Low severity rear impact simulations with average male and female dummy models in Euro NCAP test configuration

Astrid Linder[a], Kristian Holmqvist[a] and Mats Y Svensson[b]

[a] Swedish National Road and Transport Research Institute, [b] Chalmers University of Technology

Abstract

Rear impacts often cause soft tissue neck injuries, also referred to as whiplash injuries, which can lead to long term suffering. These injuries account for more than 60% of the costs of all injuries leading to permanent medical impairment for the insurance companies with respect to injuries sustained in vehicle crashes. Injury statistics have shown that females are subject to a higher risk of sustaining this type of injury than males and that recently developed anti-whiplash systems protect females less than males. In this study, simulations were run with both an average male and a recently developed average female dummy model seated in a vehicle seat. The three crash pulse severities of the Euro NCAP low severity rear impact test were applied. The motion of the neck, head and upper torso were analysed in addition to the accelerations and neck injury criterion, NIC.

Simulations with the male and the female dummy models showed differences related to both the crash severity and between the two dummies in a particular crash severity. For all three pulses the NIC values were higher for the EvaRID dummy than for the BioRID. The results of the study highlight the need for an extended test matrix. The inclusion of an average female dummy model would provide seat developers with an additional tool to ensure good whiplash protection also for female occupants.

Introduction

Whiplash Associated Disorders (WADs), also referred to as whiplash injuries, sustained in vehicle crashes is a worldwide problem. Estimates for the European Union, based on (Kullgren et al. 2007), indicate that 300 000 European Union citizens suffer whiplash injuries annually, of which 15 000 result in long term suffering and an associated socio-economic impact of approximately EUR 10 billion per annum (EEVC 2005). The US insurance research council reported that neck sprains or strains cost USD 8.8 billion annually representing up to 25% of the total expense for all crash injuries (US IRC 2008). In Sweden, such injuries account for ~70% of all injuries leading to disability due to vehicle crashes (Kullgren et al. 2007). The majority of victims experiencing initial neck symptoms recover within a few weeks or months of the crash (The Whiplash Commission 2005), however, 5–10% of individuals experience different levels of medically classified permanent disabilities (Nygren 1983; Krafft 1998; The Whiplash Commission 2005). Whiplash injuries occur at relatively low velocity changes (typically <25 km/h) (Eichberger et al. 1996; Kullgren et al. 2003), and in impacts from all directions, although rear impacts are most frequently featured in accident statistics (Watanabe et al. 2000).

Injury statistics from the mid-1960s until today show that females have a higher risk of sustaining whiplash injuries than males, ranging from 1.5 to 3 times higher (Kihlberg 1969;

O'Neill et al. 1972; Otremski et al. 1989; Morris & Thomas 1996; Dolinis 1997; Temming & Zobel 1998; Richter et al. 2000; Chapline et al. 2000; Krafft et al. 2003; Jakobsson et al. 2004; Strovik et al. 2009). In fact, concepts for whiplash protection seats have proved to be more effective for males than females (Kullgren & Krafft 2010 and Kullgren et al. 2013). These results suggest that the safety performance of different seat concepts may vary when occupied by males and females. It is important to further evaluate and understand the reasons behind such differences, in order to provide better protection for both genders, and females in particular.

Crash test dummies are used when developing and evaluating occupant protection performance of a vehicle. Today, females are not well represented, as the 50th percentile male crash test dummies currently used in low velocity rear impacts (Euro NCAP 2014), the Biofidelic Rear Impact Dummy (BioRID) correspond to a ~ 90th–95th percentile female with regards to stature and mass (Welsh & Lenard 2001). Consequently, current seats and whiplash protection systems are primarily adapted to the 50th percentile male without consideration for female properties, despite a higher whiplash injury risk in females. Recently, the world first numerical crash test dummy of an average female, EvaRID (Eva – female / RID – Rear Impact Dummy), was developed (Linder et al. 2013, Carlsson et al. 2014). Since its introduction to the market, mathematical crash simulations can now be performed with both an average male and an average female model.

