – capacity and repeatability among occupants in a modern car. *Ergonomics,* Vol. 51, No. 2, pp. 232-241.

Kaneoka, K., Ono, K., Inami, S., Hayashi, K. (1999) Motion analysis of cervical vertebrae during whiplash loading. *Spine,* Vol. 24, No. 8, pp. 763-770.

Kaneoka, K., Ono, K., Inami, S., Yokoi, N., Hayashi, K. (1997) Human cervical spine kinematics during whiplash loading. *Proceedings of International Conference on New Frontiers in Biomechanical Engineering*, July 18-19, Tokyo, Japan, pp. 265-268.

Kihlberg, J.K. (1969) Flexion-torsion neck injury in rear impacts. *Proceeding of the 13th AAAM Annual Conference,* University of Minnesota, Minneapolis, United States, pp.1-17.

Krafft, M. (2002) When Do AIS 1 Neck injuries result in long term consequences? Vehicle and human factors. *Traffic Injury Prevention*, Vol. 3, No. 2, pp. 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,* Vol. 4, No. 2, pp. 136-140.

Krafft, M., Kullgren, A., Ydenius, A., Tingvall, C. (2002) Influence of crash pulse characteristics on whiplash associated disorders in rear impacts – Crash recording in real life crashes. *Traffic Injury Prevention,* Vol. 3, No. 2, pp. 141-149.

Kullgren, A. (1998) *Validity and Reliability of Vehicle Collision Data, Crash Pulse Recorders for Impact Severity and Injury Risk Assessment in Real-Life Frontal Impacts*, Ph.D. dissertation in medical science, Karolinska Institute, Stockholm, Sweden.

Lord, S.M., Barnsley, L., Wallis, B.J., Bogduk, N. (1996) Chronic cervical zygapophysial joint pain after whiplash – A placebo-controlled prevalence study. *Spine,* Vol. 21, No. 15, pp. 1737-1745.

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*, (Bristol, Avon), Vol. 15, No. 9, pp. 649–657.

Lövsund, P., Nygren, Å., Salen, B., Tingvall, C. (1988) Neck injuries in rear end collisions among front and rear seat occupants. *Proceedings of the International IRCOBI Conference on the Biomechanics of Impacts*, September 14-16, Bergisch Gladbach, Germany, pp. 319-325.

Matsushita, T., Sato, T.B., Hirabayashi, K., Fujimura, S., Asazuma, T., Takatori, T. (1994) X-ray study of the human neck motion due to head inertia loading. *Proceedings of the 38th Stapp Car Crash Conference*, SAE Paper 942208, Society of Automotive Engineers, Inc., Warrendale, PA, United States, pp. 55–64.

McFadden, M., Powers, J., Brown, W., Walker, M. (2000) Vehicle and driver attributes affecting distance from the steering wheel in motor vehicles. *Human Factors,* Vol. 42, No. 4, pp. 676-682.

Olsson, I., Bunketorp, O., Carlsson, G., Gustavsson, C., Planath, I., Norin, H., Ysander, L. (1990) An in-depth study of neck injuries in rear end collisions. *Proceedings of the International IRCOBI Conference on the Biomechanics of Impacts, IRCOBI*, September 12-14, Bron, France, pp. 269–280.

O´Neill, B., Haddon, W., Kelly, 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*, Vol. 62, No. 3, pp. 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. *Proceedings of 41th Stapp Car Crash Conference,* Paper no. 973340, Society of Automotive Engineers, Inc., Warrendale, PA, United States, pp 339–356.

Ordway, N.R., Seymour, R.J., Donelson, R.G., Hojnowski, L.S., Edwards, W.T. (1999) Cervical flexion, extension, protrusion and retraction. A radiographic segmental analysis. *Spine*, Vol. 24, No. 3, pp. 240-247.

