THESIS FOR THE DEGREE OF DOCTOR OF PHILOSOPHY

Whiplash Associated Disorders in Frontal and Rear-End Car Impacts

Biomechanical Guidelines and Evaluation Criteria based on Accident Data and Occupant Modelling

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ABSTRACT

Whiplash associated disorders, also called whiplash injuries or AIS1 neck injuries, represent one of the most significant types of injury in car crashes regarding both frequency and long-term consequences. The injury mechanisms are not fully understood, thus making it difficult to design and evaluate protection systems in cars. The highest risk is found in rear-end impacts, but the largest number of incidents is found in frontal impacts.

This thesis focuses on occupants in frontal as well as rear-end impacts and presents an approach leading to development of AIS1 neck injury protection systems. Several parameters influencing risk of AIS1 neck injuries in frontal and rear-end impacts are identified by analysing accident data. Subsets of Volvo's accident database are used for the analyses. Additional information was collected for two of the studies regarding details in sitting posture and neck symptoms including duration, and in one study crash pulse information from on-board crash recorders is analysed. Field impact scenarios, with different AIS1 neck injury risk, are simulated using computer models and sled tests to get additional data on the loading conditions in the human body and to enable the identification of responses correlating to relative injury risk. Biomechanical guidelines have been derived, and evaluation criteria are suggested for rear-end impacts. A whiplash mitigation seat, WHIPS (Whiplash Prevention System), was developed for rear-end impacts, based on this study. The AIS1 neck injury reducing effect of WHIPS is evaluated, demonstrating not only the significant efficiency of the seat but also the feasibility of the approach chosen.

For frontal as well as rear-end impacts, women are found to have a higher AIS1 neck injury risk. In rear-end impacts, increased occupant stature is related to increased injury risk, while in frontal impacts, decreased occupant weight is related to increased injury risk. Prior neck problems is found to be a risk factor irrespective of impact direction. Sitting posture, however, is influential with respect to different parameters in frontal and rear-end impacts. In frontal impacts, change of velocity and deceleration based measures are identified as possible impact severity measures using crash recorder data. In rear-end impacts, the biomechanical guidelines are to reduce occupant acceleration, reduce relative spine movements and reduce occupant rebound. In order to reflect the biomechanical guidelines in sled tests, evaluation criteria are suggested. Concerning frontal impacts, initial relative neck movements are suggested to be kept as small as possible in this first step.

The significance of this thesis is twofold. Firstly, identification of various influential parameters and visualisation of possible injury causing kinematics, adding knowledge to the puzzle of understanding AIS1 neck injuries in frontal and rear-end impacts. Secondly, development and evaluation of a feasible and robust low-risk approach, implementing a safe direction in the development of protection systems for an injury type where the knowledge of injury mechanisms is limited.

Keywords: Neck injuries, Whiplash, Frontal impacts, Rear-end impacts, WHIPS

LIST OF PAPERS

This thesis is based on the following scientific papers.

I. Jakobsson, L., Lundell, B., Norin, H., Isaksson-Hellman, I. **WHIPS-Volvo's Whiplash Protection Study**. Accident Analysis and Prevention, Vol. 32, 2000, pp. 307-319

II. Jakobsson, L., Norin, H. **Suggestions for Evaluation Criteria of Neck Injury Protection in Rear-end Car Impacts**; Traffic Injury Prevention, Vol. 3 (3), 2002, pp. 216-223

III. Jakobsson, L., Norin, H. Svensson, M. Y. **Parameters Influencing AIS1 Neck Injury Outcome in Frontal Impacts**; Traffic Injury Prevention (accepted)

IV. Jakobsson, L. **Evaluation of Impact Severity Measures for AIS 1 Neck Injuries in Frontal Impacts using Crash Recorder Data**, International Journal of Crashworthiness, Vol. 9 (1), 2004

V. Jakobsson, L., Lundgren, K., Norin, H., Svensson, M.Y. **Evaluation Criteria for AIS1 Neck Injuries in Frontal Impacts – a Parameter Study Combining Field Data and Madymo Modeling**, Traffic Injury Prevention (submitted)

VI. Jakobsson, L. **Field Analysis of AIS1 Neck Injuries in Rear-End Car Impacts – Injury Reducing Effect of WHIPS**, Journal of Whiplash and Related Disorders (submitted)

The study design, analyses, conclusions and opinions expressed in this thesis are my own. Irene Isaksson-Hellman carried out the statistical computations in (I) and provided support in the selection of statistical methods in (III), (IV) and (VI). The tests in (I) and (II) were performed at Volvo Cars Safety Centre. The mathematical model in study (V) was run by Kristina Lundgren.

LIST OF ABBREVIATIONS AND TERMS

AIS	Abbreviated Injury Scale (AAAM, 1985), injury scale of risk for threat to life. AIS1 = minor and AIS6= fatal.
ARSV	Average Relative Spine Velocity; an evaluation criterion.
BETA	Max. Δv multiplied by Polmax; an impact severity measure.
BioRID	Biofidelic Rear Impact Dummy. BioRID I is the first prototype version and BioRID II is a production version of the final prototype BioRID P3.
C1-C7	Cervical vertebrae; C1 is the upper and C7 is the lowest vertebra in the neck.
DARR	Digital Accident Research Recorder; a crash pulse recorder in Volvo cars.
DeltaV, Δv	Change of velocity.
DeltaVmax, max Δv	Maximum change of velocity; an impact severity measure.
EBS	Equivalent Barrier Speed; an impact severity measure (Nilsson-Ehle et al. 1982).
EuroNCAP	European New Car Assessment Program; a rating program.
Hybrid III	A frontal impact crash test dummy.
IIWPG	International Insurance Whiplash Prevention Group.
ISO	International Organisation for Standardisation
MADYMO	MAthematical DYnamic MOdel; MBS-modelling software by TNO, the Netherlands.
Macc	Maximum deceleration, an impact severity measure.
Mvacc	Mean deceleration, an impact severity measure.
NIC	Neck Injury Criterion; NIC_{max} for retraction (rear-end impacts) and NIC_{min} for protraction (frontal impacts).
N_{IJ}	A neck injury criterion estimating risk of injury from axial forces and bending moments to the upper neck region.
Nkm	A neck injury criterion estimating risk of injury from shear forces and bending moments to the upper neck region.
Polmax	Maximum deceleration of a third degree polynomial approximation; an impact severity measure.
RID2	Rear-end Impact Dummy developed in the EU "Whiplash" project.
T1	Thoracic vertebrae, numbered from the top downwards.
WHIPS	Whiplash Protection Study/Whiplash Protection System; Volvo's anti-whiplash seat.
WAD	Whiplash Associated Disorders.

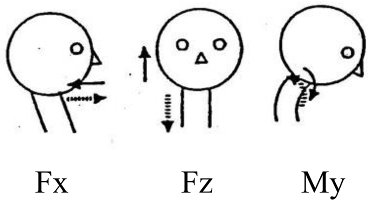
Biomechanical guidelines	General aims for mitigating risk of injuries.
Biofidelity	Correspondence to humanlike kinematics and characteristics.
Evaluation criteria	A measure quantifying injury risk, not necessarily based on biological injury mechanism research.
Impact severity measure	A measure of the crash violence, correlating to injury risk.
Kinematics	Movements.

Load limiter	A device in the belt system to control the force characteristics of the belt during a crash.
Neck link angle	Local rotation of upper (head-C1) and lower (C7-T1) neck, respectively, related to the angle of a line (so called neck link) between the two points.
Occipital condyles	The cervical spine's interface to the base of the skull.
Occupant modelling	Mathematical simulations or mechanical testing using human substitutes.
Passing symptoms	Neck symptoms lasting shorter than three months.
Persistent symptoms	Neck symptoms of a certain degree lasting more than one year.
Pre-tensioner	A device in the belt system to pre-tension the belt.
Protraction	Neck kinematics; head translating forward relative to chest.
Retraction	Neck kinematics; head translating rearward relative to chest.
Risk (rate)	Relative frequency. In papers (III) and (VI), the word rate is used instead of risk.

Fx - shear forces

Fz - tension/compression forces

My - bending moment



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Göteborg, January 2004 Lotta Jakobsson

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INTRODUCTION

Neck disorders resulting from transportation have a long history. A phenomenon called “concussion of the spine” was reported as early as 1862 (Report of the Commission, 1862). At this time the transportation causing the neck problems was the railroad. A medical doctor, Erichsen, described in “On Railroad and Other Injuries of the Nervous System” symptoms, signs and consequences very similar to what we today see as a result from car crashes (Erichsen, 1866, Keller and Chappell, 1996).

Today, Whiplash Associated Disorders (WAD) resulting from car crashes is one of the most important injury types with respect to frequency, cost to society and long term suffering for the occupant. WAD, often called whiplash injuries or AIS1 neck injuries, represent a broad set of symptoms and signs, such as neck pain, neck stiffness, weakness in the shoulder area, dizziness, headache, and memory loss (Spitzer et al. 1995). In this thesis, the term AIS1 neck injuries will be used mainly.

In 1928, the word “whiplash” was introduced by Harold Crowe at a conference describing possible neck motion in eight cases of neck injuries resulting from motor vehicle crashes. However "whiplash" was not mentioned in the literature until later and there is still an ongoing discussion whether the word should be used or not as a descriptor of the injury type, and if it is specifically for rear-end impacts (Crowe 1964). Nevertheless, the word whiplash serves to some extent to describe the neck kinematics during an impact.

During a rear-end car impact the struck vehicle is subjected to a forward acceleration and the car occupant is pushed forward by the seat backrest. The head, usually unsupported, lags behind (due to its inertia) forcing the neck into a swift extension motion. In a later phase, the head moves forward relative to the torso, into a flexion motion (Figure 1).

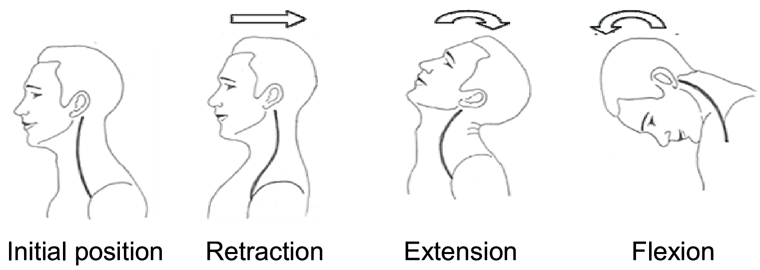

Figure 1 - General neck kinematics in a rear-end impact.

The term whiplash has also been used in the literature for the neck motion in frontal and side impacts. In frontal collisions, the neck usually experiences the same type of inertial loading from the head as it does in rear-end impacts, but in the opposite direction (Figure 2). During the initial phase of these neck loading situations, the head normally undergoes an initial horizontal translational displacement relative to the torso. The movement in frontal impacts is called neck protraction (Figure 2) and the direction in rear-end impacts is called neck retraction (Figure 1).

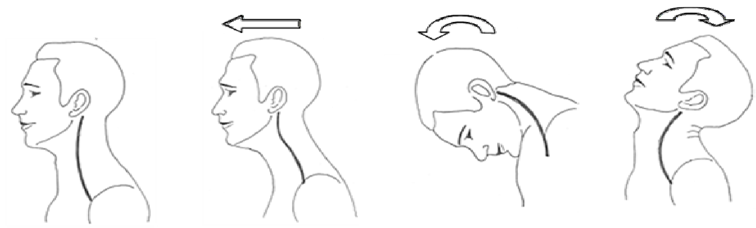

Figure 2 - General neck kinematics in a frontal impact.

Despite intense research activities, limited knowledge has been established about the injury site and what injury may give rise to the vast number of symptoms and signs reported as an AIS1 neck injury. In most of the cases, the neck problems will last for a short time. Nygren (1984) showed that one out of ten occupants, after reporting neck injury to an insurance company, sustained long-term disability (determined at least one year after the collision). Based on a review of the literature on neck symptoms, Barnsley et al. (1994) found that most patients recover in 2 to 3 months after the impact, but about 25% develop chronic pain, and 10% constant and severe pain. In Sweden (with almost 9 million inhabitants) the insurance companies have estimated that 25 000 occupants sustain AIS1 neck injuries annually. About 25% of these will be absent on sick leave one week or more. About 1500 (6%) of these will develop permanent disability (Whiplashkommissionen, 2003).

Statistics from several countries show an increase in the occurrence of neck injuries in car collisions in recent decades. In the UK and in Germany the initial AIS1 neck injury incidence has approximately doubled over the last two decades (Morris and Thomas 1996, Langwieder and Hell 1996). In Sweden, Holm et al. (1999) found that the proportion of medical impairment due to AIS1 neck injuries had increased from 16% in 1989 to 28% in 1994. Similarly, von Koch et al. (1994) found that the amount of medical impairment of the neck (≥10% disability) due to passenger car crashes in Sweden had increased from 19% in 1977 to 47% in 1991. In Sweden, 60% of the traffic injuries causing disability 1990-1995 were AIS1 neck injuries (Krafft 1998b).

