Energy absorbing car seat designs for reducing whiplash

Energy Absorbing Car Seat Designs for Reducing Whiplash

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ABSTRACT

Objective. This study presents an investigation of anti-whiplash features that can be implemented in a car seat to reduce whiplash injuries in the case of a rear impact. The main emphasis is on achieving a seat design with good energy absorption properties.

Methods. A biofidelic 50th percentile male multi-body human model for rear impact is developed to evaluate the performance of car seat design concepts. The model is validated using the responses of 7 volunteers from the Japanese Automobile Research Institute (JARI) sled tests, which were performed at an impact speed of 8 kph with a rigid seat and without head restraint and seat-belt. A generic multi-body car seat model is also developed to implement various seatback and recliner properties, anti-whiplash devices and head restraints. Using the same driving posture and the rigid seat in the JARI sled tests as the basic configuration, several anti-whiplash seats are designed to allow different types of motion for the seatback and seat-pan.

Results. The anti-whiplash car seat design concepts limit neck internal motion successfully until the head to head restraint contact occurs and they exhibit low NIC_{max} values (7 m^2/s^2 on average). They are also effective in reducing neck compression forces and T1 forward accelerations. In principle, these car seat design concepts employ controlled recliner rotation and seat-pan displacement to limit the formation of S-shape. This is accomplished by using anti-whiplash devices which absorb the crash energy in such a way that an optimum protection is provided at different severities.

Conclusions. The results indicate that the energy absorbing car seat design concepts all demonstrate good whiplash reducing performances at the IIWPG standard pulse. Especially in higher severity rear impacts, two of the car seat design concepts reduce the ramping of the occupant considerably.

Keywords: Whiplash; Car Seat Design; Rear Impact; Human-body Model; Head-and-neck Model

INTRODUCTION

Injury to the human neck is a frequent consequence of road traffic accidents. The term “whiplash” is used to describe these injuries or disorders in which the sudden differential movement between the head and torso leads to damage of soft tissue in the neck. The annual economic cost of whiplash injury has been estimated to be \$8.2 billion in the US (Edwards et al. 2005) and £1.2 billion in the UK (Avery et al. 2007). The highest risk of sustaining whiplash injury has been found to occur in rear-end collisions (Jakobsson et al. 2000, Avery et al. 2007, Watanabe and Ito, 2007).

Although improving head restraint geometry is the first step in reducing injury risk in case of a rear impact, research has shown that seats with good head restraint geometry do not always offer good protection dynamically. If the seat is not properly designed, the occupant can deflect the seatback and head restraint unfavourably. This can delay head contact time with the head restraint and lead to higher neck loads. The ramping of the occupant becomes worse at relatively higher impact severities especially if no seat-belt is worn. In such cases the head restraint may not be able to restrict the motion of the head. Moreover, seatbacks with strong structural cross members do not allow the occupant to sink into the seatback; this hinders energy absorption and acts against reducing the backset between the head and the head restraint. Such structural cross members can load the upper torso severely and lead to S-shape deformation in the neck. A strong rebound of the seatback can also exacerbate injury especially in higher severity rear impacts. These problems can be overcome by designing seats which provide good energy absorption and/or early head support as recommended by IIWPG, the International Insurance Whiplash Prevention Group (IIWPG 2006).

METHODS

Design and validation of a 50th male multi-body rear-impact human-body model

The human-body model has been developed by using MSC VisualNastran 4D with Matlab-Simulink, and validated using the responses of 7 volunteers from the JARI (Japanese Automobile Research Institute) sled tests (Himmetoglu et al. 2008), which were performed at an impact speed of 8 kph with a rigid seat and without head restraint and seat-belt (Davidsson et al. 1999). The human-body model as shown in Figure 1 is composed of rigid bodies connected by rotational springs and dampers. The body shape of the human-body model is based on the typical or normal driving posture of an average 50th percentile male (Schneider et al. 1983). The head-and-neck section of the human-body model was separately validated by specifying the motion of T1 (the first thoracic vertebra) as obtained from the JARI sled tests. The head-and-neck model which was shown to simulate the effects of active muscle response, is described in detail by Himmetoglu et al. (2007).

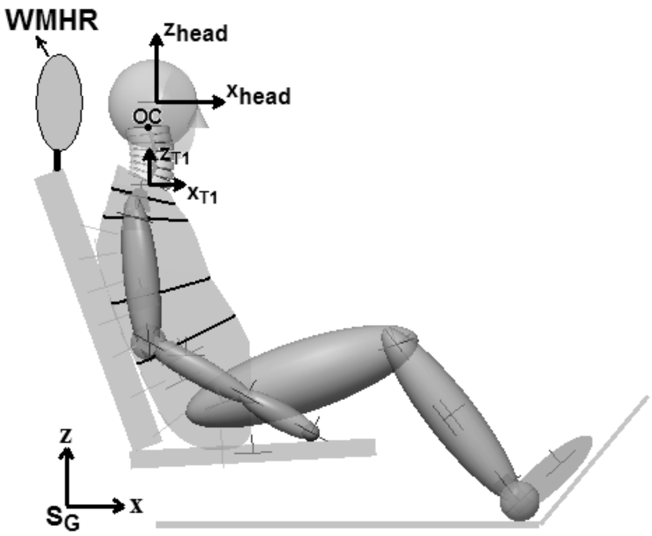

Figure 1. The human-body model in its initial position

The torso model is composed of five bodies with the locations of the joints chosen by analysing the spinal vertebra and pelvis rotations of the JARI sled test volunteers (Ono et al. 1999). The vertebrae which rotated together as a unit are grouped as one separate body. The torso joints are placed approximately at the anatomical locations of T3 (the third thoracic vertebra), T5 (the fifth thoracic vertebra), T11/T12 (between the eleventh and twelfth thoracic vertebrae) and L3/L4 (between the third and fourth lumbar vertebrae). For the neck joints, a time varying damping coefficient function based on the recorded EMG response of the neck muscles was found to better represent the volunteer responses. The damping functions for the torso joints also vary in time and this is considered to reflect the equivalent increase in resistance at the joints due to muscle contraction (Himmetoglu et al. 2008).

