SUGGESTIONS FOR EVALUATION CRITERIA OF NECK INJURY PROTECTION IN REAR END CAR IMPACTS

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ABSTRACT

Neck injuries AIS 1, often called whiplash injuries or whiplash associated disorders (WAD), is one of the most significant injury types in car crashes both with respect to frequency and degree of impairment.

Rear end impact sled tests were performed with the aim to develop evaluation criteria for neck injury protection, using a recently developed rear impact dummy (BioRID I). The occupant situations simulated and compared were front seat occupant, rear seat occupant and front seat occupant with increased head to head restraint distance. Based on accident experience, occupants in rear seats and occupants with increased distance to head restraints are at a lower and higher risk, respectively, as compared to a front seat occupant in regular sitting posture.

The method used was to correlate the test data to the known outcome from real world rear end impacts. The evaluation measurements chosen for the testing were based on the three guidelines as presented in Volvo's Whiplash Protection Study (WHIPS). The guidelines concern body acceleration, relative movements of the spine and rebound motion.

This study suggests several evaluation criteria to express the WHIPS-guidelines using the BioRID I. The suggested evaluation criteria did verify the hypothesis of the relation between neck injury risk and different occupant position and posture.

NECK INJURIES, OFTEN REFERRED TO AS WHIPLASH INJURIES or whiplash associated disorders (WAD), (Spitzer et al. 1995) and classified as AIS 1 (AAAM, 1990) are not life-threatening, but are important with regard to frequency and long-term consequences (Nygren 1984, von Koch et al 1994) causing human suffering and cost to society.

Neck injuries are reported at all impact severities (Jakobsson 1997, Otte et al 1997, Lundell et al 1998a and Jakobsson et al 1999). Several different parameters have been found to affect the injury risk in a rear end impact. Gender, stature, age, seating position and sitting posture are factors found to influence the risk of injury (Carlsson et al 1985, Lövsund et al 1988, Olsson et al 1990, Jakobsson et al 1994, Spitzer et al 1995, Krafft et al 1996, Morris et al 1996, Otte et al 1997, Krafft 1998, Temming and Zobel 1998 and Langwieder et al 1999).

The complexity of the various human and car-crash related factors causing the broad set of symptoms included in the diagnosis of WAD is tremendous. No single injury mechanism has so far been proposed as responsible for all the symptoms. Several different mechanisms have been suggested by different researchers. Those concerned include classic hyper extension mechanism (White and Panjabi, 1990); pressure gradient due to initial swift head motion (Aldman et al 1986 and Svensson et al 1993); rebound mechanisms (von Koch et al 1995); relative vertebrae motions

(Ono et al 1993, McConnell et al 1993, Jakobsson et al 1994) and several other. As long as there is no single mechanism proven to be the only one valid, it is necessary to take all possible mechanisms into consideration when evaluating neck injury risk.

One suggested criterion for AIS 1 neck injuries in rear end impact is the Neck Injury Criterion (NIC). NIC was suggested by Boström et al (1996) and is derived from the pressure gradient theory of Chalmers (Aldman et al, 1986). This criterion is a result of a series of experiments on pigs, where pressure amplitudes in the spinal canal were found to correlate with nerve cell damage (Svensson et al, 1993). Eichberger et al. (1999) later showed that a correlation between the NIC_{max} and pressure amplitudes in the spinal canal also applied to human subjects. Mechanical and mathematical simulation of rear-end impacts, have shown that NIC_{max} is sensitive to the major car and crash-related risk factors for neck injuries with long-term symptoms (Boström et al. 1997, Boström et al. 1998, Eichberger et al. 1998, Boström et al. 1999). In the test series described by Eichberger et al., as well as in that described by Wheeler et al. (1998), no volunteer suffered from injuries with long-term consequences, and no NIC_{max} values higher than 12 m^2/s^2 were recorded. The suggested threshold value for long term symptoms is NIC_{max} of $15 m^2/s^2$

In the Whiplash Protection Study (WHIPS) by Volvo (Lundell et al 1998a and 1998b, Jakobsson et al 1999) it was stated that in order to be able to know what engineering efforts to make, the results of all realistic injury mechanism research need to be addressed. Combining it with experience from accident research three biomechanical guidelines were presented (later also referred to as the WHIPS-guidelines).