The highest risk is found when the car is struck from behind. Morris and Thomas (1996) found that for UK occupants the risk of initial AIS1 neck injury was 38% in rear-end impacts, while only 15% in frontal and 15% in lateral impacts. Lundell et al. (1998a) reported similar data from Volvo's accident database in Sweden: 34% in rear-end impacts, 16% in frontal impacts, and 11% in lateral impacts. Considering the number of occupants with AIS1 neck injuries, frontal impacts may be considered as important. According to German accident data (Temming and Zobel 2000) 38% of the AIS1 neck injury cases are single frontal impacts, with an injury risk of 12%, while 15% of the injury cases are single rear-end impacts, with an injury risk of 26%. In a UK database, as many as 55% of the AIS1 neck injuries are from frontal impacts as compared to 13% in rear-end impacts (Morris and Thomas 1996). In Volvo's database, 34% of the AIS1 neck injuries are from single frontal impacts and 17% are from single rear-end impact (Jakobsson 1998). For AIS1 neck injuries leading to disability, Krafft et al. (1997) found that in Sweden 64% occurred in rear-end impacts and 23% in frontal impacts. The collection criteria varies between the databases, but the figures show that even if the risk of AIS1 neck injury is less in a frontal impact, the number of injured occupants is great because of the large number of frontal impacts. In order to reduce the total number of AIS1 neck injuries, it is very important to consider every type of crash configuration. This thesis focuses on frontal and rear-end impacts.

Accident data

Rear-end impacts

Many reports have presented a possible correlation, based on accident data, between the risk of AIS1 neck injuries in rear-end impacts and occupant and vehicle related parameters. Women have been shown to have a higher risk of injury as compared to men: figures such as 60% (Chapline et al. 2000, Morris and Thomas 1996) and 140% (Temming and Zobel 2000) are reported. In addition, women are at a higher risk regarding neck disability. Given an initial AIS1 neck injury, the risk of long-term symptoms was 44% higher for women as compared to men (Krafft 1998a). The risk of AIS1 neck injuries varies with age. The initial AIS1 neck injury risk is greater for the age group 20 to 50 than for the older and younger age groups (Lundell et al. 1998a, Temming and Zobel 2000). Krafft (1998a) reported the highest risk of long-term symptoms for occupants between 41-60 years. Lundell et al. (1998a) and Temming and Zobel (2000) studied initial AIS1 neck injury rate comparing stature and gender. Their data indicated that injury risk increases with increasing stature for both genders. Minton et al. (1997) found no correlation between disability and occupant stature and weight, given an initial AIS1 neck injury.

Several studies indicate that front seat occupants are at higher risk than rear seat occupants (States et al. 1972, Carlsson et al. 1985, Lövsund et al. 1988, Berglund et al. 2003). Berglund et al. (2003) also identified the driver to have a significantly higher risk as compared to the front seat passenger. A head-to-head restraint distance of more than 10 cm was found related to neck symptoms lasting more than one year (Olsson et al. 1990). In contrast, Minton et al. (1997) found that, for the long-term outcome, small horizontal distance was significantly associated with higher disability. Morris and Thomas (1996) found no overall benefit of head restraints, rigid or adjustable. In the latter study, the occupant sitting posture in relation to the head restraint was not known. In a study by Chapline et al. (2000), it was found that females with adequately positioned head restraints were significantly less likely to report neck pain than females with poorly positioned head restraints, the height of the head restraint being the primary factor. Viano and Gargan (1996) measured head-to-head restraint distances for drivers stopping at traffic lights and found that only 10% of drivers had the head restraint in the most favourable position to prevent neck extension. Nygren et al. (1985) found that with adjustable head restraints, 83% of drivers had the head restraints in the lowest or second lowest position. Cullen et al. (1996) reported that most adjustable head restraints were left in the lowest position. Nygren et al. (1985) showed that the vertical relationship between head and head restraint is important, and emphasised that there are parameters other than head restraint position that are important in reducing AIS1 neck injuries in rear-end impacts. The analysis of 163 occupants involved in a rear-end impact in Volvo cars during 1988-1989 indicates that horizontal distance between head and head restraint, car structure engagement, head sideways-rotated posture, reclined seat backrest and possibly head restraint stiffness could influence AIS1 neck injury outcome (Jakobsson et al. 1994, Jakobsson 2000). Sturzenegger et al. (1994 and 1995) also found that rotated and inclined head posture at the moment of impact was associated with more severe symptoms initially as well as persistence of symptoms one year after the collision.

AIS1 neck injuries in rear-end impacts are reported in a wide range of impact severity (Jakobsson 1998, Otte et al. 1997). It has been found that people sustain neck injuries frequently, even in crashes with very low impact severity (Olsson et al. 1990, Otte et al. 1997, Morris and Thomas 1996). Hell et al. (1998) reported that more than 85% of the AIS1 neck injuries in rear-end impacts occurred below 25 km/h. Using crash pulse recorder data, the effect of crash pulse characteristics has been emphasised by Krafft et al. (2000, 2002). Based on 66 real life crash pulses, mean acceleration was found to have the best correlation to the duration of symptoms (Krafft et al. 2002). Krafft et al. point out that having symptoms for more than one month may occur at low change of velocity due to a relatively high mean acceleration. In addition, it was found that at low mean acceleration, where the change of velocity is relatively high, the risk of long-term consequences was low.

Even though several studies of influencing parameters in rear-end impacts have been produced, there is still need for further investigation, especially on the influence of sitting posture and combinations of parameters.

Frontal impacts

Fewer studies have been made of AIS1 neck injuries in frontal impacts. Morris and Thomas (1996) identified belt usage as being associated with an increased neck injury risk in frontal impacts. Berglund et al. (2003) and Temming and Zobel (2000) found women to have a higher AIS1 neck injury risk than men. Temming and Zobel also found indications of increased AIS1 neck injury risk with increased occupant stature, but only very limited influence of body weight, in comparing men and women. AIS1 neck injury risk with respect to age is similar to that found in rear-end impacts (Temming and Zobel 2000, Berglund et al. 2003). Based on data from frontal impact crash recorder cases, Kullgren et al. (2000a) found that the shape of the crash pulse influenced the risk of long-term consequences to the neck. Ydenius and Kullgren (2001), using a greater number of crash recorder cases, proposed mean acceleration as the best impact severity measure for neck injuries in frontal impacts. Information from crash recorder data offers a great possibility of evaluating the influence of impact severity measures. However, there are still very few data sets containing this detailed impact severity information. In a European joint project analysing data from Folksam (Sweden), ETH (Switzerland), VW and GDV (Germany); the Folksam data showing that drivers in general had a 30% higher risk of initial symptoms than front seat passengers (Cappon et al. 2003). Risk curves based on VW accident data showed a steady increase in injury risk with increasing speed change until reaching a maximum risk value in frontal impacts of 13-17 km/h for females and 18-22 km/h for males. Folksam, on the other hand, observed in their data (based on crash recorders) that the mean acceleration explained the risk of whiplash better than change of velocity did. Based on Folksam data, the frontal impact airbags in combination with seat belt pre-tensioners were found to reduce the number of AIS1 neck injuries by 41% (Kullgren et al. 2000b). In impacts at a change of velocity between 1 and 30 km/h, airbags and pre-tensioners were found to reduce the neck injury risk by 59%.

A multi-disciplinary, in-depth investigation involving 24 occupants in frontal impacts with neck symptoms showed the complexity of WAD with respect to factors that influence occurrence as well as duration of symptoms (Jakobsson et al. 2003).

Without the possibility of statistical conclusions, occupant characteristics as well as sitting posture and behaviour at the time of impact were found to be influential with respect to both symptom intensity and duration.

For frontal impacts, there is a great need to investigate influencing parameters, both with respect to initial injury and long-term injury. In addition, it is valuable to investigate the crash pulse influence on AIS1 neck injury risk using available crash recorder data.

Injury sites and mechanisms

Several hypotheses exist regarding the injury site and type of injury covering mainly facet joints, discs, ligaments, muscles, brain stem and nerve-root ganglia. The exact injury is usually difficult to diagnose in the individual case.

Barnsley et al. (1995) and Lord et al. (1996), found indications that the cervical zygapophysial joints (facet joints) were the source of pain in several cases, by using diagnostic blocks in clinical studies. Kaneoka et al. (1999) found indications of compression of the rear-end of the zygapophysial joint, and possible impingement of the joint disc, during the neck retraction motion. The findings came from high-speed x-ray imaging in the analysis of volunteers' vertebra motion during rear-end impacts. Yang and Begeman (1996) proposed that the facet-joint capsule is stretched during rear impacts (the so called shear hypothesis). The suggestions were supported by Yang et al. (1997), who showed that shear-stiffness of the neck was reduced significantly with increased axial compression in experiments with C1-T1 specimens. Deng et al. (2000) performed rear-end impact cadaver tests using high speed x-ray imaging systems, visualising the initial neck S-shape and probable stretching of the facet joints.

The cervical inter-vertebral discs have been suggested as a possible injury site. Avulsion of the disc from the vertebral-end plate and tears of the disc after car collisions have been reported in imaging studies (Davis et al. 1991, Jónsson et al. 1994).

Several different studies have suggested the ligaments and muscles to be a possible injury site. Volle and Montazem (2001) and Krakenes et al. (2002) found signs on alar ligaments in patients with long-term AIS1 neck injuries, using advanced examination methods. Brault et al. (2000) performed volunteer tests, and found that the cervical muscles contract rapidly in response to impact and that there is a potential for muscle injury due to lengthening contractions. In addition, pain resulting from muscular stress is present for most AIS1 neck injured patient, irrespective of initial pain location.

Other possible sites of injury are the brain stem, as suggested by Ommaya (1968) and posterior nerve root ganglion. Aldman (1986) hypothesised that AIS1 neck injuries could be induced in the nerve root region of the cervical spine as a result of volume changes and subsequent pressure transients that take place during neck bending. Svensson et al. (1993 and 2000) exposed pigs to swift s-shape neck motions in the sagittal and transversal planes and recorded transient pressure changes in the spinal canal. The inspections of the pigs indicated a nerve cell membrane dysfunction in the posterior nerve root ganglia (Örtengren et al. 1996). The injury mechanism was thought to be transient pressure gradients in the spinal canal causing ganglion damage.

For rear-end impacts, several neck injury mechanisms have been suggested by different researchers. Most of the hypotheses presented refer to the initial relative motions in the cervical spine: retraction, as illustrated in Figure 1 (Aldman 1986, Svensson et al. 1993, McConnell et al. 1995, Kaneoka et al. 1999, Yang et al. 1997). Mechanisms related to the rebound phase, as illustrated by the last sequence in Figure 1, have been suggested (Krafft et al. 1997, Muser et al. 2000).

In frontal impacts, Walz and Muser (1995) separated the non-head-contact mechanism and head-contact mechanism. In a non-head-contact mechanism the neck will be exerted to a forward translation of the head resulting in S-shaped cervical spine (protraction) and thereafter in a cervical spine flexion (Walz and Muser, 1995), Figure 2. Shear forces in the area of the upper cervical spine (C0-C2) may overload the intervertebral structures in the protraction motion. For restrained volunteers in a frontal impact, Ewing et al. (1975) visualised the initial pure translational motion forming an S-shape of the cervical spine. The mechanism of transient pressure gradients in the spinal canal causing ganglion damage was suggested for protraction motion as well by Svensson et al. (2000). An example of the head-contact mechanism, which is far from the conventional "whiplash motion", was illustrated in Jakobsson et al. (2003). In an in-depth study of 24 occupants sustaining AIS 1 neck injuries in frontal impacts, two were not belted and evidence of head impacts was found. The symptoms and signs of these two occupants were not considerably different from the other 22 experiencing a non-head-contact mechanism.

In none of the impact directions is the injury mechanism fully understood. Due to this, there are obvious difficulties when developing protection systems. In order to succeed with system development, it is also important to take a unbiased and broad view, thus taking into account all possible injury mechanisms as suggested by different researchers.

Injury criteria

A couple of criteria for evaluation of neck injuries have been suggested. Based on the injury mechanism theory of Aldman (1986) and findings of Svensson et al. (1993) and Örtengren et al. (1996), a criterion called NIC (Neck Injury Criterion) was suggested (Boström et al. 1996). NIC is based on the relative velocity and acceleration between the upper and the lower neck. The NIC_{max} (retraction) has shown to be sensitive to major risk factors in rear-end impacts (Boström et al. 1997, 1998, 2000a, Eichberger et al. 1998). NIC_{min} (protraction) was suggested adequate for frontal impacts (Boström et al. 2000b).