The aim of this study was to perform mathematical simulations with both an average male and an average female dummy model seated in a vehicle seat concept model in order to quantify how the dummies responded to the same test configuration in a low severity crash in terms of loading related to risk of soft tissue neck injuries. This was done by applying the three crash pulse severities of the Euro NCAP low severity rear impact test. In order to capture the loading on the neck, the motion of the neck, head and upper torso was analysed in addition to the accelerations and Neck Injury Criteria (NIC).

Method

Simulations were run using the finite element code LS-DYNA MPP R7.1.1 (LSTC, Livermore, CA). Two finite element anthropomorphic test device (FE-ATD) models for rear impact testing were used in this study. The models were the average sized male BioRID IIg version 3.6 (licence from DYNAMore) and the average sized female EvaRID version 1.1.1 (licence from Humanetics). These models will be referred to as *FE-BioRID* and *EvaRID* respectively. The FE-BioRID consists of about 185 000 nodes and 230 000 elements with a total mass of 77.4 kg, and the EvaRID consists of about 150 000 nodes and 190 000 elements with a total mass of 62.3 kg.

The x-acceleration, angular displacement and x-displacement of the head, T1 vertebra and the relative distance between the head and T1 were analysed. The data was processed in accordance to the SAE J-211 (SAE 2003), i.e. the head x-acceleration channel was sampled at 10 kHz and filtered using an SAE CFC 180 and the remaining channels were sampled at 10 kHz and filtered using an SAE CFC 60. The X-direction of the acceleration and displacement corresponded to the horizontal direction.

In addition, the NIC (Boström et al. 2000) was calculated using the relative head to T1 accelerations, in accordance with Eq.1 and the maximum thereof (NIC_{max}), before the Head Restraint Contact (HRC) ended. The unit for NIC is m^2/s^2.

$$NIC(t) = 0.2 * a_x^{rel}(t) + \left[v_x^{rel}(t)\right]^2 \quad \textit{(Equation 1)}$$

The FE-ATD models were seated in one car seat concept model. The seat concept model were built from components of a commercial car seat from the 1990th with a fix head restraint. The seat was attached to a sled with an adjustable toe-board customised to the height specifications of a pre-defined heel-point. The sled assembly was subjected to three acceleration pulses with three severity ratings required by the Euro NCAP whiplash testing protocol (Euro NCAP, 2014, Figure 1). The Low pulse (LP), Medium pulse (MP) and High pulse (HP).

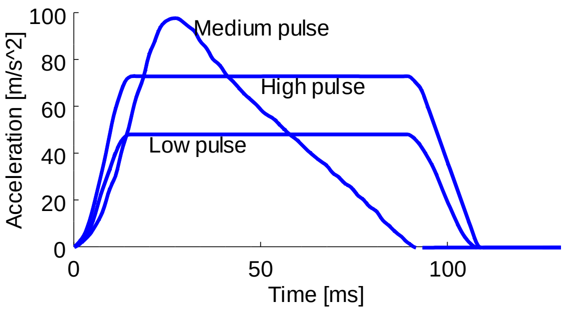

Figure 1. The three pulses of the Euro NCAP whiplash protocol that the FE-BioRID and the EvaRID were subjected to in the simulations.

The postures of the FE-ATDs were in accordance with the Euro NCAP protocol seating procedures and the design angles of the pelvis (26.5 degrees) and head (0 degrees, horizontal) were used. The models were seated by forcing the FE-models hip point (h-point) to match the pre-defined reference point of the seat (r-point), using a prescribed motion in a pre-simulation which resulted in individually deformed seats to be used for the FE-BioRID and the EvaRID models. Lastly, before initiating the simulations, a three point seat belt was added.

Using identical r-points resulted in a head-to-head restraint distance of 38 mm and a height of the FE-BioRID of 40 mm above the head restraint. The corresponding measurements for the EvaRID was a 58 mm distance to the head restraint and 30 mm below the top of the head restraint (Figure 2).