In order to obtain correct occupant responses (especially with regard to the neck behaviour) in a rear end impact crash test, a test dummy with an anthropomorphic spine which enable the effect of torso push-up motion is required (Lövsund and Svensson 1996). A dummy for this purpose, named BioRID, was developed as a Swedish joint venture. A prototype version, BioRID I, was presented in the autumn of 1998 (Davidsson et al. 1998b, Linder et al. 1998). The BioRID I (Biofidelic Rear Impact Dummy) comprises an articulated spine, a torso of silicon rubber and a modified Hybrid III pelvis. Head, arms and legs are those of a Hybrid III fiftieth percentile dummy. The spine has kyphosis and lordosis, which will allow for the torso push-up motion and the angling motion of the T1 vertebra. The torso is moulded in a soft silicone rubber, with a more humanlike shape and improved mass distribution as compared to existing dummies. The BioRID I prototype was validated against volunteer tests (Davidsson et al 1998a). The kinematics of this dummy prototype show more humanlike kinematics in rear end impacts at $\Delta V = 7$ km/h than the Hybrid III (Davidsson et al 1998b).

Using the BioRID I, and based on a hypothesis developed mainly on the real-life neck injury risk experiences, the aim of this study was to identify evaluation criteria expressing the biomechanical guidelines.

METHOD

The method used in this study was to combine experiences of real life accident outcome and sled test responses. Based on knowledge of neck injury risk factors, sled tests have been performed to study three different occupant situations. Dummy responses have been analysed, using a simple comparison method. Based on a hypothesis, different dummy responses were chosen as evaluation criteria to address the three guidelines in the Whiplash Protection Study (WHIPS). The WHIPS-guidelines, the hypothesis, and the test set up are all explained below.

THE WHIPS GUIDELINES. The three biomechanical guidelines as defined in the WHIPS-study are: 1) reduce occupant acceleration, 2) minimise relative movements between adjacent vertebrae and in the occipital joint, i.e. the curvature of the spine shall change as little as possible during the impact and, 3) minimise the forward rebound into the seat belt.

The first guideline; aiming to reduce occupant acceleration, does not have a direct connection to any suggested injury mechanism for 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 1998 and Jakobsson et al 1999), 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.

Relative motion of the spine as a cause of whiplash injuries has been suggested by several researchers (Aldman 1986, Svensson et al. 1993, Jakobsson et al. 1994, Boström et al. 1996, and Ono et al. 1997, 1998). The knowledge gained from space technology, 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 intact, no injuries are likely to occur. NIC was developed to reflect the initial relative motion of the cervical spine, addressing long-term neck injury symptoms.

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 injury producing (v. Koch et al 1995). The exact mechanism of these findings is not known.

THE HYPOTHESIS. Several studies indicate that the front seat occupants are at a higher risk than rear seat occupants (States et al 1972, Carlsson et al 1985, Lövsund et al 1988, Lundell et al 1998a, Langwieder et al. 1999). This trend can also be seen in Figure 1 which is based on a subset of 2030 restrained adults in Volvo cars, seated in out-board position with similar head restraints (Jakobsson et al 1999).