The responses of the proposed human-body model are validated using the JARI volunteer responses, as provided by van der Horst (2002). In Figures 2 to 5, the model responses are shown together with the responses of the JARI volunteers (grey lines) and the responses of Hybrid III and BioRID P3 dummies and TNO model that had been subjected to the same impact conditions. BioRID P3 and HIII (Hybrid III) responses are given by Davidsson et al. (1999). TNO responses indicate the behaviour of the human-body model of TNO Automotive combined with the detailed head-and-neck model developed by van der Horst (2002).

Figures 2 and 3 show the displacement of T1 relative to the sled in the x- and z-directions respectively, expressed in the inertial coordinate system S_G shown in Figure 1. Figure 4 displays the head angle with respect to T1. Figure 5 depicts the displacement of OC (occipital condyles) in the x-direction with respect to T1, expressed in the T1 anatomical coordinate system attached to T1 as shown in Figure 1. Figures 2 to 5 demonstrate that the human-body model shows biofidelic behaviour of the head-and-neck motion when subjected to the same rear impact conditions as in the JARI volunteer sled tests.

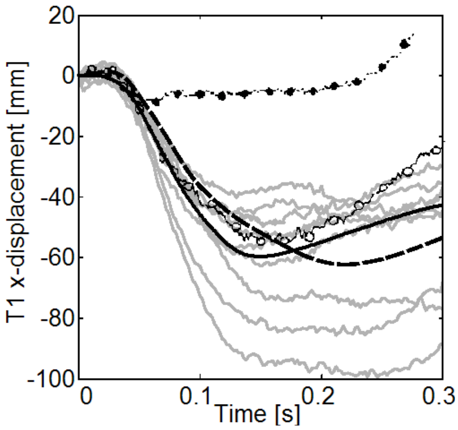

Figure 2. T1 x-displacements (- -●- - Hybrid III, ━o━ BioRID P3, ━ ━ TNO, ━ Model)

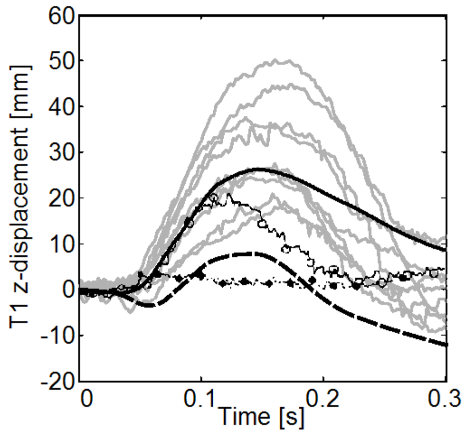

Figure 3. T1 z-displacements (- -●- - Hybrid III, ━o━ BioRID P3, ━ ━ TNO, ━ Model)

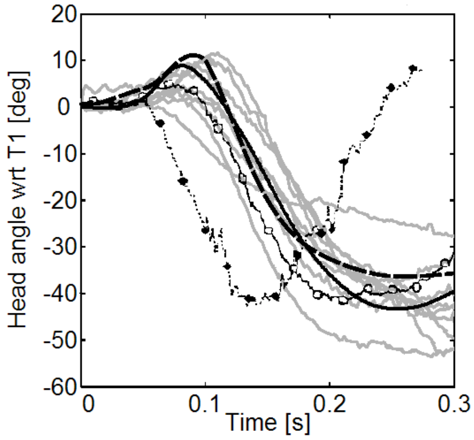

Figure 4. Head angles wrt T1 (- -●- - Hybrid III, —o— BioRID P3, — — TNO, — Model)

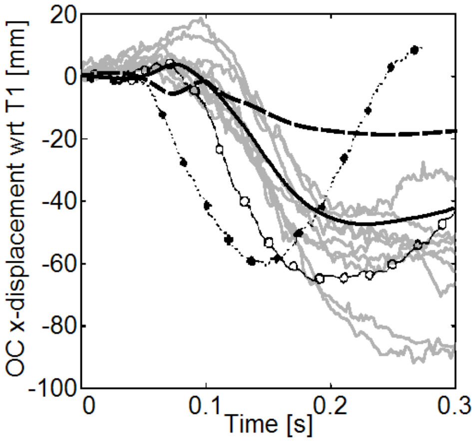

Figure 5. OC x-displacements wrt T1 (- -●- - Hybrid III, —o— BioRID P3, — — TNO, — Model)

Car seat design methodology

An anti-whiplash seat should absorb as much energy as possible while reducing the occupant acceleration and minimising the relative movements between the adjacent cervical vertebrae. The following design criteria are considered to be essential for a car seat equipped with anti-whiplash features:

a) Good head restraint geometry in terms of head restraint height and backset
b) Effective crash energy absorbing characteristics
c) Minimum neck internal motion (OC relative to T1 motion), reduced S-shape (or retraction)
d) Low neck forces (compression, tensile, shear) and moments
e) Reduced ramping
f) Minimum rearward displacement of the seat
g) Limited seatback rebound
h) No activation of anti-whiplash devices during normal use
i) Improved performance at all impact severities

It is well established that a head restraint with good stiffness and energy absorbing characteristics, positioned at the right height and with a small backset distance, would significantly reduce whiplash risk. Therefore, this study focuses on the development of seat designs with good energy absorbing characteristics which can later be combined with a good head restraint. Hence, in the computational simulations, head restraints are not included. Moreover, without the help of a head restraint, the effectiveness of seat designs in limiting neck internal motion can be better identified. In addition, as in the JARI volunteer sled tests, a seat-belt is also not included in the models. Forward rebound is also minimised by using high damping characteristics in the forward direction.