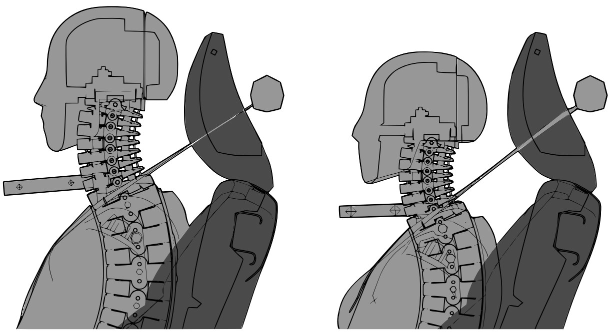

Figure 2. The initial head-to-head restraint distances of the FE-BioRID (left) and the EvaRID (right) models, when identical seat r-points were used.

Results

The simulations with the average male and female dummy models showed differences related to both the crash severity and between the two dummy models in a particular crash severity. For all three pulse severities the NIC values were higher in the EvaRID than in the FE-BioRID (Table 1).

Table 1. Maximum NIC values for the FE-BioRID and the EvaRID model and the timing of the maximum NIC value for all three crash pulse severities, LP, MP and HP.

		NIC	
Euro NCAP pulse severity	**Model**	**Maximum (m^2/s^2)**	**Timing (ms)**
Low (LP)	FE-BioRID	9.5	68
	EvaRID	12.8	77
Medium (MP)	FE-BioRID	14.2	65
	EvaRID	17.5	67
High (HP)	FE-BioRID	12.9	63
	EvaRID	16.0	66

The acceleration and kinematics results showed higher peak x-accelerations for the EvaRID, with a shorter duration compared to the FE-BioRID for all crash pulse severities. Although the EvaRID head and T1 angular displacements were lower, they resulted in a higher relative angular displacement than that of the FE-BioRID. A positive angular displacement corresponded to extension motion. The x-displacements of the head, T1 and the relative displacements thereof were less for the EvaRID than for the FE-BioRID.

The EvaRID made contact with the head rest earlier than the FE-BioRID and the difference in contact time between the dummies increased with increased crash pulse severity. The result from each crash pulse severity is shown in Figure 3, 4 and 5.