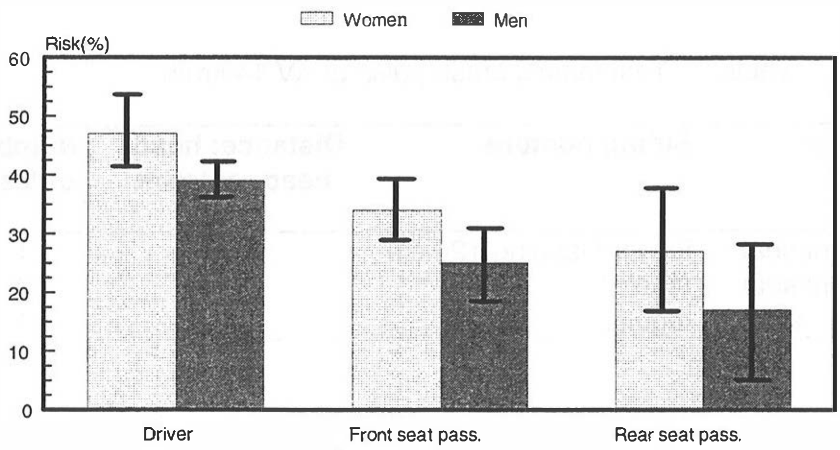

Figure 1 - Neck injury frequency (initial symptoms) including 95 % confidence intervals for men and women in different seating positions (Jakobsson et al 1999)

Front seat passengers were found to be at a significantly lower risk than drivers even though the seats are of the same design, Figure 1. The reason for this could be that drivers are more prone to move the head and upper body to a greater extent than the front seat passengers are. An increased distance between head and head restraint (and seat backrest) has shown to be related to increased risk of neck injury.

This has been shown in accident studies (Carlsson et al 1985, Olsson et al 1990, Jakobsson et al 1994) as well as in studies based on tests with volunteers (Deutscher 1996).

The above findings are the basis for the hypothesis that an occupant sitting in a conventional rear seat (test situation C) is at lower risk than a front seat occupant. An occupant sitting in a regular sitting posture in a front seat (test situation B) is at a lower risk as compared to someone leaning forward simulating the postures of a driver (test situations A).

SLED TEST SET UP. A Volvo S70 car body mounted on a Hyge sled was used. A total of 15 tests were run, using two different crash pulses and four different occupant seating configurations, as shown in Tables 1 and 2. The seats used were Volvo S70 front and rear seats of year model 1998, without the WHIPS system. In all tests, the BioRID I dummy was restrained by a seat belt. The seats were replaced between each test.

The dummy vertebral segments were adjusted in the lumbar region in order to achieve an increased distance between the head and the head restraint (Test situation A'' and A'). The head – head restraint distance was measured horizontally from the back of the head to the head restraint.

Table 1 - Test matrix; crash pulse of ΔV 11 km/h

Test situation	**Seat**	**Sitting posture**	**Distance head - head restraint (cm)**	**Number of tests**
A''	front seat	forward leaning +20 cm	27	1
A'	front seat	forward leaning +10 cm	17	2
B	front seat	regular	6-7	4
C	rear seat	regular	7-8	4

Table 2 - Test matrix; crash pulse of ΔV 14 km/h

Test situation	**Seat**	**Sitting posture**	**Distance: head-head restraint (cm)**	**Number of tests**
A''	front seat	forward leaning +20 cm	27	1
B	front seat	regular	6	2
C	rear seat	regular	7	1

The crash pulses used are shown in Figure 2. The two pulses are both of a maximum acceleration level of 13 g. The 11 km/h-pulse has a ΔV of 11 km/h and, accordingly, the ΔV of the 14 km/h pulse is 14 km/h.