Forces and moments measured in the upper and lower part of the neck are used as criteria for analysing AIS 3+ neck injuries (Mertz and Prasad 2000). Some researchers have also investigated the use of moment measurements for AIS1 neck injuries (Prasad et al. 1997, Boström et al. 1998). For rear-end impacts, Heitplatz et al. (2003) suggested a combination of forces and moments in the lower neck, called LNL index, based on a sled series using seats with different AIS1 neck injury risk outcome. The neck injury criterion N_{IJ} was developed for AIS3+ neck injuries in frontal impacts in the upgrade of FMVSS 208 (Eppinger et al. 1999). N_{IJ} has not yet been validated for AIS1 neck injuries. Based on experiments with cervical vertebra specimens, Yang et al. (1997) suggested that axial compression/tension forces together with shear force are responsible for the higher frequency of AIS1 neck injuries observed in rear as well as frontal impacts. Partly based on these suggestions, Schmitt et al. (2001 and 2002) proposed a modification of N_{IJ} for AIS1 injuries in rear-end impacts, called Nkm. Nkm takes into account shear forces and bending moments at the occipital condyles and is suggested for evaluating possible mechanisms in the flexion phase of a rear-end impact. Panjabi et al. (1999) hypothesised that a neck injury occurs when an intervertebral rotation exceeds its physiological limit. The authors developed the Intervertebral-Neck Injury Criterion (IV-NIC). IV-NIC has not yet been validated.

The NDC (Neck Displacement Criterion), proposed by Viano and Davidsson (2002) for rear-end impacts, is based on the angular and linear displacement response of the head relative to T1, from volunteer tests, proposing four different working performance guidelines for Hybrid III and BioRID II. NDC needs further evaluation.

NIC_{max}, Nkm, NDC and lower neck moment were evaluated in a recent rear-end study using a MADYMO model of the BioRID II dummy and crash pulses from real world crashes. Nkm and NIC_{max} were found most appropriate (Kullgren et al. 2003). A following study evaluated the influence of seat geometry and sitting posture on NIC_{max} and Nkm AIS1 long term neck injury predictability, by performing parameter analyses on reconstructed real-life rear-end crashes with known injury outcome (Eriksson and Kullgren, 2003). Based on this study, NIC_{max} and Nkm were considered robust criteria, but it was emphasized that seat geometry and sitting posture should be considered when estimating criteria values.

In rear-end impacts, some injury criteria are suggested but none of them reflects the whole spectra of injury mechanisms. For frontal impacts, there are almost no criteria suggested for the evaluation of AIS1 neck injuries.

Mechanical and mathematical occupant models

Mechanical occupant models

Standard anthropomorphic test dummies (mainly Hybrid III, Figure 3c), which were primarily designed for high-speed frontal impact testing, have not proven to be applicable for replicating human spinal motion in rear-end impact testing (Scott et al. 1993, Szabo et al. 1994, Cappon et al. 2000). In volunteer testing, it has been found that an essential part of the neck kinematics is due to the torso-straightening motion exerting compression forces in the cervical spine, and the angular motion of the T1 (Siegmund et al. 1997, Ono and Kaneoka 1997, Ono et al. 1997, Davidsson 2000). A dummy with these properties, called BioRID, was developed as a Swedish joint venture (Davidsson et al. 1998, Linder et al. 2002, Davidsson et al. 1999a, Davidsson et al. 1999b, Davidsson 2000, Figure 3a). Another dummy designed specifically for rear-end impact was developed in the EU "Whiplash" project (Cappon et al. 2000, Cappon et al. 2001). The dummy is called the RID2 (Figure 3b). In a recent evaluation study including the BioRID II, RID2, Hybrid III and the THOR dummy (designed for frontal impacts, Figure 3d), the Hybrid III had great problems in rear-end impact and THOR also had limitations, especially with T1 z-motions (Cappon et al. 2003). RID2 had limitations in ramping up and it was soft in forward rebound. The BioRID II had the best bio-fidelity in rear impacts. However, concerns were raised regarding its 2D motion restriction in the neck, which the authors speculated could be a problem in oblique impact situations.

Figure 3a – BioRID I

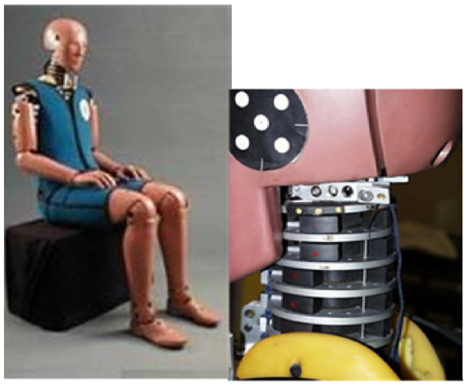

Figure 3b – RID 2

Figure 3c – Hybrid III

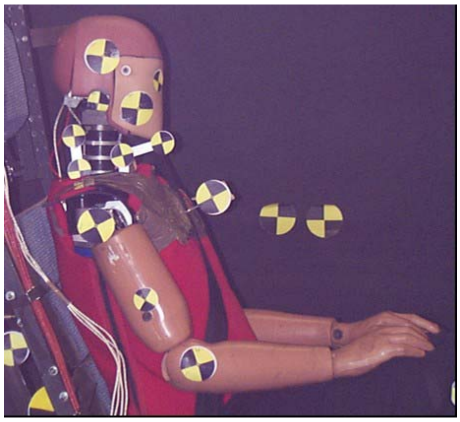

Figure 3d – THOR

For frontal impacts, the Hybrid III (Foster et al. 1977, Figure 3c) has been used in studies of AIS1 neck injuries (Bohman et al. 2000). However, the more refined neck of the THOR dummy (Haffner et al. 2001) together with a more human-like shoulder and torso would probably be a more sensitive tool for the study of neck kinematics. Also, the EU "Whiplash 2" project is considering redesigning the RID2 to get adequate stiffness and to meet the higher durability requirements for frontal impacts (Cappon et al. 2003).

Mathematical occupant models

Two techniques are used for mathematical modelling of humans or dummies: Multi Body Systems (MBS) and Finite Element Modelling (FEM). Generally, MBS models are good for parametric studies and require less computer time than FEM models, while FEM simulate material characteristics and contacts between parts more accurately. Using MBS, Volvo developed a mathematical occupant model in MADYMO 2D, with a segmented spine simulating human-like motion in rear-end impacts (Jernström et al. 1993, Jakobsson et al. 1994, Figure 9). Van den Kroonenberg et al. (1997) developed a three-dimensional human model. This model was extended by Happee et al. (1998, 2000a, 2000b) to form a human occupant model in different occupant sizes and validated in frontal and rear, as well as side impacts. MBS models of mechanical counterparts are used for AIS1 neck injury evaluation; such as BioRID in rear-end impacts (Eriksson and Boström 1999, Eriksson 2000, Eriksson and Kullgren 2003, Figure 4a) and Hybrid III in frontal impacts (Kullgren et al. 1999, Bohman et al. 2000).

Several FE models of the cervical spine have been presented (Kleinberger 1993, Dauvilliers et al. 1994, Yang et al. 1998, Lizee et al. 1998, Halldin et al. 2000, Wittek 2000). The FE model by Halldin is shown in Figure 4b.

Figure 4a – MBS model of BioRID II (Eriksson and Kullgren 2003).

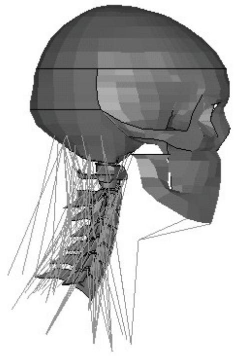

Figure 4b – FE-model of the neck (and head) (Halldin 2004).

Occupant protection principles and test methods

Rear-end impacts

In a rear-end impact, the occupant is pushed forward by the seat backrest. The body of the occupant will sink into the seat backrest. When the kinetic energy of the seat backrest has reached zero, an opposite motion of the occupant (so called rebound) will take place, the amplitude being dependent on the seat backrest properties. The general occupant motion in a rear-end impact is illustrated in Figure 5.

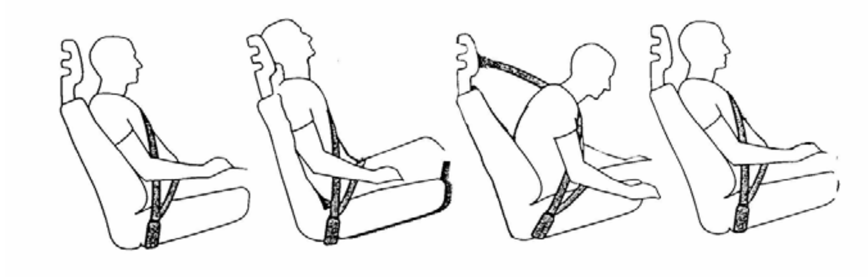

Figure 5 – General occupant motion in a rear-end impact.

Head restraints were introduced in cars in order to support the head and avoid hyperextension of the neck in a rear-end impact. Studies based on accident data with and without head restraints have shown the injury-reducing effect of head restraints to range from 14% to 55% (States et al. 1972, Asberg 1973, O'Neill et al. 1972, Lövsund et al. 1988, Nygren et al. 1985, Morris 1989). However, even with head restraints, AIS1 neck injuries are reported in rear-end impacts. The position of the head restraint will affect the head motion. Active head restraints, reducing the horizontal distance between the head and the head restraint, have been presented and built into several modern car models (Wiklund and Larsson 1998). A seat design with improved distance between head and head restraint, plus more even and close support for the back, a reduced acceleration pulse, and lower rebound was introduced by Volvo, and called WHIPS (Whiplash Protection System, Lundell et al. 1998b, (I)). During a rear-end impact, the seat backrest will move rearward together with the occupant relative to the seat cushion; first in a parallel motion and thereafter in a tilting motion (Figure 6). During the motion, deformation elements in the recliner mechanisms deform and thus absorb some of the energy.

Figure 6 – WHIPS seat backrest motion in a rear-end impact

There is not yet a standard method for dynamic testing available to evaluate the protection from AIS1 neck injuries in rear-end impact. However there are intense activities going on around the world. ISO specifies a sled test method (ISO/CD17373) but neither dummy nor criteria are suggested yet. Consumer rating methods are developed by IIWPG (the International Insurance Whiplash Prevention Group), NCAP (the New Car Assessment Program) and the Swedish Road Authority. Both NHTSA (the National Highway Traffic Safety Association) and EEVC (the European Enhanced Vehicle-safety Committee) are in the process of developing dynamic methods for evaluation of AIS1 neck injuries in rear-end impacts.

Frontal impacts

In frontal impact, the body will move forward until restricted by the seat belt and/or airbag, Figure 7.

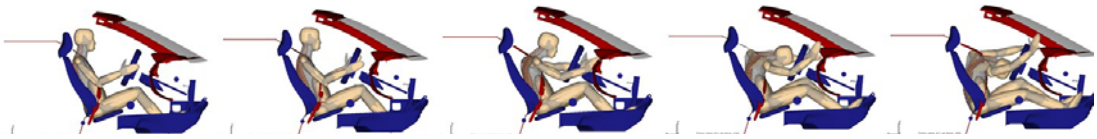

Figure 7 – General occupant motion in a frontal impact, no airbag deployment.

Seat belts have been proven to be a very effective safety measure, not only by protecting the occupant from ejection but as a link to the car's deceleration. By tuning the seat belt characteristics and inclusion of belt pre-tensioners and belt force limiters, the occupant deceleration can be tuned in relation to the car's deceleration, and the occupant protection can thus be optimized. Airbags were introduced in frontal impacts during the 80's. Being primarily a complement to the seat belt, the airbag can optimize occupant protection even more; especially in preventing head impacts into the steering wheel and other rigid structures. Much of the emphasis in belt and airbag design has been put into reducing moderate to fatal injuries. Airbag efficiency has also been mentioned, regarding AIS1 neck injuries. Based on accident data, Kullgren et al. (2000b) reported that cars fitted with airbags in combination with seat belt pre-tensioners had 41% lower percentage of reported AIS1 neck injuries than cars without airbags and pre-tensioners. Bohman et al. (2000) studied the effect of a belt pre-tensioner, belt load limiter and airbag on neck loadings, using a mid-size male Hybrid III mathematical model and 168 crash recorder pulses. It was found that a belt pre-tensioner, a belt load limiter, or an airbag have the potential to reduce neck loads below suggested reference values, as suggested by Boström et al. 2000b. At low severities, belt pre-tensioners were found to reduce the neck loadings while airbags were not as effective. The importance of the interaction between the belt pre-tensioner, the belt load limiter and the airbag was also pointed out.

There is no ongoing activity for development of a standard method suggested for evaluation of AIS1 neck injuries in frontal impacts, except for a recently started EU project, "Whiplash 2", which aims to address the issue (Cappon et al. 2003).

Methods for determining injury criteria

The most straight-forward method of developing an injury criterion for a dummy to reflect an injury is to reproduce the injury mechanism in biological models and perform corresponding dummy tests and then correlate the dummy responses to injury outcome (Kuppa and Eppinger 1998). Another method is replicating accident situations where the risk of a specific injury is known (Korner 1989). In order to be successful, these methods require a good knowledge of the injury mechanism, good quality replication of the situation, and a biofidelic dummy with responses similar to those of a human in the crash situation and body area in question. It would be difficult to use the above methods in the case of AIS1 neck injuries, where no single accepted injury mechanism explains the whole spectrum of symptoms. Therefore, to be sure of covering more than one suggested injury mechanism, a holistic (unbiased and broad) approach covering several injury mechanisms is needed. Such an approach could be based on experiences from accident analyses. Several parameters are expected to influence the AIS1 neck injury outcome. When changing these parameters in occupant modelling (or testing), the occupant responses can give valuable information to the evaluation of AIS1 neck injury risk. The present work is based on such approach.