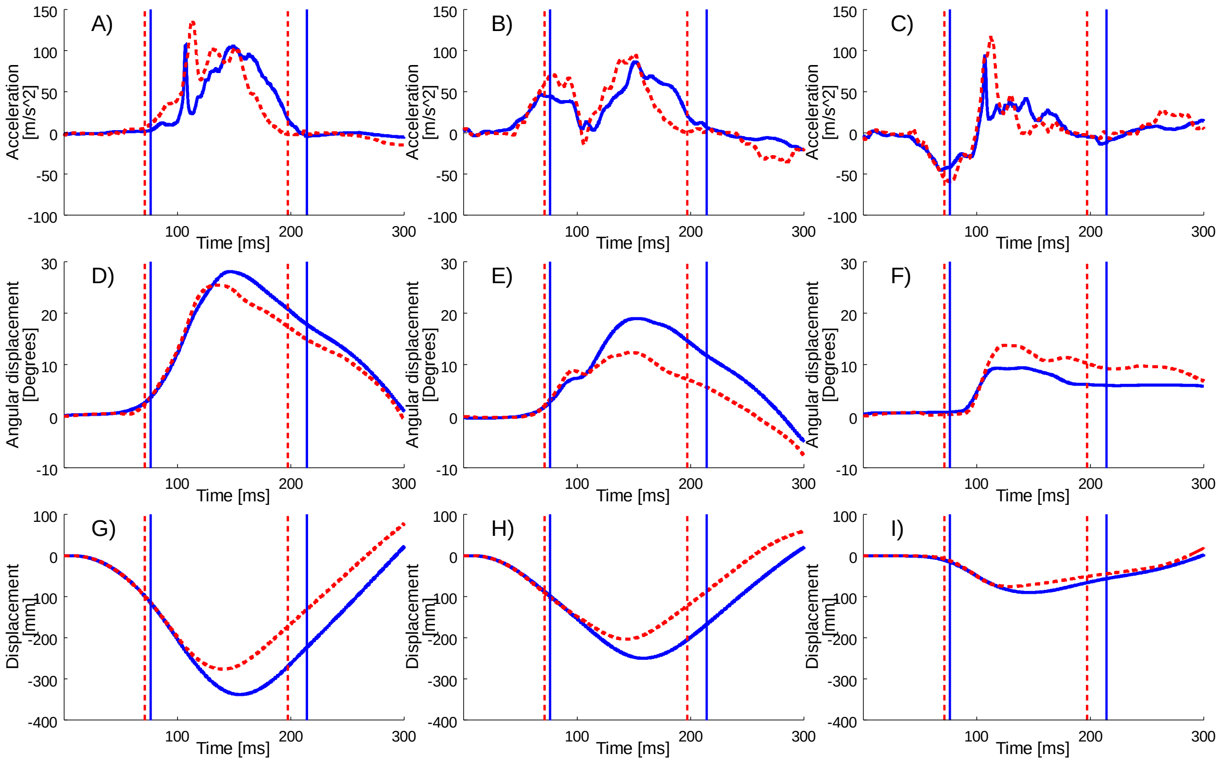

Figure 3. X-acceleration, angular displacements and x-displacements of the head (figures A, D and G), T1 (figures B, E and H) and the head relative to the T1 (figures C, F and I) for the LP Euro NCAP crash severity. Vertical lines shows the start and end of the head rest contact. EvaRID (red dotted lines) FE BioRID (blue solid lines).