Using the same driving posture as in the JARI volunteer sled tests (Davidsson et al. 1999) and the rigid seat model, several anti-whiplash car seat design concepts have been considered. The rigid seatback without a head restraint and seat-belt can be regarded as one of the worst systems for rear impact. A rigid seatback could imitate, to some extent, the adverse effects of a seatback with strong structural cross members and very stiff foam that do not allow the torso to sink into the seatback significantly. Without the seat-belt, the occupant runs the risk of ramping up the seatback and even ejecting in high severity rear impacts. Developing seat design concepts with a rigid seatback can be considered as a practical approach in multi-body dynamic modelling, since the seatback stays rigid for all conditions while in the case of a typical car seat with a degree of frame compliance, foam stiffness and suspension movement, the dynamic characteristics need to be correctly estimated for all impact speeds.

A high severity crash pulse of ΔV(delta-V)=35 kph with mean and peak accelerations of 7.1g and 16g respectively is used to set the limits for the rotation of the seatback and the seat rearward displacement in order to prevent ejection and impact with the rear seat. This crash pulse, which is derived from FMVSS301 flat moving barrier test results (Viano 2002), represents quite a severe case. Therefore, at this extreme condition, the maximum seat-pan rearward displacement allowed is set to be 10 cm and the maximum seatback angle allowed from the vertical for the retention of unbelted occupant is set as 40 deg. This amount of rotation is based on the results of the human-body model simulations performed at this severe pulse with an initial seatback angle of 20 deg from the vertical and with a friction coefficient of 0.35 for all surfaces between the human-body and the seat. This friction coefficient is based on the experimental data given by Verver (2004).

Test Procedure

In order to test the car seat design concepts using the human-body model, the hands and arms are positioned as shown in Figure 1 to adopt a posture practiced in whiplash dynamic tests (IIWPG 2006). A head restraint, called WMHR, is attached to the seatback but in the simulations the head is allowed to penetrate WMHR freely without resistance, hence it has no effect on the motion of the head. This simulates the free head motion in the JARI volunteer sled tests and also allows the evaluation of the effectiveness of the seat in limiting neck internal motion until the head contacts the head restraint. The initial seatback angle is set to 20 deg from the vertical as in the JARI sled tests.

The head restraint WMHR satisfies the minimum height requirement by the European standard (UN-ECE Regulation No.17, Edwards et al. 2005). Nonetheless, an additional vertical height of 35 mm is added for this head restraint in order to compensate for the spine straightening. This value corresponds to the average upward displacement of T1 as obtained in the JARI volunteer sled tests (see Figure 3). Hence, the top of WMHR becomes level with the top of the head. Avery and Weekes (2006) suggested that backset values less than 45 mm could cause discomfort. Hence, the backset for WMHR is set to 60 mm, within the range of a good head restraint geometry, to allow head comfort. The depth of WMHR is selected as 100 mm.

IIWPG (2006) specifies head restraint contact time, maximum T1 forward acceleration, upper neck (rearward) shear and tension forces for the dynamic rating of seats and head restraints. For this purpose, IIWPG uses a standard dynamic test performed at ΔV=16 kph with a_{mean}=5g and a_{peak}=10g. In order to evaluate the anti-whiplash seat design concepts as well as the rigid seat, and to compare the results with the IIWPG criteria, the standard dynamic crash test pulse specified by the IIWPG was used in the simulations.

In the human-body model, the OC loads on the head are expressed in the head coordinate system located at the head centre of gravity as shown in Figure 1. The positive shear and the positive normal forces on the head are defined in the directions of +x and +z axes of the head coordinate system respectively, therefore tensile force is negative and compression force is positive by definition. As in dummies, these forces and moments are assumed to be acting at the OC. The maximum T1 forward acceleration is taken as the highest acceleration of T1 in the x-direction, as expressed in the coordinate system S_G (see Figure 1). Although IIWPG criteria are specified for the BioRIDIIg dummy only, these specifications can still be used for the human-body model for comparison purposes.

The characteristics of the anti-whiplash car seat design concepts

A number of energy absorbing car seat design concepts comprising anti-whiplash devices (AWDs) are proposed and the motions that they induce on the human-body model, when subjected to rear impact, are investigated. These concepts allow the motions for the seatback and seat-pan to be independent of each other. They are controlled by passive anti-whiplash devices consisting of spring and damper units. These devices become operational only when the corresponding breakaway forces and/or torques are exceeded. Therefore, the crash energy is absorbed by these devices in such a way that an optimum protection is provided at different severities. The required characteristics of the AWDs were determined using a wide range of crash pulses (ΔV between 4.5kph and 35kph) with different severities and pulse shapes (Linder et al. 2001, Krafft et al. 2004, Linder et al. 2003). Figure 6 shows six design concepts for anti-whiplash car seats. For all seats, the masses of the seat and head restraint are representative of typical car seats (Verver 2004).

In this paper, the abbreviation RG is used to represent the basic rigid seat which simulates the seat used in the JARI volunteer sled tests. RO represents the modified rigid seat with a rotational spring-damper AWD which enables the seatback to rotate with respect to a fixed seat-pan, whereas SPO has a horizontal translational spring-damper AWD which permits the whole seat to translate backwards. In SPO, there is no rotational motion between the seatback and the seat-pan.

The seat design concept WMS combines both the translational and rotational AWDs used in SPO and RO respectively, whereas the DWMS concept has the same two AWDs as WMS but with the translation AWD inclined by 30 degrees from the horizontal allowing the seat-pan to have both backward and downward motions simultaneously. For these two designs, the rotational and translational AWDs are activated when $\Delta V(kph)>4.5$ and $\Delta V(kph)>10.5$ respectively.