OBJECTIVES

The overall objective of this study is to combine accident data analyses, biomechanical data and occupant modelling to define and implement a method for development of and evaluation of AIS 1 neck injury protection systems. The specific objectives are:

- Based on accident data: identify and quantify parameters potentially influencing the risk of AIS1 neck injuries in frontal and rear-end impacts.
- Based on crash recorder data: evaluate impact severity measures for AIS1 neck injury risk in frontal impacts.
- To evaluate occupant kinematics and responses in frontal and rear-end impacts, respectively, using occupant models (mathematical and mechanical).
- Define biomechanical guidelines for the reduction of the potentially injury-related occupant kinematics in frontal and rear-end impacts, respectively.
- Investigate possible evaluation criteria for AIS1 neck injuries in frontal and rear-end impacts, respectively.
- Based on accident data: assess the effectiveness of a seat (WHIPS), developed as a result of this study.

METHODS AND MATERIALS

The holistic approach used in this study is a combination of various activities, schematically shown in Figure 8.

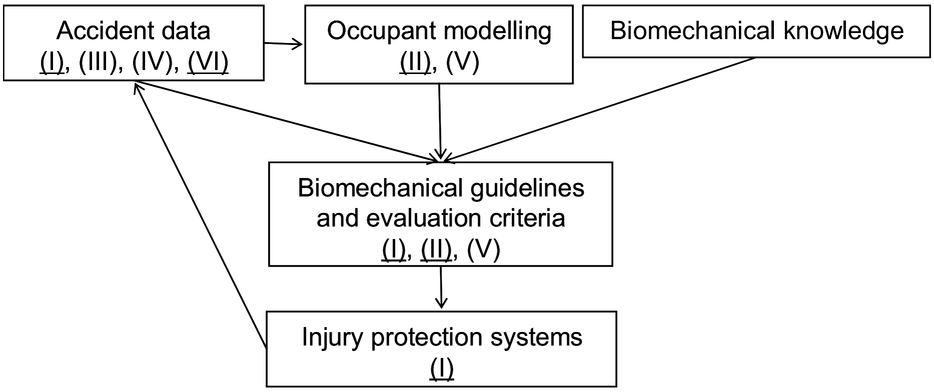

Figure 8 – Methodologies and deliverables; the tasks of the approach used in this thesis. Arrows indicate the information flow between the tasks. The numerals refer to the appended papers. The underlined numbers indicate studies of rear-end impacts, the others concern frontal impacts. Occupant modelling refers to both mechanical testing and mathematical occupant modelling.

Knowledge gained from analyses of accident data was used in parameter studies with occupant models. Biomechanical guidelines were defined by synthesising the accident data, the modelling results and biomechanical literature data. For rear-end impacts, the guidelines together with the accident data findings were evaluated in sled-test series in order to transform the guidelines into measurable evaluation criteria. In frontal impact, mathematical occupant modelling was used in the study of evaluation criteria. For rear-end impacts, the field performance was also evaluated for a seat (WHIPS), the development of which was based on this study and which was installed in vehicles from 1998.

The activities will be described in this thesis, structured according to the tasks in Figure 8, divided into the two impact directions, and thereafter followed by a general discussion and conclusions.

Rear-end impacts

Accident data

The aim of analysing accident data was to evaluate important parameters with respect to risk of AIS1 neck injuries in rear-end impacts and to evaluate the effectiveness of the WHIPS seat, the development of which was based on this study. Two separate studies were carried out.

In (I), a data set of 2030 adult occupants involved in a rear-end impact in Volvo cars during the period 1975-1998 were selected from Volvo's statistical accident database. Only cars with an estimated specific repair cost were available, excluding cars with minor impact damage. The influence of impact characteristics, occupant characteristics and sitting position were evaluated, Table 1. The distribution of AIS1 injuries in rear-end impacts was also calculated per body part.

Table 1 - Parameters analysed in study (I).

	Parameters analysed
impact characteristics	Equivalent Barrier Speed (EBS), influence of stiff car structure
occupant characteristics	gender, stature, age
seating parameters	seating position

(VI) included rear-end impacts from 1999-2002 with Volvo cars of model year 1999-2002, without any repair cost criteria. A total of 1608 front seat adult occupants were included in the subset in study (VI). The main parameters analysed (Table 2) were occupant characteristics, prior neck status and sitting posture, together with the influence of WHIPS. The AIS1 neck injury reducing effects of cars with WHIPS as compared to cars of model year 1999 without WHIPS, were calculated both for initial symptoms as well as symptoms lasting more than one year.

Table 2 - Parameters analysed in study (VI)

	Parameters analysed
impact characteristics	impact severity based on car damage
occupant characteristics	gender, age, stature, weight
seating parameters	seating position, turned head, head to head restraint distance
safety systems	WHIPS
prior neck status	prior neck problems

Occupant modelling

The aim of occupant modelling was to visualise occupant kinematics and evaluate situations found in accident data to influence AIS1 neck injury risk. In rear-end impacts, occupant modelling was performed using both mathematical and mechanical occupant models.

Mathematical occupant modelling was used to enhance understanding of occupant kinematics resulting in biomechanical guidelines for reduction of AIS1 neck injury risk. This study was performed prior to this thesis (Jakobsson et al. 1994 and Jakobsson 2000). The mathematical model used was a medium-sized male occupant model in MADYMO 2D, comprising a mechanical equivalent of the complete spine in the sagittal plane (Figure 9).

Figure 9 - Mathematical rear-end occupant model in MADYMO 2D. The lines perpendicular to the seat backrest and head restraint illustrate the borders of the different contact surfaces in the seat model.

A total of six different combinations of occupant postures, seat design or crash pulse were studied. Five of these were identified in the accident data to represent a higher or lower AIS1 neck injury risk as compared to the reference situation (Jakobsson et al. 1994). The six situations were:

- reference situation; an occupant in regular sitting posture in a standard Volvo seat, Figure 9
- increased seat backrest inclination (higher risk)
- forward-leaning occupant (higher risk)
- lowered head restraint (higher risk)
- stiffer and less energy-absorbing head restraint and upper part of seat backrest (higher risk)
- crash pulse with reduced acceleration level at unchanged change of velocity (lower risk)

A total of 12 responses were measured for the six different occupant and crash situations. The responses most consistent with the anticipated relative AIS1 neck injury risk were assumed to reflect a relation to injury.

A sled test series was performed in (II) using a mechanical occupant model, BioRID I, with the aim to develop quantitative measures reflecting injury risk, so called evaluation criteria.

Sled tests in three different situations were carried out. The three situations were:

- front-seat occupant in regular sitting posture
- front-seat occupant leaning forward
- rear-seat occupant in regular sitting posture

The situations were chosen based on findings in accident data. Increased head to head restraint distance was suggested to be related to increased risk of AIS1 neck injuries (Carlsson et al. 1985, Olsson et al. 1990, Jakobsson et al. 1994). Also, indications were found that rear seat occupants had a lower risk of AIS1 neck injuries as compared to front seat occupants (Lövsund et al. 1988 and (I)).

Biomechanical guidelines and evaluation criteria

Since no injury mechanisms or injury criteria have been established to cover all the symptoms of AIS1 neck injuries in rear-end impacts, the objective was to develop biomechanical guidelines to be used in car design (I). The biomechanical guidelines should describe desired occupant kinematics in a rear-end impact. Biomechanical literature data, the accident data and the results and experiences from the occupant modelling were synthesised into guidelines regarding the dynamic biomechanical response of the occupant. The literature data consisted of injury mechanism theories and occupant motion analyses.

Evaluation criteria for rear-end impacts were derived from the sled test series in (II), by evaluating dummy responses relevant to the defined biomechanical guidelines. For each of the guidelines, the responses most consistent with the anticipated relative AIS1 neck injury risk were suggested as evaluation criteria (Figure 10).

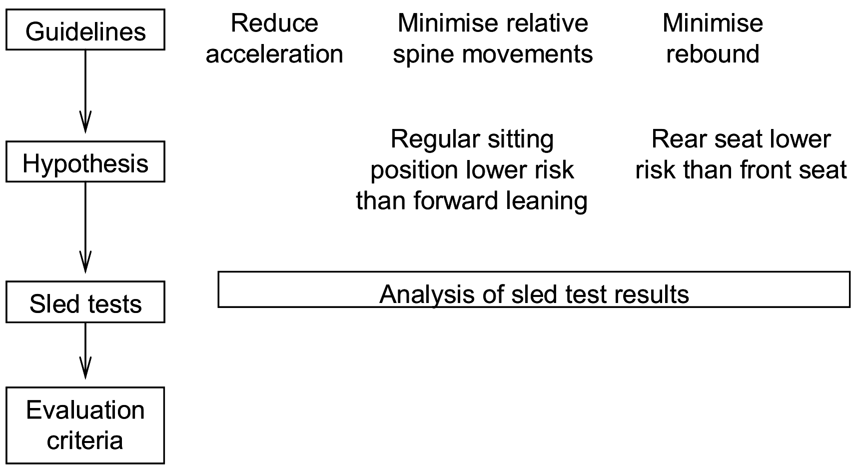

Figure 10 - Method in (II), describing the activities leading to evaluation criteria in rear-end impacts.

Frontal impacts

Accident data

With the aim of gaining more knowledge of the AIS1 neck injury scenario in frontal impacts, two statistical studies of parameters influencing AIS1 neck injury risk were performed. (III) is a statistical study, mainly of occupant parameters. In (IV), possible impact severity measures were evaluated using information from onboard crash pulse recorder data.

(III) analysed a subset of frontal impacts between 1996 and 1999 from Volvo's statistical accident material. The total of 485 frontal impacts, involved 616 occupants, who had answered an additional follow-up questionnaire. Table 3 lists the parameters on which study (III) focused. The choice of parameters was based on findings in previous studies and those found to be influential in this study. The parameters were studied with regard to the rate of *initial* (all AIS 1 neck injuries), *passing* (recovery within three months) and *persistent* symptoms (symptoms of certain degree one year after the collision).

Table 3 - Parameters analysed in study (III)

	Parameters analysed
impact characteristics	impact configuration, Equivalent Barrier Speed (EBS)
occupant characteristics	gender, age, stature, weight, Body Mass Index (BMI)
seating/occupant parameters	seating position, sitting posture, turned head, preparation, muscle tension, steering wheel grip, reaction
safety systems	seat belt usage, belt pre-tensioner activation, airbag activation
occupant kinematics	head impacts
prior neck status	prior neck symptoms

(IV) studied Volvo cars in frontal impacts (1994-2000), with information from an activated crash pulse recorder (DARR – Digital Accident Research Recorder). A total of 226 occupants in 157 vehicles with crash pulse information were analysed with respect to possible impact severity measures. Logistic regression analyses as well as graph plot analyses were used when evaluating the investigated impact severity measures shown in Table 4.

Table 4. Parameters (impact severity measures) analysed in study (IV).

Investigated impact severity measures
maximum deceleration
maximum change of velocity (max. Δv)
mean deceleration
duration
maximum polynomial deceleration (polmax)
BETA = (max. Δv) x (polmax)
time of maximum deceleration
time of max polynomial deceleration
Δv at 20 ms
Δv at 30 ms
Δv at 40 ms
Δv at 50 ms
Δv at 60 ms
Δv at 70 ms

Figures 11a-c shows an example of a DARR-pulse, including polynomial approximation and stepwise mean decelerations.

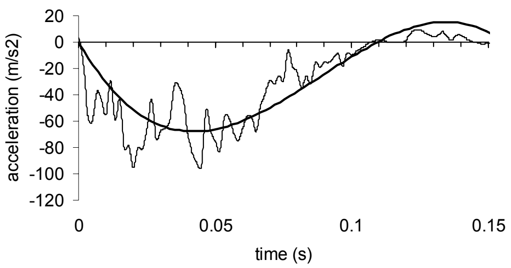

Figure 11a – An example of a DARR pulse including polynomial approximation of third degree.

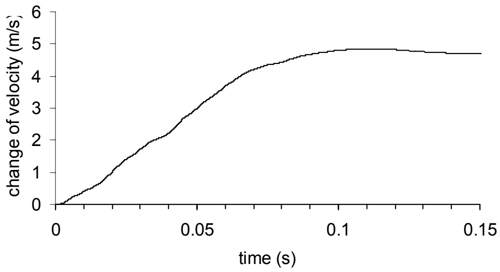

Figure 11b – Accumulated change of velocity for the pulse in Figure 11a.