Otremski, I., Marsch, J.L., Wilde, B.R., McLardy Smith, P.D., Newman, R.J. (1989) Soft tissue cervical spinal injuries in motor vehicle accidents. *Injury*, Vol. 20, No. 6, pp. 349-351.

Panjabi, M.M., Ito, S., Pearson, A.M., Ivancic, P.C. (2004) Injury mechanisms of the cervical intervertebral disc during simulated whiplash. *Spine,* Vol. 29, No. 11, pp. 1217-1225.

Park, S.J., Lee, Y.S., Nahm, Y.E., Lee, J.W., Kim, J.S. (1998) Seating physical characteristics and subjective comfort: design considerations. *Special Publication of Society of Automotive Engineering,* Paper No. SP-1358, Society of Automotive Engineers, Inc., Warrendale, PA, United States, p. 51-62.

Parkin, S., MacKay, G.M., Cooper, A. (1995) How drivers sit in cars. *Accident Analysis and Prevention,* Vol. 27, No. 6, pp.777-783.

Persson, R., Hirschfeld, H., Nilsson-Wikmar, L. (2007) Associated sagittal spinal movements in performance of head pro- and retraction in healthy women: A kinematic analysis. *Manual Therapy*, Vol. 12, No. 2, pp. 119-125.

Pettersson, K., Hildingsson, C., Toolanen, G., Fagerlund, M., Björnebrink, J. (1997) Disc pathology after whiplash injury. A prospective magnetic resonance imaging and clinical investigation. *Spine*, Vol. 22, No. 3, pp. 283-287.

Porter, J.M., Porter, C.S. (2001) *Occupational accommodation; An ergonomic approach in an introduction to modern vehicle design*, Happian-Smith, J, Butterworth-Heineman Ltd, Oxford, United Kingdom, 2001, pp. 233-276, ISBN 0750650443.

Quinlan, K.P., Annest, J.L., Myers, B., Ryan, G., Hill H. (2004) Neck strains and sprains among motor vehicle occupants—United States, 2000. *Accident Analysis and Prevention,* Vol. 36, No. 1, pp. 21–27.

SCB, Statistiska Central Byrån (Statistics Sweden). (2005) *Vikt och längd i befolkningen*, (Weight and stature in the population). Stockholm, Sweden. Available in Swedish at: http://www.scb.se/templates/tableOrChart____47966.asp [Accessed 10 Mars 2008].

SCB, Statistiska Central Byrån (Statistics Sweden). (2008) *Sveriges befolkning 31/12 2007*. (Swedish population 31/12 2007). Stockholm, Sweden. Available in Swedish at: http://www.scb.se/templates/tableOrChart____78315.asp [Accessed 10 Mars 2008].

Siegmund, G., King. D., Lawrence. J., Wheeler. J. (1997) Head/neck kinematic response of human subjects in low-speed rear-end collisions, *Proceedings of the 41st Stapp Car Crash Conference*, Paper No. 973341, Society of Automotive Engineers, Inc., Warrendale, PA, United States, pp. 357-385.

SIKA, Statens Institut för Kommunikations Analys, (Swedish Institute for Transport and Communications Analysis). (2007) *Distances covered in 2006*. Publication 2007:11. Ostersund, Sweden. Available at: http://www.sika-institute.se/Doclib/2007/SikaStatistik/ss_2007_11.pdf [Accessed 2 Jan 2008].

Spitzer, W., Skovron, M.L., Salmi, L.R., Cassidy, J.D., Suissa, S., Zeiss, E. (1995) Scientific monograph of the Quebec task force on whiplash-associated disorder; Redefining "Whiplash" and its management. *Spine Supplement*, Vol. 20, No. 8, S1-S73.

Stemper, B.D., Yoganandan, N., Pintar, F.A. (2004) Gender- and region dependent local facet joint kinematics in rear impacts: implications in whiplash injury. *Spine*, Vol. 29, No. 16, pp. 1764–1771.