The downward motion is introduced in order to reduce the compression forces which occur due to spine straightening in the very early stages of the impact. A 30 degree-incline from the horizontal is selected for this purpose since lower angles were not found to reduce the compression force appreciably whereas higher angles could not limit neck internal motion as well as the selected angle. Besides, higher angles would cause large normal and frictional forces between the translational AWD and the supporting seat structure.

In both RFWMS and DRFWMS, an inner seatback frame (SB) pivots about an outer seatback frame (OF) at R* as shown in Figure 6. When the breakaway torque at the rotational AWD at R* is overcome due to the pressure applied by the torso on the inner seatback frame, a rotation at R* occurs which is in the opposite direction to the rotation at R of the outer seatback frame. This action provides better occupant retention at high severity impacts by reducing the effective seatback angle; it also moves the head restraint forward with a net effect of reducing the backset. The difference between RFWMS and DRFWMS is that the latter has an inclined translational AWD by 30 degrees from the horizontal. In both RFWMS and DRFWMS, the AWDs at R, R* and P are activated when $\Delta V(kph)>4.5$, 10.5 and 10.5 respectively.

It should be noted that for all of the design concepts, no AWD is activated for values of ΔV's less than 4.5 kph in order to prevent activation during normal daily use. This can easily be achieved in practice by using a sacrificial shear element or through active control.

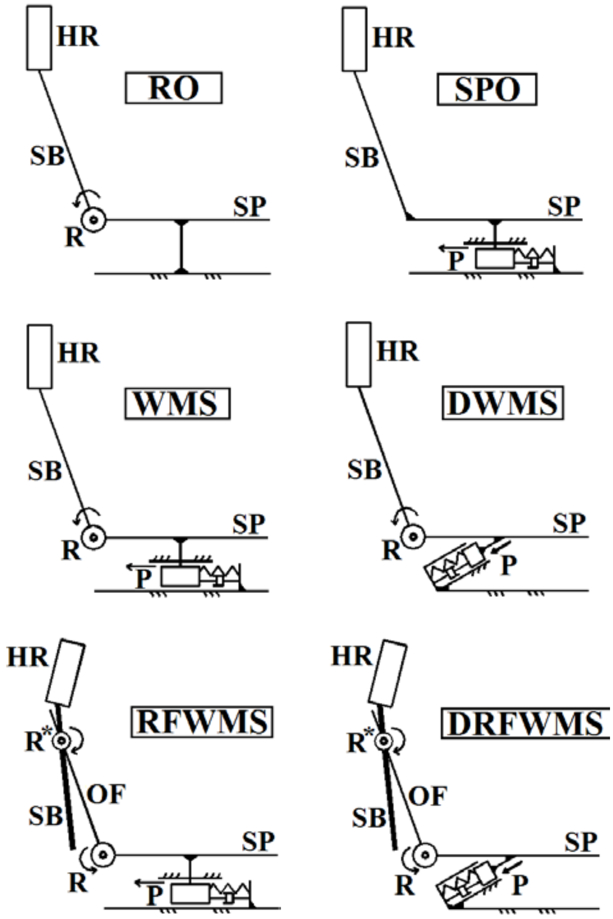

Figure 6. Anti-whiplash car seat design concepts (HR: head restraint, SB: seatback, SP: seat-pan, OF: outer seatback frame, P: translational AWD, R & R*: rotational AWD)

Figure 7 shows the stiffness function of the rotational AWD at R for all systems. The breakaway torque is around 850 Nm. For rearward rotation at R, a constant damping coefficient of 1 Nms/deg is used which is an estimation of the damping coefficient for the recliner structure in typical car seats (Eriksson 2002). High damping (400 Nms/deg) is applied at R when the seatback starts rotating forward (rebound motion), thus seatback rebound is minimised.

Figure 8 shows the stiffness and damping functions of the rotational AWDs at R* for both RFWMS and DRFWMS. In order to obtain optimum performance and to prevent undesired activation of the AWD at R*, (especially at lower severities), a breakaway torque of 1350 N was selected after having subjected RFWMS and DRFWMS to a wide range of crash pulses. The AWD at R* also applies high damping for the reverse (rebound) motion. Finally, the stiffness and damping functions for the translational AWDs are shown in Figure 9.