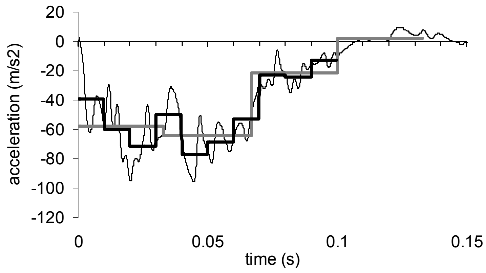

Figure 11c – Pulse as in Figure 11a, including stepwise mean decelerations of 33 ms and 10 ms intervals, respectively.

Occupant modelling

Mathematical occupant modelling with the aim to visualise neck kinematics and investigate possible evaluation criteria was performed in (V). Situations with known relative AIS1 neck injury risks in frontal impacts (III) were simulated using a MADYMO human occupant model in four different pulses and three different sitting postures; a total of 36 simulations in 24 pairs.

The reference situation in (V) was a restrained medium-sized male occupant multibody human model in MADYMO 3D (Happee et al. 2000b) positioned in a Volvo driver environment (Figure 12a). Two situations with increased AIS1 neck injury risk were compared to the reference situations: occupant with less weight and occupant straightening the arms during impact, respectively. The occupant weight was reduced by using the "masses" of the small female model (TNO, Happee et al. 2000b), except for the head mass which was unchanged. The arm resistance was simulated by straightening the arms forward towards a plane (Figure 12b). For the modified situations in any crash pulse and sitting posture, only the parameter of weight or arm position, respectively, was changed as compared to the reference situations.

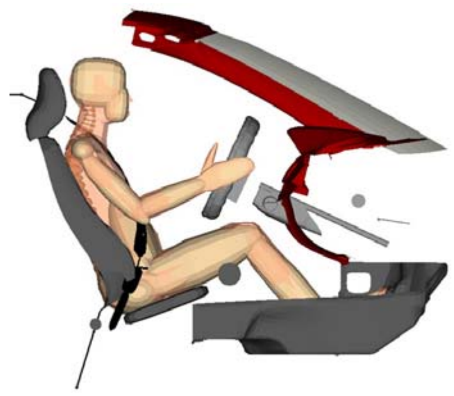

Figure 12a - Mathematical occupant model, in normal sitting posture, used in the parameter study of frontal impact (V).

Figure 12b - Mathematical occupant model with simulated arm resistance to steering wheel in normal sitting posture.

Three different sitting postures were simulated for each situation: normal sitting posture, forward leaning and rearward leaning. Four different crash pulses were used in order to ensure that the evaluation criteria identified would be valid in a broad impact severity scenario. The pulses were based on real life pulses from car crashes with Volvo cars. The maximum change of velocity (max. Δv) and mean deceleration of the chosen pulses can be seen in relation to the real life crash pulses in study (IV), Figure 13.

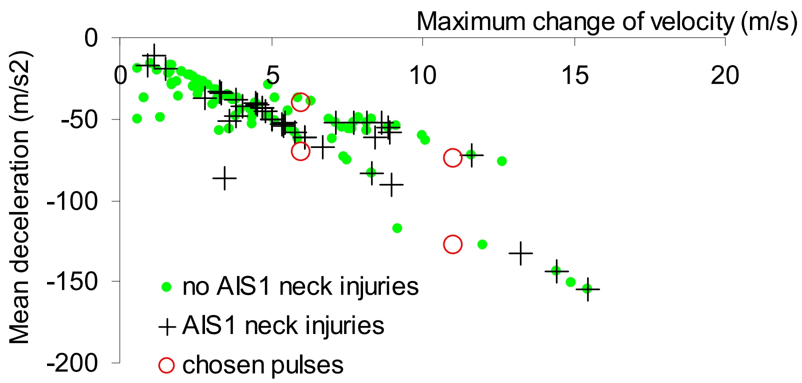

Figure 13 - Maximum change of velocity (max. Δv) and mean deceleration of the chosen pulses in study (V) and the pulses in study (IV) including AIS1 neck injury information for the occupants.

Biomechanical guidelines and evaluation criteria

As for rear-end impacts, neither injury mechanisms nor injury criteria have been established to cover all the symptoms of AIS1 neck injuries in frontal impacts. The objective is to define biomechanical guidelines as well as evaluation criteria to be used in development of protection systems. The biomechanical guidelines should outline the desired occupant kinematics in a frontal impact. Knowledge from the differences in neck kinematics in the occupant modelling series in (V) was used, mostly, as the first step in defining guidelines for the desired occupant kinematics in a frontal impact. Neck kinematics were evaluated by calculating the upper neck link angle versus lower neck link angle. The neck link angles were calculated as the local rotation of head and lower neck (T1), respectively, relative to the neck link angle (angle of a line between upper and lower neck), Figure 14. This neck link model has previously been used in rear-end impacts by Davidsson (2000).

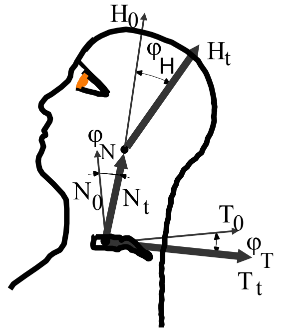

Figure 14 – Neck link model in 2D. The lines represent angular position at impact start 0 and at time t for T=T1 vertebra, N=neck link and H=head.
Upper neck link angle = $\varphi_H - \varphi_{NL}$
Lower neck link angle = $\varphi_{NL} - \varphi_T$

In order to develop protection systems aiming at reducing the AIS1 neck injury risk in frontal impacts, evaluation criteria are needed as quantitative measures reflecting AIS1 neck injury risk. In (V) several possible evaluation criteria for AIS1 neck injuries in frontal impacts were evaluated, using a human occupant model in MADYMO 3D. Occupant responses were evaluated with respect to the anticipated relative AIS1 neck injury risks for the different situations. The total of 36 simulations were compared in 24 paired situations: comparing each modified situation (weight reduction / arm resistance) with the reference situation of the same sitting posture and crash pulse. The evaluated criteria were; NIC_{min}, N_{IJ}, Nkm and upper and lower neck forces and moments.

RESULTS AND DISCUSSION

Rear-end impacts

Accident data

In the statistical study of initial AIS 1 neck injuries in rear-end impacts 1975-1998 (I), parameters such as occupant characteristics and seating position were focussed on. The main findings are:

- AIS1 neck injuries are by the far most common injury type in rear-end impacts, followed by thoracic/lumbar spine injuries.
- The AIS1 neck injury risk is almost constant, irrespective of level of EBS (Equivalent Barrier Speed).
- Involvement of rigid car structure indicates a higher AIS1 neck injury risk compared with when the rigid structure is not deformed.
- Tendency towards higher AIS1 neck injury risk for front-seat occupants compared to rear-seat passengers (Figure 15)
- Significantly higher AIS1 neck injury risk for drivers as compared to passengers (Figure 15).
- Females are at higher AIS1 neck injury risk than men, irrespective of seating position, stature and age.
- When separating the occupants by gender as well as seating position, an increase in AIS1 neck injury risk can be clearly related to increase in occupant stature.
- The highest AIS1 neck injury risks (up to approx. 50%) are in the age groups 20-30 and 30-40. The lowest risk is found in the youngest age group of less than 20 years.

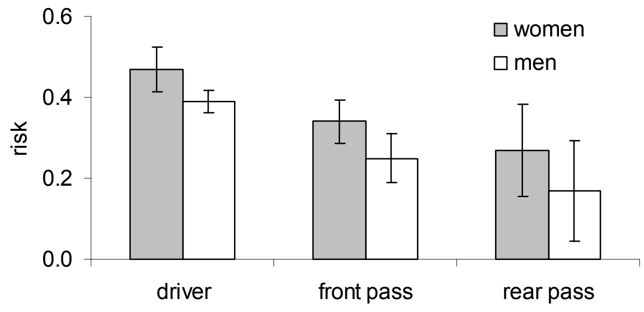

Figure 15 - AIS1 neck injury risk, including 95% confidence intervals, for men and women in different seating positions.

In (VI) a more recent dataset of rear-end impacts was analysed; accident years 1999-2002. The main findings are:

- Prior neck problems are a significant risk factor and should be considered when analysing influencing parameters.
- Significantly increased risk of AIS1 neck injuries at higher impact severity, based on crash damage (higher impact severity determined by longitudinal rear member deformation). However, the risk of initial AIS1 neck injuries is as high as 25% even when the car damage is less than engaging the rear members.
- Significant increased AIS1 neck injury risk for increased occupant stature, weight and age, respectively.
- Sitting posture influences AIS1 neck injury risk. Factors such as turned head and increased head to head restraint distance, respectively, significantly increase AIS1 neck injury risks.
- The injury reducing effect of WHIPS as compared to the previous design of Volvo seats is 33% for initial AIS1 neck injuries and 53% for AIS1 neck injuries lasting longer than one year.
- The injury reducing effect in WHIPS is higher for women than for men, Figure 16.

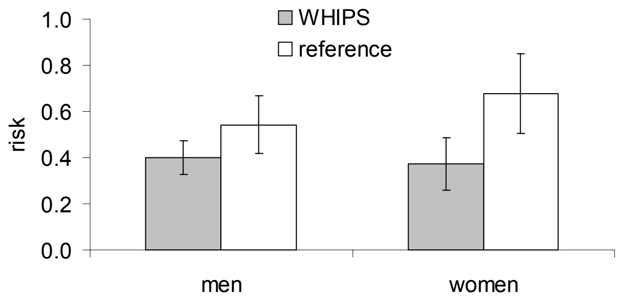

Figure 16. AIS1 neck injury risks for men and women, respectively, in WHIPS seats as compared to prior Volvo seats (reference); front seat occupants (> 14 years old) without prior neck problems involved in rear-end impacts of moderate severity, including 95% confidence interval.

Sitting posture is an important parameter with respect to AIS1 neck injury risk. A significantly higher risk was found for occupants with turned head at the time of impact as well as those with increased head-to-head restraint distance (VI), confirming earlier studies (Olsson et al. 1990, Jakobsson et al. 1994, Silverbåge-Carlsson et al. 2003). The influence of sitting posture could be one explanation for the difference in risk of AIS1 neck injury for the driver compared to the front seat occupant (I, VI); because the driver can be assumed to move his head and upper body, during driving and in intersections, to a greater extent than the front-seat occupant. This was confirmed to some extent in (VI) where 26% of the drivers as compared to 20% of the front seat passengers reported head rotation at any degree and direction during impact.

Individual differences of the occupants (mainly gender and stature) are important with regard to risk of sustaining AIS1 neck injuries in rear-end impacts (I, VI). The findings in the present study confirm prior studies (Morris and Thomas 1996, Temming and Zobel 2000). The existence of prior neck problems is also an important factor (VI). Occupant characteristics together with sitting posture are important parameters and should be taken into account in field data analysis, especially in small sample data sets. This should also be kept in mind and observed during development of test procedures and in the development of AIS1 neck injury protection systems.

The fact that injuries to the thoracic and lumbar spine account for the second largest group of injuries in rear-end impacts stresses the importance of regarding the whiplash problem as an issue related to the whole spine (I). Minton et al. (1997) found that lumbar spine and cervical spine injuries occur together. The exact relationship was not stated. However, due to the design of a human spine, it is obvious that motions in the lower part of the spine affect the motions in the upper part. Thus an even back support along the whole spine should be an objective. The tendency towards a lower risk of initial AIS1 neck injuries in the rear seat as compared to the front seat (I) could be related to seat design and supports the principle of considering the whole seat interaction. One of the differences between front and rear seat characteristics is the less occupant rebound motion in a conventional, well-attached rear-seat back-rest (II).

Several studies have suggested that rear seat passengers have a lower risk of sustaining initial AIS1 neck injuries (Carlsson et al. 1985, Lövsund et al. 1988, Berglund et al. 2003) supporting the findings in (I). However, Krafft et al. (2003) reported a higher disability risk for the female rear seat passengers compared to female front seat passengers. The reason for this was difficult to understand, especially since it was not valid for male passengers. The results of Krafft et al. (2003) are difficult to compare to the results in (I) mainly because of the different injury duration focus, study set-up and analysis methods, and also differences in car models and knowledge of the presence of head restraints and seat belts. In (I), the occupants were all wearing seat belts and all seats were equipped with head restraints offering a very homogenous sample, however no conclusions regarding long term or disability could be drawn.

Unfortunately, there was no onboard crash pulse sensor available for rear-end impacts to enable a detailed study of the influence of the impact severity. In (I) the impact severity was estimated based on photo information. EBS did not reflect increased initial AIS1 neck injury risk. However, when grouping the cars according to whether the impact area involved rear members (reflecting a probable increase in the crash pulse amplitude), there was a tendency of higher initial AIS1 neck injury risk for those with engaged rear members as compared to those with impact area outside rear members, at equivalent EBS. This is an inaccurate measure of differences in the crash pulse shape, but it confirms what was first speculated by Olsson et al. (1990) and more recently confirmed by Krafft (1998b) and Krafft et al. (2002) using crash pulse recorder information. Krafft (1998b) found that given initial symptoms, disability seemed to be more related to the acceleration level. In (VI), the impact severity was estimated using car damage information. Since there was no repair cost limit for the data collection, many of the crashes had minor car damage, which made it difficult to estimate the impact severity using photos. The crashes in (VI) were placed in two impact severity groups; minor and moderate. All cars with deformed longitudinal rear members or more deformation were grouped as moderate impact severity. The vast majority of the impacts were of minor impact severity and for those impacts, the risk of initial symptoms was 25% which shows that even at very low impact severity, AIS1 neck injuries need to be considered. These figures indicate that other parameters (mainly occupant and posture related) are as important, or possibly more so, than impact severity.