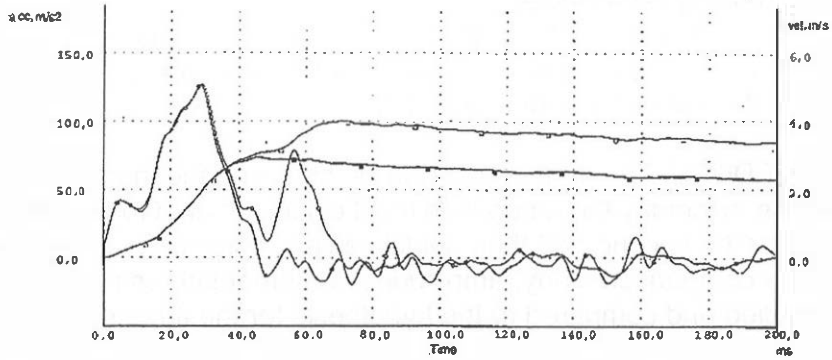

Figure 2 - Acceleration and velocity time history of the two pulses used in the study

THE BIORID I AND INSTRUMENTATION. The dummy used in the tests was the BioRID I prototype dummy (Davidsson et al 1998b). BioRID I and the transducers used are shown in Figure 3.

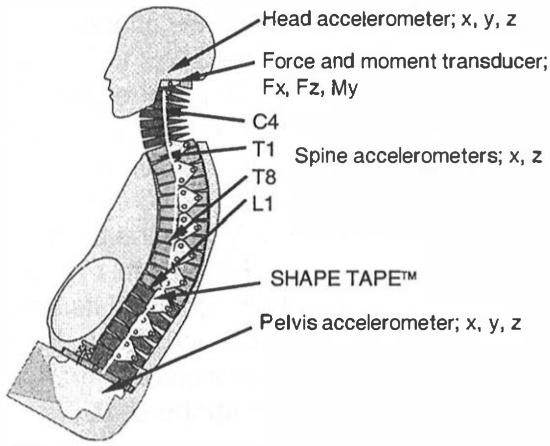

Figure 3 - The BioRID I and instrumentation

The tri-axial accelerometers in the head and pelvis were conventional HIII sensors and positioned according to HIII standard. Uni-axial accelerometers were placed in x and z directions on the side of C4, T1, T8 and L1 vertebrae. The x-axis of a vertebra is defined as the median plane of the vertebrae in anterior-posterior direction. Z-axis is perpendicular to the x-axis of each vertebra. The neck force and moment transducer in the occipital joint was a Denton model 4037. Belt force transducers were attached to the outboard part of the shoulder- and hip portions of the 3-point belt, respectively. The accelerometer monitoring the sled pulse was mounted on the sill.

A displacement measurement system, called SHAPE TAPE™ (ref. Measurand), is fitted along the side of the BioRID's spine. It comprises a steel band (6 mm wide, 0.5 mm thick) with 16 attached curvature measuring sensors along 60 cm of the band. The curvature signals from the sensors are post-test converted to a data-set describing the contour and movements of the spine during the test. The final evaluation program was not complete at the time of publication; hence detailed conclusions from the SHAPE TAPE™ data cannot be presented yet.

The different force, moment and acceleration signals were filtered and processed according to SAE J211 except for the eight spine accelerometers. Due to a non-biofidelic vibration phenomenon of the spine in the prototype BioRID I, the spine accelerometers were filtered with the very tough filter of CFC18 (30 Hz).

NIC was calculated using the formula:

$$NIC= a_{rel} \times 0{,}2 + (v_{rel})^2 \qquad (1)$$

In equation 1, a_{rel} and v_{rel} are the relative T1-C1 acceleration and velocity, respectively. NIC_{max} is the initial maximum amplitude.

ANALYSIS PROCEDURE. The method used when choosing the most relevant evaluation criteria was to identify the responses most closely related to the different WHIPS-guidelines. For the second and third guidelines a simple comparison study was performed. In the comparison study, amplitudes and other interesting parameters were studied and compared to the hypothesis for the three different test situations (A, B and C).