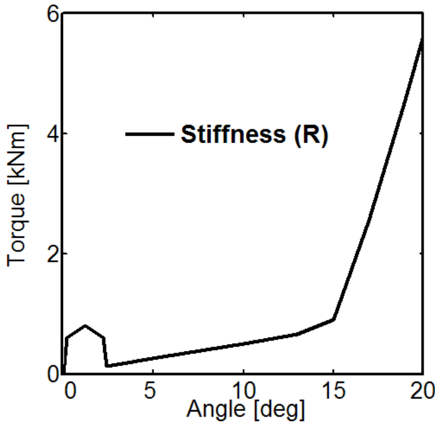

Figure 7. Stiffness function for R

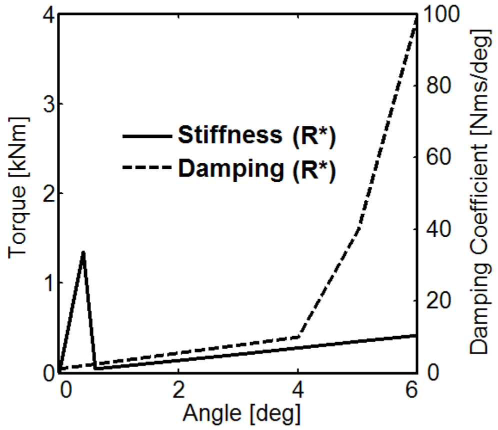

Figure 8. Stiffness and damping functions for R*

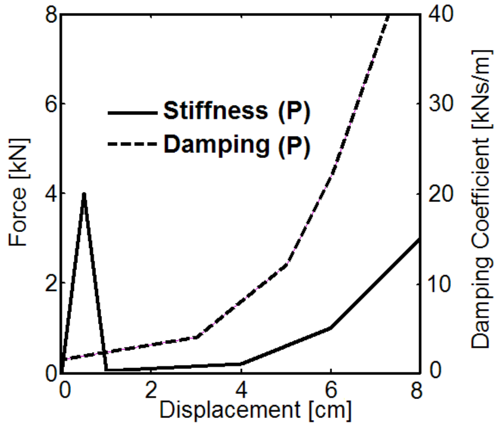

Figure 9. Stiffness and damping functions for P

Figure 10 indicates the typical responses of the translational AWD at P and the rotational AWDs at R and R* when the seat design concepts with combined rotational and translational AWDs are subjected to the IIWPG standard pulse (ΔV=16 kph, a_{mean}=5g, a_{peak}=10g). Although the AWD that controls the rotational motion at the recliner (at R) is activated at a lower ΔV value with respect to the translational AWD, once both ΔV thresholds are exceeded, the seat-pan moves backwards rapidly at the initial stages of the impact (between 0 to 50 ms) in comparison to the backwards rotation of the seatback. In other words, the seat moves backwards initially without considerable recliner rotation. The response of the AWD at R* shows a delay of about 65 ms. However, during this period, the recliner and the seat-pan are in motion, thus the AWDs at R and P are absorbing energy. When the breakaway torque is overcome, the inner seatback frame rotates rapidly with respect to the outer seatback frame, providing relatively earlier head to head restraint contact.

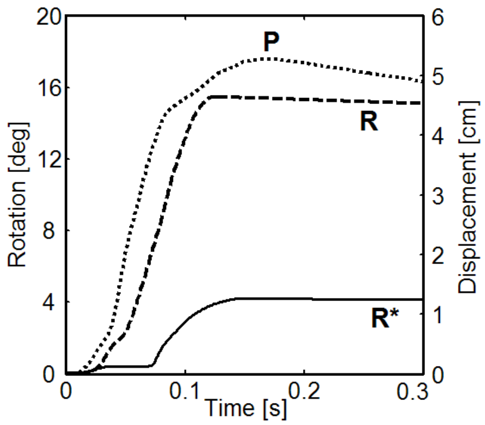

Figure 10. AWD displacements in response to the IIWPG standard pulse

RESULTS

In this section, the performance of the rigid seat (RG), recliner only motion seat (RO), seat-pan only motion seat (SPO) and the four anti-whiplash energy-absorbing seats (WMS, DWMS, RFWMS and DRFWMS) are evaluated by using the IIWPG standard pulse and the severe crash pulse (ΔV=35 kph, a_{mean}=7.1g, a_{peak}=16g). The results of the simulations are presented in Table 1. A friction coefficient of 0.35 is used for all contacts between the human-body and the seat (Verver 2004). The initial value of the normal force (which is the compression force at t=0) is set to zero as this is a usual practice in displaying the values for the OC normal forces. Head restraint contact times correspond to contact with the head restraint WMHR. NIC_{max} (Neck Injury Criterion) is also calculated. NIC is associated with the S-shape deformation of the neck and is based on the relative acceleration and velocity between the OC and T1.

In Table 1, the largest values of OC (upper neck) forces are presented. OC shear and tensile forces indicate how strongly the head is thrown backward relative to the seat. For all seats, the largest OC tensile and shear forces occur approximately at the same time, which corresponds approximately to the instant when maximum head retraction in the form of an S-shape is developed. According to the IIWPG neck force classification (IIWPG 2006), shear forces appear to be on the border of moderate-to-high, or higher, whereas tensile forces are well within the low neck force range. The compression force occurs very early in the impact. WMS and RFWMS reduce the maximum OC compression forces whilst DWMS and DRFWMS cause further reduction in the compression forces by allowing the seat-pan to also move downward by an amount of 1.75 cm during the first 50 ms of the impact. RO, the fixed seat-pan with a rotational AWD at the recliner (at R), also shows low compression force as the seatback rotates quickly, but it generates the highest shear and tensile forces.

Table 1. Seat performance in response to the IIWPG standard and severe crash pulses

IIWPG standard crash pulse							
	RG	**RO**	**SPO**	**WMS**	**DWMS**	**RFWMS**	**DRFWMS**
Fshear [N]	235	358	249	248	240	240	273
Ftensile [N]	-333	-343	-329	-316	-295	-306	-297
Fcomp [N]	252	98	225	113	84	132	102
$maxT1_{x\text{-}acc}$ [g]	10	10.2	8.9	7	7.85	6.5	7.8
NIC_{max} [m^2/s^2]	11.8	11.4	11.13	7.68	7.06	6.81	6.28
HrCt [ms]	50	101	62	108	107	95	94
maxSB-$\Delta\theta$ [deg]	0	15.8	0	15.5	15.6	11.1	11.43
maxSP-Δx [cm]	0	0	5.41	5.28	4.62	5.3	4.6
maxSP-Δz [cm]	0	0	0	0	2.66	0	2.65

Severe crash pulse				
	WMS	**DWMS**	**RFWMS**	**DRFWMS**
maxSB-$\Delta\theta$ [deg]	20.1	20.2	15.1	15
maxSP-Δx [cm]	6.9	5.94	6.97	6
maxSP-Δz [cm]	0	3.43	0	3.46

Maximum forward T1 x-accelerations ($maxT1_{x\text{-}acc}$) as shown in Table 1 are less than the IIWPG threshold value of 9.5g for all the anti-whiplash seat design concepts. The evaluation of T1 x-acceleration and the upper neck forces become more compatible with the IIWPG criteria when head restraint contact is enabled. The head restraint changes the dynamics of the system and the values of these parameters significantly.