One part of the accident analysis was the evaluation of the seat developed, based on the work in this thesis. The data collected in (VI) gives a unique possibility to compare the AIS1 neck injury outcome for WHIPS and the seat previously used. For 2/3 of the cars in the sample, the only change in design between the two groups was the seat change. Also the large amount of information for each case, such as details regarding occupant characteristics and sitting posture, made it possible to control for parameters not usually available in large accident data. In order to reduce confounding, occupants with prior neck problems were excluded from the analysis. The injury reducing effect of WHIPS in moderate impact severity (approximate level of WHIPS activation) is 33% for initial symptoms and 53% for symptoms lasting more than one year. The benefit for women is higher than for men, reducing the initial AIS1 neck injury risk for women down to approximately the same risk as for men in WHIPS (Figure 16). It is too early to conclude the reason for this. The ambition in the development phase of WHIPS was to cover a large span of occupant sizes as well as impact severities (Lundell et al. 1998b, (I)). The results from the accident analyses support this approach. In order to confirm the exact range of best effectiveness and explain the reasons for gender differences, a larger data set is needed enabling a division in selected groups.

Findings in accident data represent an important source of information. The combination of analyses from in-depth studies and aggregated accident data would have the best potential to provide wider knowledge of what the real-life situation is like. Used in a structured way, it offers a good basis for the development of biomechanical guidelines and evaluation criteria.

Occupant modelling

For the six different occupant and crash situations in the occupant modelling study in Jakobsson et al. (1994), the following occupant responses were most consistent with the anticipated relative AIS1 neck injury risk:

- shear and tensile forces between adjacent vertebrae in upper and lower neck
- head angular acceleration
- the volume-change rate of the lower neck

This early study pointed out the influence of shear and tensile forces. This is in line with studies suggesting relative forces between adjacent vertebrae as possible injury mechanisms (McConnell et al. 1995, Kaneoka et al. 1999). More recent neck injury criteria N_{IJ} (Eppinger et al. 1999) for frontal impacts and Nkm (Schmitt et al. 2002) for rear-end impacts have been suggested. Both N_{IJ} and Nkm combine moments and forces (tensile and sagittal shear, respectively). In a recent study by Kullgren et al. (2003) using a MADYMO model of BioRID II and real world crash pulses, Nkm and NIC_{max} were found to reflect AIS1 neck injury risk, supporting the first as well as the third occupant response finding in the earlier study of Jakobsson et al. (1994).

Also the knowledge gained from analysing the occupant motions in the simulations adds to the knowledge from accident data, emphasising the importance of regarding the whiplash problem as an issue concerning the whole spine. Motion in the cervical spine area could probably be affected by local impact in the lumbar area.

Biomechanical guidelines and evaluation criteria

Based on the findings in accident data, biomechanical literature and the results of occupant modelling, three biomechanical guidelines for rear-end impacts were defined in (I). The three biomechanical guidelines were:

- Reduction of occupant acceleration
- Minimising relative movement between adjacent vertebrae and in the occipital joint
- Minimising forward rebound into the seat belt

The guidelines summarise an approach to the whiplash protection issue. They address most of the suggested injury mechanism hypotheses and cover a variety of different scenarios (Jakobsson 1998, Lundell et al. 1998a, (I)). The guidelines were formulated in 1994, based on the best available knowledge regarding AIS1 neck injuries. The driving force was to condense available knowledge and make possible to progress towards injury protection systems. During subsequent years, scientific studies have supported the guidelines. The findings in study (VI) are one such example.

The first guideline; aiming at reducing occupant acceleration, does not have a direct connection with any suggested injury mechanism for AIS1 neck injuries. In accident analysis, the crash pulse shape rather than impact velocity has been found to relate to injury risk (Olsson et al. 1990, Krafft et al. 2002, (I)), indicating that reducing occupant acceleration should be favourable. Volunteer tests have also shown that below certain occupant accelerations, the likelihood of sustaining an injury is expected to be minor for most healthy persons. In situations where parts of the body are unsupported, for instance while the head has not yet come into contact with the head restraint, reduced torso acceleration will reduce local loads and displacements in the spine.

Relative movements between adjacent vertebrae were found to reflect the anticipated AIS1 neck injury risk differences between the different situations simulated in Jakobsson et al. (1994). Relative spine movements have also been suggested by several researchers as a possible mechanism causing AIS1 neck injury (Aldman 1986, McConnell et al. 1995, Kaneoka et al. 1999, Yang et al. 1997). The knowledge gained from sending astronauts into the space, and also from the performance of rearward facing child seats in a frontal impact (Aldman 1964), tells us that the ultimate aim is to keep the spine as evenly supported as possible. If the spine is completely stationary, no injuries are likely to occur.

The third guideline aims at reducing the resulting occupant rebound in order to minimise the interaction with the seat belt. Seat belt interaction has been suggested as causing injury (Krafft et al. 1997). The exact injury mechanism of these findings is not known.

In this thesis it is hypothesised that if the three biomechanical guidelines are used in the car design process, then the risk of AIS1 neck injuries in rear-end impacts can be reduced. Since the biomechanical guidelines are not conventional biomechanical injury criteria corresponding to established biomechanical injury mechanisms, it is impossible to assign specific thresholds at this stage. However, the ultimate goal would be to achieve zero loading, while every reduction may be regarded as a step in the right direction. Furthermore, since the biomechanical guidelines are to some extent related to different injury mechanism hypotheses, all three guidelines must be addressed at the same time. Increased response of any of the biomechanical guidelines should be avoided, since reductions in the other responses may be countered and no real positive effect achieved.

Based on the sled test series in (II), evaluation criteria were chosen for measurable evaluation of the three biomechanical guidelines in rear-end impacts. The following evaluation criteria were most consistent in monitoring relative AIS1 neck injury risk for the forward leaning sitting posture and rear seat occupant as compared to front seat occupant in normal sitting posture:

- Occupant acceleration be measured along the spine and in the pelvis in a horizontal (x) direction.
- Average relative velocities along the spine (ARSV) to reflect the relative spine movements.
- NIC_{max} was judged to be an adequate criterion reflecting differences in sitting posture.
- Total Maximum Belt Force or Torso Rebound Velocity to reflect the effect of forward rebound.

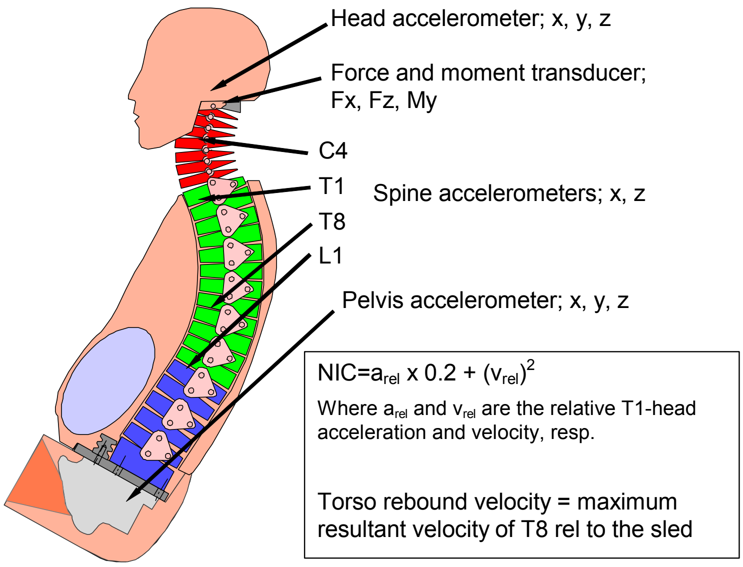

Figure 17. The BioRID I and instrumentation.

Relative spine velocity resembles relative acceleration, between six interspaced positions, integrated over time, and is a result of external forces acting on the back. The six positions are head, pelvis and four positions in the spine as illustrated in Figure 17. The maximum values (in the seat back-rest loading phase) of each interspaced relative velocity along the spine are combined to form an average output value. The relative velocity was assumed to correlate to internal displacements and loads in the spine, since the relative velocity between adjacent spinal elements was stopped mainly by the resistance of the internal structures of the spine. These loads are potentially injury-inducing and thus the ARSV (Average Relative Spine Velocity) was considered to reflect the second guideline on relative movements between adjacent vertebrae. One important advantage of ARSV is that it is easy to apply in a crash test dummy, since it only requires that a number of accelerometers be attached to the spine. However, in order to better detect local changes in stiffness of a seat backrest, a more direct and precise measurement should be developed; mapping local as well as global bending of the dummy's spine. For this purpose, a measurement system is needed which enables the monitoring of the shape of the spine during the impact motion.

NIC_{max} was developed to monitor the initial relative cervical motion, and in this study it did not seem to take into account the less elastic response of the rear seat, which is believed to be the most prominent property of the rear-seat in relation to the front seat. NIC_{max} did distinguish between the situations with different distances between head and head restraint. Based on this, NIC_{max} was judged to be an adequate criterion for some situations in the guideline of relative spine movements. However, based on this study, it cannot be recommended as a single criterion in a rear-end impact test evaluation.

Two evaluation criteria for forward rebound were suggested. The Torso Rebound Velocity would probably be the criterion primarily recommended, since the belt force is dependent on force transducer location and initial belt tension, which could be difficult to control between different test set-ups. Rebound velocity of the torso (at T1 level) has also been suggested by Hell et al. (2002) as a criterion reflecting the rebound phase.

Evaluation criteria based on neck loads were not included in the study since the neck loads available in the upper neck varied throughout the test series due to probable variation in dummy positioning. More recent studies have suggested criteria based on upper neck readings, such as Nkm (Schmitt et al. 2002) and also on lower neck loads, LNL-index (Heitplatz et al. 2003). In this study, the neck loads were much more affected by the dummy positioning than were the acceleration signals; this shows the importance of drawing conclusions based on several equivalent tests as well as having a controlled dummy positioning procedure.

Frontal impacts

Accident data

In the statistical study in (III), occupant characteristics, kinematics (head impacts) and behaviour at the time of impact are found to be the most prominent areas of parameters with regard to the risk of AIS1 neck injuries in frontal impacts. The main findings are:

- Women have a significantly higher risk of initial neck symptoms than men.
- Occupants under the age of 50 have a significantly higher risk of neck symptoms than those over.
- Occupants weighing less than 65 kg have a significantly higher risk than heavier occupants (Figure 18). Significance is also found for women separately.
- For women, a higher risk with a lower BMI (Body Mass Index) was found, identifying the thinnest women as being most at risk. This relationship did not, however, apply to men.

- Occupants who stated that they tensed their neck (incl. shoulder) muscles at the time of impact are at significantly higher risk of initial neck symptoms than occupants who did not.
- Occupants tightly gripping the steering wheel or straightening their arms show a significantly increased risk of initial symptoms in comparison with those who did not report such an activity (Figure 19).
- Drivers stating that they impacted their head against a frontal interior structure are found to be exposed to a significantly higher risk of initial and persistent neck symptoms than those who did not. This is especially true for men. The difference is not affected by impact severity or occupant stature.
- No significant difference between different impact angles could be found.
- EBS (Equivalent Barrier Speed) does not show a significant relationship to the AIS1 neck injury risk.
- No significant findings are made with respect to belt pre-tensioner and airbags, mainly due to the small number of samples.
- Occupants reporting prior neck problems have a higher rate of persistent symptoms (> 1 year) but no difference with respect to passing symptoms (< 3 months) as compared to those without prior neck problems. Beside this, there is no distinct pattern for the duration of neck symptoms.

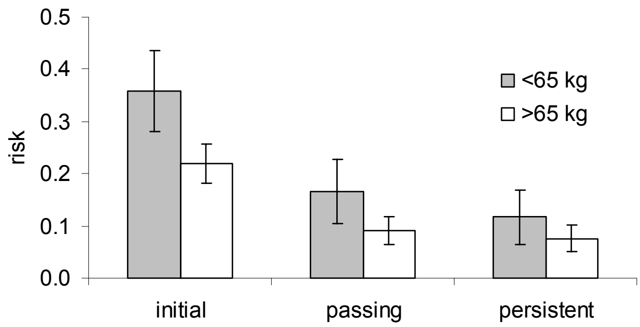

Figure 18 - Risk of initial, passing and persistent symptoms by occupant weight.