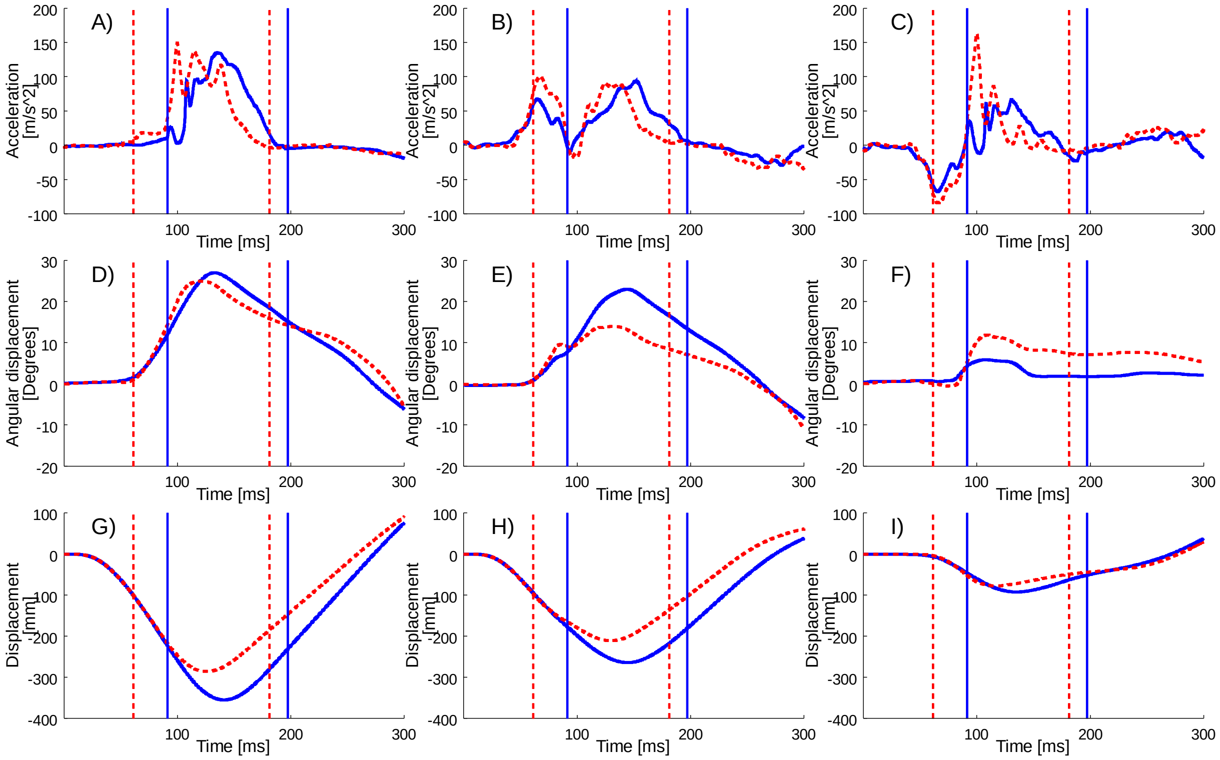

Figure 4. X-acceleration, angular displacements and x-displacements of the head (Figures A, D and G), T1 (Figures B, E and H) and the head relative to the T1 (Figures C, F and I) for the MP Euro NCAP crash severity. Vertical lines shows the start and end of the head rest contact. EvaRID (red dotted lines) FE BioRID (blue solid lines).

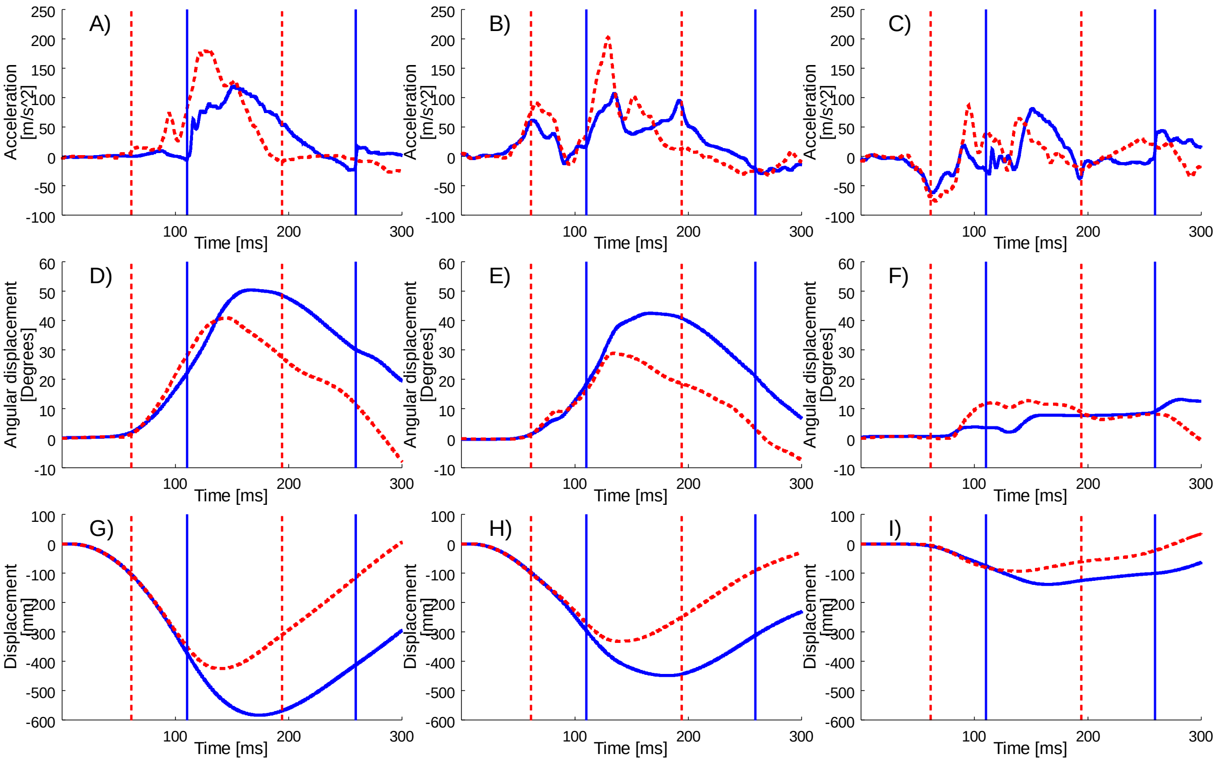

Figure 5. X-acceleration, angular displacements and x-displacements of the head (Figures A, D and G), T1 (Figures B, E and H) and the head relative to the T1 (Figures C, F and I) for the HP Euro NCAP crash severity. Vertical lines shows the start and end of the head rest contact. EvaRID (red dotted lines) FE BioRID (blue solid lines).