The head restraint contact times (HrCt) are 105 ms on average, higher than 70 ms (IIWPG threshold value) for the seat design concepts without the inner seatback frame design (RO, WMS and DWMS). On the other hand, the head restraint contact times for RG and SPO (i.e. seat designs with fixed seatbacks) are 50 ms and 62 ms respectively. Backward rotation of the seatback aids in energy absorption, but this moves the head restraint away from the head, thus extending the head restraint contact time. This is normal for seat designs focusing on energy absorption (Avery et al. 2007). Furthermore, the rigid body modelling approach does not allow the human-body model to sink into the seatback, consequently causing the backset distances to remain effectively larger, resulting in later head restraint contact times. The seats with the inner seatback frame design (RFWMS and DRFWMS) have slightly reduced contact times (95 ms) since the head restraint moves forward as the inner seatback frame rotates in the opposite direction relative to the outer seatback frame under the pressure from the torso.

The anti-whiplash seat design concepts with combined rotational and translational AWDs have favourable energy absorption characteristics and they produce much lower NIC_{max} values compared to RG, RO and SPO. In relation to NIC (Boström et al. 1996), whiplash-mitigating seats can decrease the degree of S-shape or retraction as shown in Figure 11. In the simulations, the most pronounced S-shape occurs when the lower neck is in extension and at the same time the upper neck has the maximum flexion. The most pronounced (maximum) S-shape is identified by monitoring the intervertebral angles of the neck. It can be seen that, for RG, the initial neck posture as shown in Figure 1, is transformed into an S-shape and then transition from S-shape to extension takes place, followed by hyperextension. On the other hand, for WMS, head retraction relative to the upper torso is very much limited; hence the initial neck posture is transformed into neck extension without considerable S-shape deformation. The simulations also indicate that the anti-whiplash seat design concepts such as WMS have the potential to allow larger backset values as a result of limited head retraction (Figure 11).

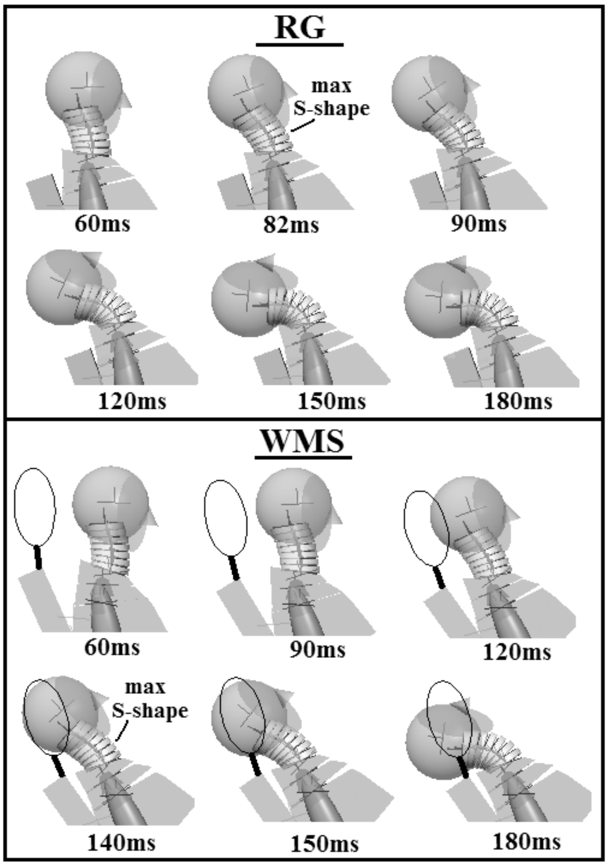

Figure 11. Comparison of head-and-neck responses of RG and WMS to the IIWPG standard pulse

As the seats absorb energy, they can limit and delay the development of neck internal motion until the head contacts the head restraint. While head with respect to T1 motion is being minimised with the aid of AWDs, the neck muscle activity that begins at around 75 ms (Ono et al. 1997) becomes effective without any appreciable neck internal motion. Therefore, in the later stages of the impact, the neck becomes more resistant to S-shape and neck extension formation as the AWDs complete their motions. These results are in agreement with the findings of Stemper et al. (2006) who compared the effects of precontracted neck muscles in aware occupants with reflex muscle contraction in unaware occupants by subjecting a validated head-and-neck model to an acceleration pulse applied horizontally at T1 with a severity of ΔV=10.5 kph. In comparison to the reflex muscle contraction in the unaware occupant simulation, precontracted neck musculature with maximum contraction levels before impact stabilised the head-and-neck, eliminated S-shape curvature and decreased spinal motions and soft tissue distortions. These findings supported the results of human volunteer experiments in the literature. Considering the above discussion, the anti-whiplash seat design concepts are expected to reduce the injury risks associated with the S-shape injury mechanism.

The inner seatback frame rotation as in RFWMS and DRFWMS reduces the maximum seatback angular displacement (maxSB-$\Delta\theta$) by 4 deg in comparison to WMS and DWMS (see Table 1). Simulations using the IIWPG standard pulse have not shown much difference in the ramping effect for the seat designs considered. Besides, since the IIWPG standard pulse is a medium severity pulse and the head restraint WMHR has good geometry, the ramping of the body has not posed any injury risk. However, the presence of such an inner seatback frame effectively reduces the ramping of the body at higher severity impacts. When the severe crash pulse (ΔV=35 kph, a_{mean}=7.1g, a_{peak}=16g) is simulated, the counter rotation of the inner seatback frame decreases the maximum seatback angular displacement by 5 deg. For each anti-whiplash seat design concept, Figure 12 shows the instant when the torso has just started to descend and this approximately corresponds to the highest position of the head. It can be seen that at this severe crash pulse, RFWMS and DRFWMS provide better occupant retention compared to WMS and DWMS.