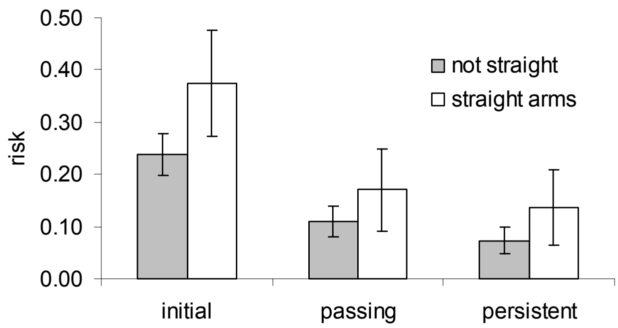

Figure 19 - Risk of initial, passing and persistent symptoms for drivers with or without straight arms during impact.

The conclusions from the impact severity measure study (IV) are:

- Using logistic regression analysis, AIS1 neck injuries are found to have significant correlation to maximum change of velocity, and mean deceleration, as well as maximum value of a polynomial approximation of the acceleration pulse (Polmax).
- Stepwise in 33ms intervals (during the first 100ms) the average mean acceleration is generally higher for those with neck symptoms as compared to those without. This is, however, not distinguishable when separated in max. Δv groups.
- Occupants with AIS1 neck injuries are found as low as maximum change of velocity below 10 km/h and mean deceleration below 20 m/s^2, indicating that other non impact severity parameters are influential as well.

With the aim of evaluating the influence of different parameters on the risk of AIS1 neck injuries in frontal impact, a broad variety of parameters were analysed in (III) and (IV). Some of the most prominent parameters in these studies are not usually available in statistical accident data, such as occupant reaction and preparation activities, details of head impacts, and details regarding car crash pulse. The importance of having a wide range of information when seeking influencing parameters is emphasised by the results in this study. The number of observations in this study was, however, sometimes too small to permit the evaluation of all interesting combinations of parameters.

In (III) using EBS, no relationship between AIS1 neck injuries and impact severity was found. EBS is, however, an insensitive severity measure and does not reflect, for example, differences in crash pulse shape. Kullgren et al. (2000a) emphasised that the shape of the crash pulse influences the risk of long-term neck consequences. In (IV) it was shown that both maximum change of velocity and amplitude of deceleration (using a polynomial approximation, Polmax) influenced the risk of initial AIS1 neck injury. When taking both measures into account using multiple regression analysis, the amplitude (Polmax) was found to be the only significant impact severity measure. However, when calculating stepwise average mean accelerations for different groups of maximum change of velocity (max. Δv) the relationship between max. Δv and AIS1 neck injury risk was quite obvious. As an example, among the impacts below max. Δv 10 km/h, only 3 out of 45 were injured. While in impacts above max. Δv 30 km/h as many as 9 of 24 were injured. Max. Δv could be a confounder when grouping all pulses together in studying the influence of pulse shape.

As in rear-end impacts, occupant characteristics are important with respect to AIS1 neck injury risk in frontal impacts (III). The risk for women is significantly higher than for men. Younger occupants, especially those aged between 30 and 50 are more at risk, and when comparing occupants younger than 50 with those older than 50, significance could be found for initial as well as passing symptoms. Significance is also found for women separately. In rear-end impact situations, the risk of AIS1 neck injuries is found to increase with increased stature (I, VI). This trend could not be found for frontal impact situations, even if the genders were studied separately. Regarding the weight of the occupant, a significantly higher AIS1 neck injury risk is found for occupants weighing less than 65 kg than for those weighing 65kg - 80kg. In order to better understand why occupant weight but not occupant stature has an effect in frontal impacts, a combined measure BMI (Body Mass Index) was used. For women a relationship between BMI and initial symptoms was found, identifying the thinnest women as being most at risk. No relationship could be seen for men. It is not possible to explain the differences between gender and the reason why not only light women but also thin women have the highest risk, using this material.

One interesting finding is the clear influence of tensed neck (incl. shoulder) muscles (III). A higher risk of sustaining initial neck symptoms is found when muscles were tensed. This is significant for both the total number of occupants and women separately. For men, however, significance is only found in the sub-group of passing symptoms. There are several questions to be asked related to these findings: Why are there gender differences? How do different people interpret the question of muscle tension? Is it possible for the occupants to remember their actions at the time of impact? Is the memory of the accident influenced by the severity of the outcome? The answers to these questions cannot be drawn from this study. In volunteer studies the effect of muscle tension has been studied. Siegmund (2001) found that type and level of awareness had an effect on the resulting muscle and kinematic responses. The influence of neck muscle tension, in addition to other preparation activities should be further explored.

One of the parameters shown to be most closely related to AIS1 neck injury risk is the head impacting the interior structure (III). This parameter mainly applies to men, but the reason for this is not obvious. The AIS1 neck injury risk due to head impacts is found regardless of occupant stature and impact severity, at least according to EBS (III). This finding has not been reported earlier and is an important area to analyse further as it will probably give valuable information on possible injury mechanisms.

For some of the parameters (head impacts, weight) differences are found between men and women. The differences are difficult to understand, and both anatomical as well as behavioural differences in gender are probably relevant. There are some differences among the parameters with regard to the different symptom groups. Some of the parameters seem to be more related to passing symptoms, such as age and low weight (for women), whilst others seem to be more related to persistent symptoms, such as head impact and prior neck problems.

Study (III) makes it clear that there are several parameters other than conventional impact severity that influence the risk of AIS1 neck injuries in frontal impacts. The complexity of influencing parameters was also emphasised in an in-depth multi-disciplinary study of 24 occupants with WAD from frontal impacts in Volvo cars (Jakobsson et al. 2003). In the in-depth study, several different occupant kinematics were identified, all resulting in symptoms classified as whiplash associated disorders. Among these, two unbelted occupants experienced neck compression caused by head impacts which is far from traditional whiplash motion. Compared to occupants restrained only by a seatbelt, occupants with arm resistance influence showed a greater representation of symmetrical neck symptoms. In Jakobsson et al. 2003, factors influencing the duration of symptoms were found to be neck posture related and physical as well as psycho-social factors such as strong negative reactions, bad prognosis expectations and a stressed daily situation. No relationship between long term symptoms and estimated change of velocity was found, but those having primary high intensity symptoms were more likely to have long duration symptoms.

With the help of the identified parameters and the understanding of the complex influence of different occupant related parameters, this is a step towards increasing our understanding of AIS1 neck injuries in frontal impacts.

Occupant modelling, biomechanical guidelines and evaluation criteria

The occupant modelling in (V) aimed at increasing the understanding of occupant kinematics, giving directions for biomechanical guidelines as well as evaluating possible injury criteria for frontal impacts. In all the simulations in (V), the occupant's neck moves in an initial protraction motion, until the head flexes forward into the forward flexion motion. In some of the situations, an initial pure extension phase is seen.

Typical neck kinematics are seen for the different situations, respectively, as visualised by plotting upper and lower neck link angles, Figure 20. Occupants with less mass have a more extended neck in the initial protraction phase and also a generally more pronounced upper neck angle. Occupants with initial arm resistance have generally greater lower neck angle at the time when the upper neck link shifts from extension to flexion. This is found equal in time when the neck link reached its greatest length, which also approximately corresponded to time of maximum neck tension. The arm resistance offers an additional load path and the T1 rotation is reduced initially because of the less bending of the upper torso. The types of injury mechanisms the two kinematic observations represent are difficult to state, based on this study. Because of the consistency in the kinematics responses (same finding for all three sitting postures and all four pulses) and the fact that occupants with less weight as well as those with straight arms are found more vulnerable in epidemiology studies, it would be interesting to further study these kinematics responses in the search for possible injury mechanisms. In order to do that, a neck with more detailed geometries and biofidelic local kinematics is needed.

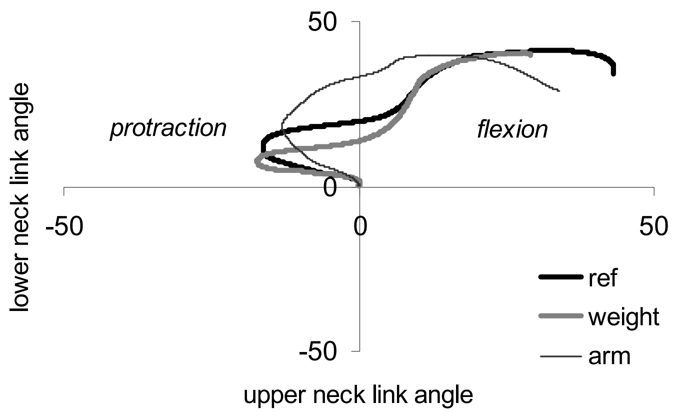

Figure 20 - Example of neck kinematics with upper neck link angle plotted versus lower neck link angle. Each quadrant represents a neck kinematics; upper left quadrant is protraction motion, upper right quadrant is flexion motion.

The general guidelines to be drawn from this study is that in frontal impacts, the upper and lower neck movements should be kept as small as possible. Supporting indications are found in this study that both the protraction phase as well as the protraction-flexion shift phase could be injury producing.

NIC_{min} is found, in comparison of 50% of the 24 pair-wise situations, to consistently reflect the anticipated relative AIS1 neck injury risk in the initial protraction phase. In the protraction-flexion shift phase, criteria such as N_{IJ}, Nkm and upper neck shear forces in approximately 40% of the situations are found to reflect the anticipated AIS1 neck injury risk differences, while lower neck tension force reached almost 60%. In the full flexion phase, upper and lower neck extension (My) only to a minor extent correlate to anticipated AIS1 neck injury risk relation.

An important finding in (V) is the influence of sitting posture, which shows the complexity of the issue when the dummy responses are not consistent between the different sitting postures. This was especially obvious for NIC_{min}: having 100% consistency when the occupant was in the regular sitting posture, but less than 50% for the rearward or forward leaning occupant. There is no obvious reason for this, but it emphasizes the importance of considering different sitting postures, as well as a spectrum of impact severity in injury protection system development and evaluation.

GENERAL DISCUSSION

Method

The complexity is immense of the various human, car and crash related factors causing the broad set of symptoms included in the diagnosis of WAD. No single injury mechanism has so far been proposed as being responsible for all the symptoms. This means that a method that covers a variety of symptoms needs to be used. The method chosen in this study is a holistic approach, combining knowledge regarding parameters in the crash situation influencing AIS1 neck injury risk with the injury mechanism hypotheses and occupant modelling presented. The feasibility of the method was supported by the evaluation of a car seat (WHIPS), which is standard in all Volvo cars since year model 2000. This seat was based on the work in this thesis and was shown to have a good AIS1 neck injury reducing effect in rear-end impacts (VI).

Recently, Eriksson and Kullgren (2003) used a similar approach in evaluating possible AIS1 neck injury criteria in a detailed parameter study, by combining field data findings with occupant modelling. In the search for possible evaluation criteria, Heitplatz et al. (2003) also used a similar approach, testing different car seats with different known field AIS1 neck injury outcome. The method used in the present study could be used in other areas, especially where the injury mechanisms are unclear. A version of this method has been used for the study of ankle injuries in frontal impacts (Forssell et al. 1996).

The present work consists of statistical analyses of four different accident data samples and two series of occupant modelling using mechanical and mathematical occupant models, respectively. The total study is dependant on the results in each method used, which in turn are dependant on the limitations in the specific method. In the text below, the limitations will be discussed together with the interpretation of the results. The detailed discussion regarding the specific results can be found in the previous chapter of results and discussions, separated for frontal and rear-end impacts.

Accident data

Analysis of accident data constitutes an important source of knowledge and adds to the understanding of possible injury mechanisms as well as set the direction for improved design of injury protection systems with the aim of reducing AIS1 neck injuries. In this study, the results of accident analysis emphasise the importance of considering the whole spine of the occupant as well as taking into consideration different individual characteristics and behaviour, including sitting posture, at the time of impact. It would be desirable to have a large body of statistical material containing in-depth information including occupant characteristics (gender, age, weight, stature) measurements of sitting posture, follow-up of symptoms, psycho-social information, and detailed information about the car and the crash. Usually, however, the information is either too narrow in scope or the cases too few. In the future, an aim should be to include more details relating to sitting posture and behaviour, details regarding type and duration of neck symptoms and, where possible, crash pulse data from crash recorders.

The four separate accident studies were based on different accident data sets. They were all based on Volvo cars in Sweden. Generalization for other cars and countries can only be speculated and varies, depending on which parameter in question. When studying the influence of occupant related parameters, there is no obvious reason for general differences between countries or car models. It would rather be seen as a strength to have a homogenous data set reducing the influence of country and car related factors. However, in (IV) when analysing details of the crash pulse, the car structure is important. Whether the results from this study can be extended to other car models is difficult to say, at this time, because analysis of crash recorder data is still a very new topic. Only Folksam has presented such data (Kullgren 1998, Krafft 1998b). Folksam's data is also based on a limited number of car models and at a first comparison, there are both similarities and dissimilarities between the Folksam data and the Volvo data. Continuous efforts should be made in collecting and analysing crash recorder data.