The HR contact time for the EvaRID was 5 ms earlier than for the FE-BioRID in the LP, 30 ms earlier for the MP and 50 ms earlier for the HP. The maximum head relative to T1 angular displacement and the horizontal head relative to T1 displacement the peak values for the EvaRID and FE-BioRID are shown in Table 2.

Table 2. Maximum head relative to T1 angular displacement and the horizontal head relative to T1 displacement values for the FE-BioRID and the EvaRID model and the timing of the maximum values for all three crash pulse severities, LP, MP and HP.

		Head rel. T1 Angle		Head rel. T1 Displacement	
Euro NCAP pulse severity	**Model**	**Maximum (angle)**	**Timing (ms)**	**Maximum (mm)**	**Timing (ms)**
Low (LP)	FE-BioRID	9	140	75	145
	EvaRID	14	125	90	129
Medium (MP)	FE-BioRID	6	108	92	134
	EvaRID	12	109	77	177
High (HP)	FE-BioRID	9	259	138	165
	EvaRID	13	147	93	138

The seatback angle differed between models and crash pulse severity, showing that the angle was higher for the FE-BioRID than for the EvaRID (Figure 6). The deflection angles were similar for the LP and MP and the maximum seatback angle close to twice as high as those in the HP.

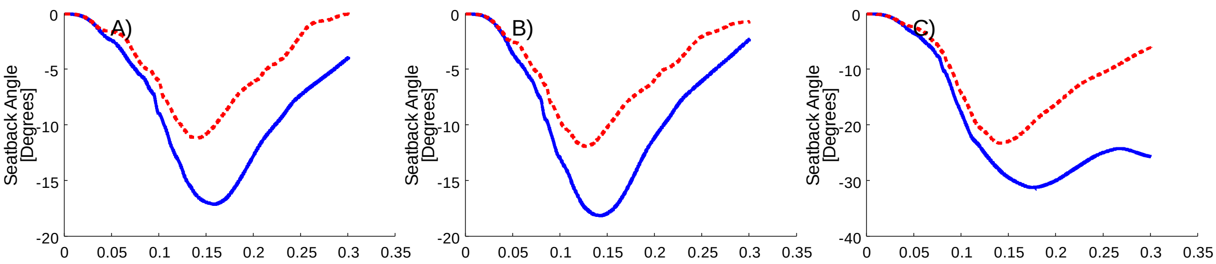

Figure 6. The seatback deflection angles for the LP (left) MP (middle) and HP (right) of the FE-BioRID (solid blue line) and the EvaRID (dotted red lines).

Discussion

Real-world car accident statistics shows that females have a higher risk of sustaining whiplash injuries than males. Alarmingly, studies have also shown that anti-whiplash concepts are more effective for males than females (Kullgren and Krafft 2010 and Kullgren et al. 2013). In order to improve whiplash protection concepts for both sexes, and in particular for females, it is important to better understand what influences the dynamic response and the injury risk. The average male and female differs in among others height, weight, joint stiffness and geometrical properties (Carlsson et al. 2014). These factor might influence the dynamic interaction with the seat during a crash and thus the injury protective performances of the seat. Mathematical simulations in this study with a model of an average male and an average female in one seat model concept showed that the results were consistent for all crash pulse severities with respect to differences in timing, and peak values between the FE-BioRID and the EvaRID. The Low and Medium pulse provided similar magnitude of angular displacement of the seat for both models, while the High pulse gave a larger response in both models. The relative angular displacement of the head to the T1 was consistently larger in the neck of the EvaRID model which was subjected to a larger extension than the neck of the FE-BioRID.