RFWMS and DRFWMS decrease the backset by 1.5 to 3 cm and this corresponds to 4 to 6 deg of rotation at R*. In the simulations, the inner seatback frame rotation at R* reduces the backset by 1.8 cm and 2.7 cm typically for the IIWPG standard and severe crash pulses respectively, depending on the point where the head makes the first contact with the head restraint.

As shown in Table 1, the maximum rearward displacement of the seat-pan (maxSP-Δx) varies between 6 cm to 7 cm at the severe crash pulse whereas for the IIWPG standard pulse, it is between 4.6 cm to 5.4 cm. For DWMS and DRFWMS, the maximum downward displacement of the seat-pan (maxSP-Δz) is 2.65 cm and 3.45 cm in response to the IIWPG standard and severe crash pulses respectively.

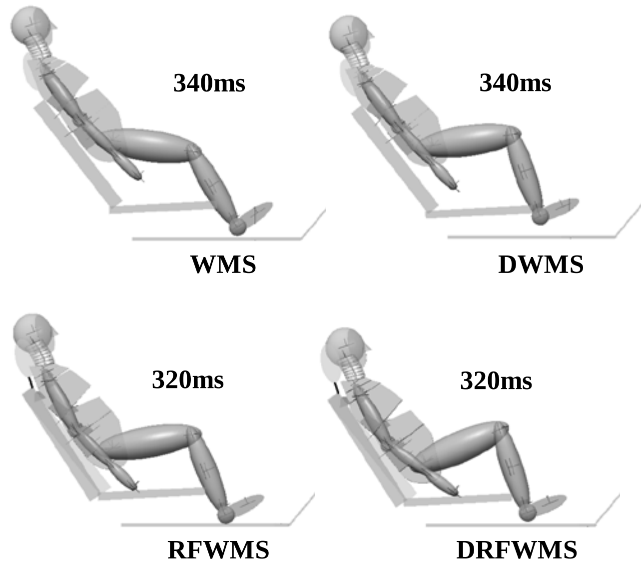

Figure 12. Comparison of the ramping effect of anti-whiplash seat design concepts at the severe crash pulse

DISCUSSION

Using passive devices only, it is a challenging task to design seats that can operate optimally for all levels of severities. The simulation test results of several anti-whiplash seat design concepts have been investigated using mainly the IIWPG standard pulse and the human-body model specifically developed for rear impact. The design strategy used in this paper has been applied to a seat with a rigid seatback and seat-pan. No head restraint and seat-belt is used in the simulations. The results indicate that the anti-whiplash seat design concepts, namely WMS, DWMS, RFWMS and DRFWMS all demonstrate good whiplash reducing performances (with only slight differences) at the IIWPG standard pulse. As expected, RG, RO and SPO show poor performance.

RG and SPO have fixed seatbacks, as a result of which a strong reaction force to the upper torso develops immediately, thus causing severe S-shape deformation rapidly. This is accompanied by strong spine straightening which leads to high compression forces. In RO, the rotational AWD at the recliner only accounts for energy absorption and therefore, the seatback is rotated rapidly. This leads to reduced compression force but on the other hand causes high shear and tensile forces. RG, RO and SPO have high NIC_{max} and maximum forward T1 x-acceleration values, which are indications of high injury risk.

The anti-whiplash car seat design concepts (WMS, DWMS, RFWMS and DRFWMS) show similar effectiveness in minimising neck internal motion. In principle, these four designs employ controlled recliner rotation and seat-pan displacement to limit the formation of S-shape. Their T1 forward acceleration is also lower than the recommended IIWPG limit (9.5g) specified for energy absorbing seats. Their NIC_{max} values are much lower than the proposed injury threshold value of 15 m^2/s^2 (Boström et al. 1996). The head restraint contact time is around 100 ms on average but this would be much lower in reality with a real seat that has some compliance due to the seat foam and suspension which allows the torso to sink into the seatback, hence reducing the contact time. The anti-whiplash car seat design concepts induce moderate to high shear but low tensile OC forces according to the IIWPG ratings and much reduced compression forces compared to RG and SPO. However, the use of a good head restraint in conjunction with the AWDs would provide head support in good time, which in turn would prevent neck extension and reduce the shear force applied to the neck by the head. A good head restraint would also help to further limit S-shape deformation and prevent the development of the most pronounced S-shape as investigated in this study.

It can be concluded that there is not much difference among the performance of the four anti-whiplash seat design concepts regarding their responses to the IIWPG standard pulse. However, the seat design concepts with the inner seatback frame have some advantages over the ones without the inner seatback frame. With the aid of inner seatback frame rotation at R*, they provide earlier head restraint contact and reduce the effective seatback angle. Especially in higher severity rear impacts, the inner seatback frame rotates further which helps to reduce the ramping of the body considerably, preventing its ejection and interaction with the car interior and the rear seat occupant. However, the characteristics of the AWD at R* must be adjusted properly so that the inner seatback frame rotation at R* must be accompanied by a sufficient amount of outer seatback frame (OF) rotation at R to avoid increasing the loading on the upper torso in any case.

At the severe crash pulse, the seat design concepts having the downward motion produce slightly less ramping. DRFWMS performs the best as it does not let the head rise over the head restraint and also lowers the position of the head relative to the vehicle floor. This offers good protection for the tall and unbelted occupants in the case of a severe rear impact.

In this study, the rebound effects have not been considered as it would be immaterial due to the absence of seat-belt and head restraint. Besides, since the forward rebound of the seat components is minimised, the rebound of the torso is insignificant for all severities as observed from the simulations.

The proposed energy absorbing seat design concepts have been shown to limit the neck internal motion successfully, hence reducing injury risks associated with S-shape deformation. However, early head support is also essential to limit the loading on the head-and-neck. As indicated by Viano and Olsen (2001), early head support can enable the head-and-neck to benefit from a lower relative velocity of impact on the head restraint. Therefore, an anti-whiplash seat can perform best if it absorbs the crash energy effectively and at the same time provides early head support. Hence, if a good head restraint is used in conjunction with the AWDs, the seat design concepts with the inner seatback frame are expected to produce lower head-and-neck loads than WMS and DWMS.