Due to difficulties in collecting the crash recorder data, only a small selection (157) of impacts with onboard crash data was available for analysis (IV). However, since there was no systematic selection of the cases the results are probably not affected by a systematic error. In (I) and (III), the data was from Volvo's accident data base containing only car impacts with a specific repair cost level (today 35.000 SEK), excluding minor impacts. This is a limitation and has to some extent been compensated for in rear-end impact analysis by the study in (VI), without impact severity limitations. The findings with respect to influencing parameters showed several similarities between the two rear-end impact studies (I) and (VI).

The results of the accident analyses in (I), (III), (IV) and (VI) should be regarded as comparative studies of the parameters evaluated. No effort has been made to compare absolute risk values between the studies or with other studies, since risk values are very dependent upon the collection criteria in the dataset. However, the directions of the findings were all in line with previous reported analyses (Morris and Thomas 1996, Temming and Zobel 2000, Berglund et al 2003) as well as adding some new findings of important parameters for AIS1 neck injuries.

As for all studies involving individuals, the accuracy of the reported parameters can be questioned. For all the accident data studies in this thesis, the occupant related parameters are mostly self reported, except for study (I) and (IV) where the injury data is a combination of self-reported and taken from medical journals. To get a consistent reporting of AIS1 neck injury for a large number of occupants is difficult. The ultimate consistency and objectiveness would be to have a standardized examination protocol performed by one examiner for all the occupants. For obvious reasons, however, this type of data will have to be more selective and less in amount. In study (III) and (VI), the initial AIS1 neck injury as well as the details of the symptoms and signs after three months and one year were provided through a questionnaire. This method was chosen because it gave the best consistency between the cases. The alternative would have been to gather follow-up medical reports, but then there would be information missing (some occupants do not attend follow-up) as well as interpretation difficulties of the medical reports by a third person. Providing all occupants with a questionnaire where they report their problems in a consistent way, may not be objective, but since the symptoms are mainly pain-based which by definition is subjective, this would give the best quality for the purpose of these studies. In addition, it can be questioned how well one remembers the sitting posture at the time of impact. That question is relevant and the probability of inaccuracy of the responses needs to be taken into consideration in the interpretation of the results. However, since there are probably no major systematic differences of inaccuracy between the two groups of injured/non-injured, the conclusions regarding influential parameters are probably not affected too much. Used in a careful way, the increased knowledge of influence of sitting posture and behaviour gives valuable information in the development of injury protection systems.

The parameters found influential in this study are to some extent similar for frontal and rear-end impacts. Regarding frontal as well as rear-end impacts, gender is an important risk factor with respect to neck injury risk (I, III, VI). In rear-end impacts increased occupant stature is related to increased injury risk (I, VI), while in frontal impacts, occupant weight seems more related to injury risk (III). Prior neck problems is a risk factor irrespectively of impact direction (III, VI). Sitting posture is influential both in frontal and rear-end impacts; however, with respect to different parameters. In rear-end impacts, the head-to-head restraint distance as well as head rotation significantly influenced risk of AIS1 neck injury (VI), while in frontal impacts, tight grip of steering wheel, tensed neck muscles and straightened arms were all related to increased risk of AIS1 neck injury (III). For both frontal and rear-end impacts, EBS was not found to be a good impact severity measure (I, IIII). In frontal impacts, the available crash recorder data in (IV) enabled the exploration of some possible impact severity measures. It also showed that even at low values of the impact severity measures, AIS1 neck injuries were found, indicating that other parameters (such as occupant characteristics and posture) are possibly as important as the car crash pulse.

The findings in the present study confirm earlier studies as well as introducing a focus on additional influencing parameters. The influence of straightened arms, tensed muscles, tight steering wheel grip and head impacts in frontal impacts have not been reported earlier. This new knowledge will help to give insight into possible neck kinematics related to increased AIS1 neck injury risk.

Occupant modelling

By using mathematical occupant models, it was possible to visualise the effect of the different parameters and to some extent identify important injury evaluation measures. At the time when the rear-end impact mathematical occupant modelling was carried out, the model used was the most advanced rear-end impact occupant model that was practical for studying the parameters chosen (Jakobsson et al. 1994). It comprised the important features of individual vertebral segments as well as the possibility of changing several characteristics of the seat backrest. It was further refined, extensively, to a model of BioRID, and has been used for several successful parametric studies of AIS 1 neck injuries in rear-end impacts (Eriksson 2000, Eriksson and Kullgren 2003). Today, there are several advanced models, making it possible to carry out detailed studies of neck movements. However, even if the early model in Jakobsson et al. (1994) was less detailed and refined, it is still useful in indicating the trends in occupant kinematics as a function of seat and occupant properties. The recent study of Kullgren et al. (2003), using the BioRID model, confirmed to some extent the results in Jakobsson et al (1994), by identifying similar injury related measures.

The model chosen in the frontal impact parameter study in (V), is a human occupant multi-body mathematical model, validated for frontal impacts. The model comprises the simplicity of a multibody model as well as a segmented spine and humanlike torso and shoulders enabling humanlike general kinematics. The occupant model was not validated in its environment, because of lack of validation data, thus the responses can not be seen as absolute values. This is believed not to influence the conclusions of the study since the aim was to compare differences of response for identified situations. It is a strength, adding a robustness to the results, that the present study evaluates the effects of the chosen situations in three different sitting postures and four different crash pulses. However, it is a limitation that only two situations with increased relative AIS1 neck injury risk were simulated. The results are thus only valid for the situations of reduced occupant weight and initial resistance of straightened arms as related to a reference situation with lower AIS1 neck injury risk. The reason for this was that the two situations were the only ones with significant higher risk found in the accident data that were possible to simulate. Even though mathematical models enable the study of the effect of different occupant characteristics more easily than mechanical models, there are limitations on which parameters are reliable to adjust. Today, the easiest occupant characteristics to adjust in mathematical models are stature and weight, but one should aim at obtaining enough knowledge of the influence of other characteristics such as gender, in order to evaluate the effect of more parameters in a comparative study.

In study (II), the rear-end impacts crash test dummy prototype BioRID I was used. The production version, BioRID II, has replaced the prototype. There are minor differences between the two dummy versions which probably slightly affect the absolute values of the responses. However it is not likely that the relative differences between the tested situations are significantly affected; thus the conclusions from this study are likely to be valid even with the production version of the dummy, BioRID II. Another limitation in study (II) was the lack of a documented dummy positioning procedure, leading to large variability in the upper neck force and moment responses, which were thus excluded. Recent studies have suggested measurements based on the upper neck force transducer to have good correlation to AIS 1 neck injury risk (Schmitt et al 2002, Kullgren et al 2003).

Biomechanical guidelines, evaluation criteria and test procedures

Biomechanical guidelines were defined as a part of the study. The three biomechanical guidelines for rear-end impacts are general, regarding occupant acceleration, relative spine movements and reduced forward rebound (I). In frontal impacts, the first step towards establishing guidelines is taken, suggesting that the initial upper and lower neck movements should be kept as small as possible (V). Interesting findings of possible injury producing kinematics in the protraction phase as well as in the protraction-flexion shift phase are made by plotting upper neck link angle versus lower neck link angle. In order to explore these possible injury related kinematics, more geometrically biofidelic models are needed.

The biomechanical guidelines can be criticised for being too general. However when lacking exact injury mechanisms, they serve an important purpose by describing the desired occupant kinematics, and constituted a necessary step in proceeding towards improvement measures in car design.

In frontal impact, possible evaluation criteria were evaluated using mathematical occupant modelling (in three sitting postures and four crash pulses) of two situations with known higher AIS1 neck injury risk as compared to the reference situation (V). No criterion was totally consistent with the anticipated relative AIS1 neck injury risk. Quantitative measurements for rear-end impacts were achieved by breaking the biomechanical guidelines down into evaluation criteria, using a sled test series and a hypothesis based on accident data. The set of evaluation criteria suggested for rear-end impacts, in this study, is an initial attempt at defining robust measures for evaluating AIS1 neck injury protection systems. Effort should be put into evaluating more parameters so as to improve the evaluation criteria and best reflect the origin of the biomechanical guidelines. In addition, as injury mechanisms become better understood, there should be an emphasis on defining evaluation criteria corresponding to the new improved injury mechanism. For frontal impacts, this work has just recently been started and basic injury mechanism research is needed as well as more parameter studies using occupant modelling.

Ultimately, it would be desirable to have a single criterion addressing a single injury. This is not possible for AIS1 neck injuries today. Thus an unbiased and broad view, addressing all possible injury mechanisms, is the best way of evaluating the risk of AIS1 neck injuries. The exact injury type and location as well as the injury mechanism have not been established. It is not clear whether the broad set of symptoms can be explained by a single injury or if there are several injury locations. Moreover it is unclear whether short and long-term symptoms originate from the same injury.

The choice of evaluation criteria is very much dependent on the test procedure, especially the choice of dummy. A human-like dummy, validated for the specific impact situation, is necessary. There are many different objectives regarding test procedures. They could be designed for use in the development of injury protection systems, but could also be used for evaluating different systems on a rating basis. For frontal impacts, few studies have been made in this area (Cappon et al. 2003). However for rear-end impacts, the development of official test procedures for evaluation of whiplash protection in rear-end impacts is very intense, with ongoing discussion in a number of groups (e.g. ISO, IIWPG, EuroNCAP). The most important aspect for test procedures in evaluating AIS1 neck injury protection systems is taking into consideration the spectrum of different situations in which these injuries occur. Since the occurrence of injury is spread over a large range of impact severity, a safety system must possess the quality of addressing the whole severity span as well as the span of occupant size and sitting posture. Development of test procedures should, however, be carried out with caution and with an eye on all relevant findings in accident data and research into injury mechanism.

The significance of this study is twofold. Firstly, the identifications of various influencing parameters as well as visualisation of possible injury causing kinematics add knowledge to the puzzle of understanding the occurrence of AIS1 neck injuries in frontal and rear-end impacts. Secondly, the development and evaluation of a feasible approach for injury mitigation when the injury mechanism knowledge is limited. The approach was possible to implement in the process of safety systems development (I) with a successful injury reducing outcome (VI). It represents a robust approach for addressing an injury where the mechanism of injury has not been identified, taking low risks, and implementing a safe direction in the development of new injury protection systems.

CONCLUSIONS AND RECOMMENDATIONS

A procedure for evaluation of AIS1 neck injuries based on a number of sub-methods has been developed and evaluated. The method is a holistic approach, combining knowledge regarding parameters in the crash situation influencing risk of AIS1 neck injury as well as presented injury mechanism hypotheses.

Based on the accident analyses in the present study, the importance is shown of having detailed information regarding the occupant (characteristics as well as sitting posture and behaviour) and high quality impact severity information. Because of its consequences on injury outcome, it is recommended to include this information when collecting and analysing AIS1 neck injury accident data. The most central parameters identified in this study are:

- Occupant characteristics, such as women in frontal and rear-end impacts; increased stature and weight in rear-end impacts; and reduced weight in frontal impacts and prior neck problems, irrespectively of impact direction.
- Sitting posture, such as increased head to head restraint distance and rotated head in rear-end impacts; tight steering wheel grip; straightened arms; and tensed neck muscles in frontal impacts.
- Head impacts in frontal impacts.
- EBS was not found related to risk of AIS1 neck injuries for neither frontal nor rear-end impacts. In frontal impacts possible impact severity measures are identified, based on crash recorder data.

Combining accident data and occupant modelling, biomechanical guidelines are suggested as a first step towards requirements for development of AIS1 neck injury protection systems. In rear-end impact the aim should be to reduce occupant acceleration, reduce relative spine movements and reduce occupant rebound. In frontal impact, initial neck movements should be kept as small as possible.

For rear-end impacts, evaluating occupant acceleration, average relative spine velocity, NIC_{max} and forward torso rebound velocity are suggested as evaluation criteria. In frontal impacts several possible criteria are evaluated, none of which were consistent in all three tested sitting postures and four crash pulses. NIC_{min} and neck tension had the best confidence for evaluating the initial protraction phase and the protraction-flexion shift phase, respectively. More studies are needed addressing the significance of different evaluation criteria for AIS1 neck injuries, for both frontal and rear-end impacts. This study highlights the importance of considering different sitting posture, occupant size and impact severity, in the development of criteria as well as when designing and evaluating AIS1 neck injury protection systems.

A car seat (WHIPS) which addressed AIS1 neck injuries in rear-end impacts was developed, based on the biomechanical guidelines and the approach developed in the present study. Using accident data, the AIS1 neck injury reducing effect of WHIPS is evaluated in this study. As compared to previously used seat designs in the same car models, a significant AIS1 neck injury reducing effect of WHIPS is found, both for initial neck problems (33%) as well as problems lasting more the one year (53%). These findings demonstrate that the method used is a robust approach for addressing an injury where the injury mechanism has not been fully understood, and implementing a safe direction in the development of injury protection systems. The approach employed in the present study can be used for AIS1 neck injuries in all impact direction as well as for other injury types where the injury mechanisms are complicated.

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