The simulations in this study was performed with one seat model concept. Further knowledge into what to aim for in the future in terms of seat designs providing the best protective performances for both males and females could be gained with simulations using both the average male and female models. The dimension of the torso of the average male and female differs in dimension such as weight, centre of gravity, width and height (Carlsson et al. 2014). The influence of how flat or curved the seat back from side to side is and the influence of specific components of the seat back and its influence on the protective performances on both parts of the population are aspects that could be quantified.

Mathematical simulations with average male and female dummy models showed differences related to both the crash severity and between the two dummy models in a given crash severity. For all three pulses the NIC values were higher for the EvaRID than for the FE-BioRID. In addition, a lower NIC threshold value has been suggested to be used for the female model (Schmitt et al. 2012). The NIC value occur early in the event, before the head to head restraint contact (Table 1 and Figures 2-5). This is in the retraction phase of the neck where hypothesises of injury causing loading has been formulated. A similar seat back deflection angle was found for the LP and MP (Figure 6) and the highest NIC values were calculated for the MP pulse. The LP and MP corresponds to the same change of velocity with a higher acceleration for the MP than the LP. Higher acceleration of the pulse has been shown to correspond to higher risk of injury (Krafft 1998). The results of the study highlight the need for an extended test matrix. The inclusion of an average female dummy model would provide seat developers with an additional tool to ensure improved whiplash protection also for female occupants.

The injury statistics shows that there is a need for assessing the protective performances of seats with models of both males and females in order to promote seat concepts that provide the best possible protection for the whole population. This study shows that using the mathematical models that are available today can provide insight that can be used in future testing.

Acknowledgement

The study was funded by the Swedish Governmental Agency for Innovation Systems, VINNOVA.

References

Boström, O., Fredriksson, R., Håland, Y., Jakobsson, L., Krafft, M., Lövsund, P., ... & Svensson, M. Y. (2000). Comparison of car seats in low speed rear-end impacts using the BioRID dummy and the new neck injury criterion (NIC). *Accident Analysis & Prevention*, *32*(2), 321-328.

Carlsson, A., Chang, F., Lemmen, P., Kullgren, A., Schmitt, K-U., Linder, A., & Svensson, M. Y. (2014). Anthropometric Specifications, Development, and Evaluation of EvaRID—A 50th Percentile Female Rear Impact Finite Element Dummy Model. *Traffic injury prevention*, *15*(8).

Chapline, J. F., Ferguson, S. A., Lillis, R. P., Lund, A. K., & Williams, A. F. (2000). Neck pain and head restraint position relative to the driver's head in rear-end collisions. *Accident Analysis & Prevention*, *32*(2), 287-297.

Dolinis J. (1997). Risk Factors for "Whiplash" in Drivers: a Cohort Study of Rear-End Traffic Crashes, *Injury* 28(3): 173–179.

EEVC (European Enhanced Vehicle-safety Committee) Working Group 20 Report – Working Document 80 (2005). Updated State-of-the-Art Review on Whiplash Injury Prevention. http://www.eevc.net/

Eichberger A., Geigl BC., Moser A., Fachbach B., & Steffan H. (1996). Comparison of Different Car Seats Regarding Head-Neck Kinematics of Volunteers During Rear End Impact. *Proceedings of the International Research Conference on the Biomechanics of Impact*, (pp. 153-164), IRCOBI, Dublin (Ireland).

Euro NCAP. The dynamic assessment of car seats for neck injury testing protocol version 3.2; 2014.

Jakobsson L., Norin H., & Svensson MY. (2004). Parameters Influencing AIS 1 Neck Injury Outcome in Frontal Impacts, *Traffic Injury Prevention*. 2004; 5(2):156-163.

Kihlberg JK. (1969). Flexion-Torsion Neck Injury in Rear Impacts. *Proceedings of the 13th Association for the Advancement of Automotive Medicine (AAAM) Conference*, pp. 1–16.

Krafft M. (1998). Non-fatal injuries to car occupants. Injury assessment and analysis of impacts causing short- and long-term consequences with special reference to neck injuries. *Doctoral thesis, Stockholm: The Institute of Clinical Neuroscience Carolinska Institute*.