It should be noted that the compliance of the seatback foam and suspension has not been taken into account in this study in order to provide a comparison with the existing JARI test results with a rigid seatback. As in the actual commercial seats used in the automotive industry, the seatback foam and suspension compliance allow the occupant to sink into the seatback rapidly with little resistance at the very early stages of the impact, reducing head restraint backset distance and contact time. Therefore, seatback foam and suspension compliance will further improve the protection provided by the proposed whiplash mitigating designs.

REFERENCES

Avery M, Weekes AM. (2006) Dynamic Testing of Vehicle Seats to Reduce Whiplash Injury Risk: An International Protocol, Proc. *ICrash 2006 Conference*, Athens, Greece.

Avery M, Giblen E, Weekes AM, Zuby DS. (2007) Developments in Dynamic Whiplash Assessment Procedures, Proc. *International Conference on Neck Injuries in Road Traffic and Prevention Strategies*, Munich, Germany.

Boström O, Svensson MY, Aldman B, Hansson HA, Håland Y, Lövsund P, Seeman T, Suneson A, Säljö A, Örtengren T. (1996) A New Neck Injury Criterion Candidate-Based on Injury Findings in the Cervical Spinal Ganglia after Experimental Neck Extension Trauma, Proc. *International IRCOBI Conference*, Dublin, Ireland, pp 123-136.

Davidsson J, Ono K, Inami S, Svensson MY, Lövsund P. (1999) A Comparison between Volunteer, BioRID P3 and Hybrid III Performance in Rear Impacts, Proc. *International IRCOBI Conference*, Sitges, Spain, pp. 165-178.

Edwards M, Smith S, Zuby DS, Lund AK. (2005) Improved Seat and Head Restraint Evaluations, Proc. *19th ESV Conference*, Washington DC, USA, Paper 05-0374-O.

Eriksson L. (2002) Three-Dimensional Mathematical Models of the BioRID I and Car Seats, for Low-Speed Rear-End Impacts, *Traffic Injury Prevention*, Vol. 3, pp. 75-87.

Himmetoglu S, Acar M, Taylor AJ, Bouazza-Marouf K. (2007) A Multi-body Head and Neck Model for Simulation of Rear Impact in Cars, *Proceedings of IMechE Part D Journal of Automobile Engineering*, Vol. 221, pp. 527-541.

Himmetoglu S, Acar M, Taylor AJ, Bouazza-Marouf K. (2008) Development and Validation of a Multi-body Human Model for Rear Impact Simulation, Submitted to the *Proceedings of IMechE Part D Journal of Automobile Engineering*.

IIWPG. (2006) International Insurance Whiplash Prevention Group, RCAR-IIWPG Seat/Head Restraint Evaluation Protocol, Version 2.5.

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

Krafft M, Kullgren A, Lie A, Tingvall C. (2004) Assessment of Whiplash Protection in Rear Impacts - Crash Tests and Real-life Crashes, Swedish National Road Administration, Stockholm, Sweden. Available at http://www.folksam.se.

Linder A, Avery M, Krafft M, Kullgren A, Svensson MY. (2001) Acceleration Pulses and Crash Severity in Low Velocity Rear Impacts - Real World Data and Barrier Tests, Proc. *17th ESV Conference*, Amsterdam, The Netherlands, Paper 216.

Linder A, Avery M, Krafft M, Kullgren A. (2003) Change of Velocity and Crash Pulse Characteristics in Rear Impacts: Real-World Data and Vehicle Tests, Proc. *18th ESV Conference*, Nagoya, Japan, Paper 285.

Ono K, Kaneoka K, Wittek A, Kajzer J. (1997) Cervical Injury Mechanism Based on the Analysis of Human Cervical Vertebral Motion and Head-Neck-Torso Kinematics During Low-Speed Rear Impacts, SAE paper 973340.

Ono K, Inami S, Kaneoka K, Gotou T, Kisanuki Y, Sakuma S, Miki K. (1999) Relationship Between Localized Spine Deformation and Cervical Vertebral Motions for Low Speed Rear Impacts Using Human Volunteers, Proc. *International IRCOBI Conference*, Sitges, Spain, pp. 149-164.

Schneider LW, Robbins DH, Pflueg MA, Snyder RG. (1983) Development of Anthropometrically Based Design Specifications for an Advanced Adult Anthropomorphic Dummy Family - Volume 1, University of Michigan, Transportation Research Institute, Ann Arbor, Report No. UMTRI-83-53-1.

Stemper BD, Yoganandan N, Cusick JF, Pintar FA. (2006) Stabilizing Effect of Precontracted Neck Musculature in Whiplash, *Spine*, Vol. 31, pp. E733-E738.

van der Horst MJ. (2002) Human Head Neck Response in Frontal, Lateral and Rear End Impact Loading: Modelling and Validation, PhD Thesis, Eindhoven University of Technology, Eindhoven, The Netherlands.

Verver MM. (2004) Numerical Tools for Comfort Analyses of Automotive Seating, PhD Thesis, Eindhoven University of Technology, Eindhoven, The Netherlands.

Viano DC. (2002) Role of the Seat in Rear Crash Safety, Society of Automotive Engineers, Warrendale, PA.

Viano DC, Olsen S. (2001) The Effectiveness of Active Head Restraint in Preventing Whiplash, *Journal of Trauma*, Vol. 51, pp. 959-969.

Watanabe Y, Ito S. (2007) Influence of Vehicle Properties and Human Attributes on Neck Injuries in Rear-end Collisions, Proc. *20th ESV Conference*, Lyon, France, Paper 07-0160.