RESULTS

DUMMY REPEATABILITY AND BEHAVIOUR. The 15 tests analysed in this study were from three different test series. Even though performed on different occasions the accelerometer response in the two test situations with four similar tests showed a variation of less than 10%, which can be considered as acceptable repeatability. The largest variation was found in similar test situations performed at different occasions, which was attributed to be mainly due to small variations in dummy positioning. The upper neck readings, especially, were very sensitive to the initial positioning of the dummy. Due to the flexibility of the spine, a small difference in the initial pelvis position and orientation resulted in major differences of the force and moment responses at the occipital joint. Due to this sensitivity and based on the variety of responses in these tests, evaluation criteria based on forces and moments in the neck cannot be recommended in this study. When there are established and well documented positioning procedures for the BioRID, this would be possible.

When loaded by the seat, the BioRID I straightened its spine and the head lag caused an s-shape retraction shape of the cervical spine. In the forward leaning tests, the dummy rolled up along the spine in a smooth motion. Hence, the BioRID I behaviour showed a humanlike interaction with the seat.

TEST RESULTS AND ANALYSIS

Occupant acceleration. Since the rationale for the first guideline of reducing occupant acceleration is more related to crash pulse, rather than sitting position and sitting posture, no correlation study was performed. As would be expected, the acceleration responses of the higher test speed (ΔV 14 km/h) are higher than corresponding tests performed in lower test speed (ΔV 11 km/h), Figure 4.

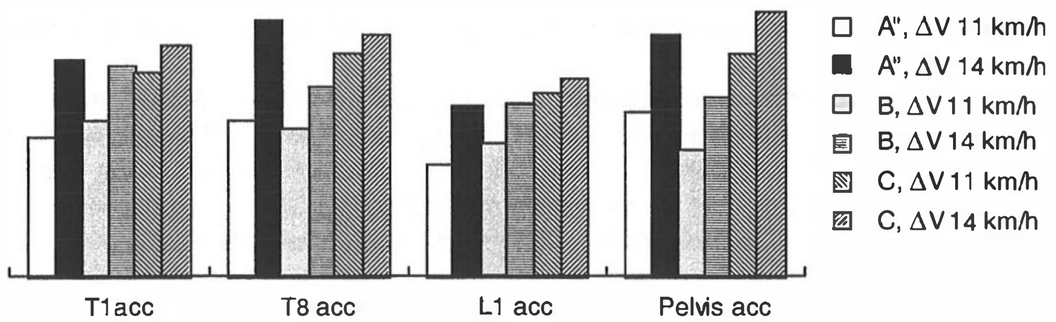

Figure 4 - Comparison of spine peak acceleration

The body accelerations most closely related to the first guideline is suggested to be at the locations closest to seat interaction. As evaluation criteria for mapping occupant acceleration, the maximum of pelvis and spine L1 to T1 accelerations is suggested as evaluation criteria for this guideline.

Spine movements. Several different measures were studied for the second guideline. When analysing the accelerometer signals throughout the spine, the Average Relative Spine Velocity (ARSV) was found to best correspond to the hypothesis. ARSV was defined as the mean value of all the stepwise relative velocities throughout the spine. The relative spine velocities were calculated as the difference in resultant velocities between two adjacent locations of spine accelerometers. The accelerometer locations were head, C4, T1, T8, L1 and pelvis. The maximum amplitude of relative spine velocity, until the time of the rebound of the specific body section, was chosen and mean values in the different situations are diplayed in figures 5 and 6.