Krafft M., Kullgren A., Ydenius A., & Tingvall C. (2002). Influence of crash pulse characteristics on whiplash associated disorders in rear impacts - crash recording in real life crashes, *Traffic Injury Prevention*. 3(2), 141-149.

Kullgren, A., Krafft, M., Lie, A., & Tingvall, C. (2007,). The effect of whiplash protection systems in real-life crashes and their correlation to consumer crash test programmes. *Proceedings of the 20th ESV Conference,* (pp. 1-7), Lyon (France).

Kullgren A., Krafft M., Tingvall C., & Lie A. (2003). Combining crash recorder and paired comparison technique: Injury risk functions in frontal and rear impacts with special reference to neck injuries. *Proceeding of the 18th ESV Conference,* Paper No. 404, Nagoya (Japan).

Kullgren A., Stigson H., & Krafft M. (2013). Development of whiplash associated disorders for male and female car occupants in cars launched since the 80s in different impact directions. *Proceedings of the International Research Conference on the Biomechanics of Impact*, (pp. 51–62), IRCOBI, Gothenburg (Sweden).

Linder, A., Schick, S., Hell, W., Svensson, M., Carlsson, A., Lemmen, P., ... & Tomasch, E. (2013). ADSEAT–Adaptive seat to reduce neck injuries for female and male occupants. *Accident Analysis & Prevention*, *60*, 334-343.

Morris, A. P., & Thomas, P. (1996). Neck injuries in the UK co-operative crash injury study (No. 962433). Warrendale, PA: *Society of Automotive Engineers*; 1996; 317–329. *SAE Technical Paper*.

Nygren, Å. (1983). Injuries to Car Occupants - Some Aspects of the Interior Safety of Cars. *Acta Oto-Laryngologica*. 95(s395): 1-135, doi: 10.3109/00016488309139642.

O'Neill B., Haddon W. Jr, Kelley AB., & Sorenson WW. (1972). Automobile Head Restraints: Frequency of Neck Injury Claims in Relation to the Presence of Head Restraints. *Am J Public Health.* 62(3): 309–406.

Richter, M., Otte, D., Pohlemann, T., Krettek, C., & Blauth, M. (2000). Whiplash-type neck distortion in restrained car drivers: frequency, causes and long-term results. *European Spine Journal*, *9*(2), 109-117.

SAE. (2003). Surface vehicle recommended practice: J211; *Society of Automotive Engineers*.

Schmitt K-U., Weber T., Svensson M.Y., Davidsson J., Carlsson A., Björklund M. & Linder A. (2012). Seat testing to investigate the female neck injury risk – preliminary results using a new female dummy prototype, *Proceedings of the International Research Conference on the Biomechanics of Impact*, (pp. 263), IRCOBI, Dublin (Ireland).

Storvik, S. G., Stemper, B. D., Yoganandan, N., & Pintar, F. A. (2008). Population-based estimates of whiplash injury using nass cds data-biomed 2009. *Biomedical sciences instrumentation*, *45*, 244-249.

Temming J., & Zobel R. (1998). Frequency and Risk of Cervical Spine Distortion Injuries in Passengers Car Accidents: Significance of Human Factors Data, *Proceedings of the International Research Conference on the Biomechanics of Impact*, (pp. 219-233) IRCOBI, Göteborg (Sweden).

The Whiplash Commission (2005). *Final Report* http://www.whiplashkommissionen.se/pdf/WK_finalreport.pdf.

US Insurance Research Council (US IRC). (2008). Auto injury insurance claims: countrywide patterns in treatment, cost, and compensation. Malvern, PA.

Watanabe, Y., Ichikawa, H., Kayama, O., Ono, K., Kaneoka, K., & Inami, S. (2000). Influence of seat characteristics on occupant motion in low-speed rear impacts. *Accident Analysis & Prevention*, *32*(2), 243-250.

Welsh, R., & Lenard, J. (2001). Male and female car drivers – differences in collision and injury risks. In: Proc. 45th AAAM, Texas, USA, pp. 73–91.