Sterner, Y., Toolanen, G., Gerdle, B., Hildingsson, C. (2003) The incidence of whiplash trauma and the effects of different factors on recovery. *Journal of Spinal Disorders & Techniques,* Vol. 16, No. 2, pp. 195-199.

Svensson, M.Y., Boström, O., Davidson, J., Hansson, H-A., Håland, Y., Lövsund, P., Sunesson, A., Säljö, A. (2000) Neck injury in car collisions – a review covering a possible injury mechanism and the development of a new rear-impact dummy. *Accident Analysis and Prevention,* Vol. 32, No. 2, pp. 167-175.

Temming, J. (1998) Human factors data in relation to whiplash injuries in rear end collisions of passenger cars. *SAE International Congress and Exposition,* Paper No. 981191, Society of Automotive Engineers, Warrendale, PA, United States.

Temming, J., Zobel, R. (1998) Frequency and risk of cervical spine distortion injuries in passenger car accidents; Significance of human data. *Proceedings of the 1998 International IRCOBI Conference on the Biomechanics of Impact.* September 16-18, Gothenburg, Sweden, pp. 219-233.

Thomas, C., Faverjon, G., Harteman, F. (1982) Protection against rear-end accidents, *Proceedings of the 1982 IRCOBI Conference on Biomechanics of Impacts.* September 9-10, Cologne Germany, pp. 17-29.

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*, Vol. 41, No. 1, pp. 114-121.

Viano, D. (2003) Seat influences on female neck responses in rear crashes: A reason why women have higher whiplash rates, *Traffic Injury Prevention*, Vol. 4, No. 3, pp. 228–239.

Vägverket (Swedish road administration). (2008) Holders of driving licences. Available in Swedish from: http://www.vv.se/templates/page3wide____4015.aspx [Accessed 6 April 2008].

Welsh, R., Clift, L., Morris, A., Cook, S., Watson, J. (2003) *Assessment of cars for small drivers*, Department of transportation. Loughborough University, United Kingdom. ESRI-report (PPAD 9/33/85).

Whiplashkommissionen (Swedish commission on whiplash-related injuries). (2005) Slutrapport (Final report). ISBN 91-975655-0-4 Sandvikens tryckeri, Sandviken, Sweden . Available also from: http://www.whiplashkommissionen.se/rapporter/rapporter.html [Accessed Mars 2008].

Yang, K.H., Begeman, P.C. (1996) A proposed role for facet joints in neck pain in low to moderate speed rear end impacts, Part I: Biomechanics. *Proceedings of 6th Symposium, Injury Prevention through Biomechanics,* Wayne State Univ. Detroit, United States, pp. 59–63.

Yang, K.H., King, A.I. (2003) Neck kinematics in rear-end impacts. *Pain Research & Management,* Vol. 8, No. 2, pp. 79–85.

Yoganandan, N., Cusick, J.F., Pintar, F.A., Rao, R.D. (2001) Whiplash injury determination with conventional spine imaging and cryomicrotomy. *Spine,* Vol. 26, No. 22, pp. 2443–2248.

Yoganandan, N., Pintar, F.A., Cusick, J.F. (2002) Biomechanical analyses of whiplash injuries using an experimental model. *Accident Analysis and Prevention,* Vol. 34, No. 5, pp. 663–671.

Yoganandan, N., Pintar, F.A., Cusick, J.F., Kleinberger, M. (1998) Head-neck biomechanics in simulated rear impact. *Proceedings of 42nd Annual Association for the Advancement of Automotive Medicine Conference*, October 5-7, Charlottesville, Unites States, pp. 209-231.

Örtengren, T., Hansson, H-A., Lövsund, P., Svensson, M.Y., Sunesson, A., Säljö, A. (1996) Membrane leakage in spinal ganglion nerve cells induced by experimental whiplash extension motion: A study in pigs. *Journal of Neurotrauma,* Vol. 13, No. 3, pp.171-180.