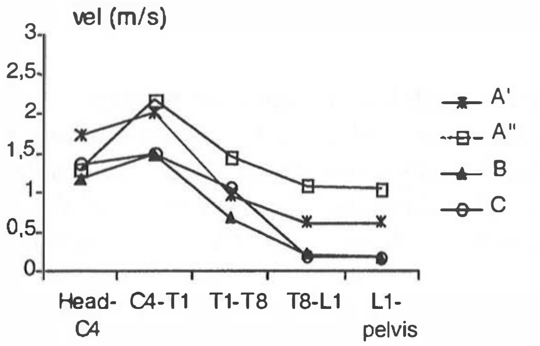

Figure 5 - Relative spine velocity of mean values in tests with ΔV 11 km/h

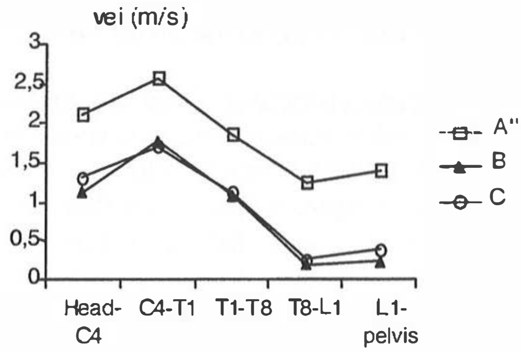

Figure 6 - Relative spine velocity of mean values in tests with ΔV 14 km/h

Table 3 - ARSV (standard deviations in parentheses) in tests with ΔV 11 km/h

Test situation	ARSV (stdev) m/s
A"	1,40
A'	1,34 (0,15)
B	0,74 (0,05)
C	0,86 (0,05)

Table 4 - ARSV (standard deviations in parentheses) in tests with ΔV 14 km/h

Test situation	ARSV (stdev) m/s
A"	1,84
B	0,88 (0,03)
C	0,96

As can be seen in Figures 5 and 6, the relative spine velocities is generally higher for the forward leaning posture. However, the difference is small when comparing regular sitting posture for the front and rear seat occupants. When calculating the average values of the mean relative spine velocities (ARSV) for each situation, (Tables 3 and 4) there is a clear difference between the two different sitting postures. The values of regular sitting postures in front and rear seat are too similar to be judged differently. The trend of the results is similar between the two different crash pulses.

NIC was created to address the initial relative motion in the cervical spine. The NIC_{max} in each test, calculated according to equation 1, is presented in Tables 5 and 6.

Table 5 - NIC_{max} in tests with ΔV 11 km/h

Test situation	NICmax (stdev) m^2/s^2
A"	22
A'	23 (1)
B	18 (4)
C	25 (1)

Table 6 - NIC_{max} in tests with ΔV 14 km/h

Test situation	NICmax (stdev) m^2/s^2
A"	35
B	21 (1)
C	28

As expected, NIC_{max} for different occupant postures in the front seat resulted in higher NIC_{max} for the forward leaning dummy as compared to the regular seated dummy. The higher NIC_{max} in the rear seat was mainly due to the high occupant acceleration due to the stiffer seat.

<u>Forward rebound.</u> When evaluating the third guideline (concerning forward rebound), mainly differences between front and rear seat behaviour were studied. The Total Belt Force and the Torso Rebound Velocity were found to best correspond to the hypothesis. The Total Belt Force was defined as the maximum value of the force measured in the lap belt and shoulder belt simultaneously. The Torso Rebound Velocity was defined as the maximum resultant velocity of T8 relative to the sled. The values for each test are presented in Tables 7 and 8.

Table 7 - Total Belt Force and Torso Rebound Velocity in tests with ΔV 11km/h

Test situat.	Total belt force (stdev) kN	Torso Rebound Velocity (stdev) m/s
A"	1,1	2,0
A'	1,5 (0)	1,7 (0,1)
B	1,7 (0,3)	1,5 (0,1)
C	1,0 (0,4)	1,2 (0,2)

Table 8 - Total Belt Force and Torso Rebound Velocities in tests with ΔV 14km/h

Test situat.	Total Belt Force (stdev) kN	Torso Rebound Velocity (stdev) m/s
A"	1,8	2,6
B	2,4 (0,1)	2,1 (0,1)
C	1,0	1,3

There is a trend, but not significant however, toward higher values in the front seat as compared to the rear seat for both the Total Belt Force and the Torso Rebound Velocity. The lower belt force in the forward leaning test is probably due to belt slack.

DISCUSSION

Ultimately, it would be desirable to have only one or two criteria addressing one injury type. For neck injury this is not possible. Because of the broad set of WAD symptoms and the fact that there is no single injury mechanism proposed so far as responsible for all these symptoms, a holistic view, addressing all possible injury mechanisms is the best in evaluating risk of neck injury.

The level of neck injury risk is rather constant throughout the range of impact severity (Jakobsson et al. 1999). Ultimately, tests should be performed at a variety of velocities and with different pulse shapes. This study presents results of two different impact severity levels, which are both in the range of high accident exposure. The results from the two crash pulses show similar tendencies, but it would strengthen the findings to complement them with a wider range of impact severity.

The hypothesis used in this study is based on experience from accident analysis. It is not proven that the differences in risk of neck injury between the driver and the front seat passenger are due only to different seating postures. It is not possible to exclude factors such as difference in awareness of the impact or steering wheel interaction. In order to know this, in-depth study with enhanced data collection is necessary. The hypothesis is based mainly on findings regarding initial symptoms. The validity of long term symptoms is not fully evaluated, especially for rear seat occupants compared to front seat occupants. The part of the hypothesis regarding occupant posture is, however, related to long-term symptoms since increased distance between head and head restraint has been found to be related to increased risk of long-term symptoms of neck injuries (Olsson et al 1990, Jakobsson et al 1994).

The Average Relative Spine Velocity (ARSV), suggested as the evaluation criteria for relative spine movements, is probably not sensitive enough to sense local differences in characteristics of the seat backrest, since the results show small differences for the rear and front seats in regular sitting postures. A more direct and precise measure would be to monitor the local as well as the global bending of the spine. When finally processed, the data from the SHAPE TAPE™ will provide this.

NIC 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 advantage of the rear seat. NIC was developed for long-term symptoms and it distinguishes between the situations with different head to head restraint distance. Based on this test series, NIC_{max} seems to be an adequate criterion for some situations in the second guideline of relative spine movements.

The suggested evaluation criteria of rebound could be affected by test set-up and occupant - seat belt interaction. The shoulder belt force transducer could affect the belt retractor function and thereby influence the results. It ought to be evaluated whether there is a more reliable placement of the transducer. The Torso Rebound Velocity could be affected by the occupant being retracted by the belt before reaching maximum velocity, requiring evaluation not only of the seat characteristics but the belt characteristics as well. A comparable test series with no belt use is recommended to evaluate this.

In order to perform a parameter study based on real world injury outcome, a dummy with humanlike kinematics is required. The BioRID I fulfilled the expectations of such a dummy. Due to lack of a pelvis H-point tool initially, the pelvis positioning varied throughout the test series, resulting in unacceptable large variation in neck loadings. Hence, it was not adequate to recommend evaluation criteria based on neck loads and moments based on this test series. However, the fact that the variations of the other sensors were acceptable small proves that BioRID I is a practical and reliable tool and sensitive for different occupant positions in real life situations.

CONCLUSIONS

Evaluation criteria based on real-life accident experience and the variety of suggested injury mechanisms is probably the best way of evaluating seat designs with respect to neck injuries in rear end impact.

Evaluation criteria were identified to express the guidelines concerning occupant acceleration, relative movements of the spine and rebound effect. The suggested evaluation criteria did verify the hypothesis of the relation between neck injury risk and different occupant position and posture.

•The occupant acceleration is suggested to be measured throughout the spine and pelvis.

•Average relative velocities throughout the spine (ARSV) is suggested to reflect the relative spine movements by using conventional accelerometers. As a more direct and precise measure, evaluation criteria mapping local as well as global bending of the spine, should be developed.

•Based on this test series, NIC_{max} seems to be an adequate criteria for some situations in the second guideline of relative spine movements.

•The effect of forward rebound is suggested to be evaluated either by Total Belt Force or Torso Rebound Velocity.

The BioRID I was found to be a practical and reliable tool for evaluating occupant response in different rear end impact situations.

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