REACTIVE SEAT DESIGN FOR OPTIMUM WHIPLASH MITIGATION AT DIFFERENT CRASH SEVERITIES

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ABSTRACT

This paper presents the development of reusable whiplash mitigating car seats that can effectively manage the response of the seatback to rear impact for a wide range of crash severities. For this purpose, computational multi-body models of a generic car seat and a biofidelic 50th percentile male human model for rear impact are developed. Three reactive car-seat design concepts are proposed whose effectiveness are demonstrated by simulating rear impacts at severities ranging from 4.5 to 30 kph. Among the proposed seat concepts, the one which employs a modification on the conventional seatback structural design, provides the most optimum neck protection at all crash severities.

Keywords: whiplash, seats, rear impacts, sled tests, models

WHIPLASH RELATED INJURIES or disorders are caused by the sudden differential movement between the head and torso, and they can result from impacts in all directions. Whiplash related injuries or shortly "whiplash" is classified as an AIS-1 (Abbreviated Injury Scale 1) type injury by the Association for the Advancement of Automotive Medicine (AAAM, 2005). The Quebec Task Force had also made a classification of whiplash-associated-disorders (WAD) and grouped them in four different grades (Spitzer et al., 1995). Table 1 presents these classifications and the associated clinical outcomes in which neck complaint occurs for all injury severities other than AIS-0 and WAD-0.

It has been found that rear-end collisions in car accidents pose a high risk of sustaining whiplash related injuries (Avery et al., 2007; Eis et al., 2005). Road traffic accident data shows that single rear impacts with almost full overlap (50% to 100%), represent the most common rear impact configuration in which whiplash related injuries occur (Hell et al., 1998; Eis et al., 2005). Although whiplash is regarded as a minor injury, it can still lead to long-term disablement and discomfort in the neck associated with substantial economical cost which has been estimated to be £1.2 billion in the UK (Avery et al., 2007) and $8.2 billion in the USA (Edwards et al., 2005) annually.

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 related injury risks in rear-end collisions. Whiplash effect is also known to be reduced by seats designed to absorb the energy of the impact and to reduce the relative motion between the head and the upper torso.

In order to develop a good anti-whiplash car seat, road traffic accident data should be consulted to determine the rear-impact severity range where the majority of whiplash related injuries occur statistically. Within this range, it is also important to identify the interval where the whiplash related injury risk is high and long-term symptoms (more than one month) do exist.

Table 1. Classification and Symptoms of Whiplash Related Injuries

AIS	WAD	Clinical Outcome
0	0	No physical symptoms and no neck-complaint
1	1	Microlesion (microscopic muscular damage): (comprising pain, stiffness or tenderness in the neck without any physical symptoms)
1	2	Macrolesion (major muscular/bone/ligament damage): (including decreased range of motion of the neck and tenderness)
1	3	Neurological signs (nerve cell defect/irritation): (involving missing or reduced deep tendon reflexes, and sensory deficits)
2	4	Fracture or dislocation in the neck

A car-seat may perform well when it is tested using a single crash pulse, but in real-world crashes the seat may be subjected to a variety of crash severities and may underperform at these conditions. The results of Farmer et al. (2008) and the first ever EuroNCAP whiplash tests can be considered to pinpoint this problem. So, it is imperative to investigate seat response for a sufficiently wide range of crash severities. In this study, a car-seat design approach is presented which can enable the seat to provide optimum whiplash protection at various crash severities.

A judicious selection of a crash pulse range is needed for rear-impact whiplash assessment and seat design. Considering the recent road-traffic accident data, a ΔV range between 5 and 30 kph can be considered for whiplash risk assessment in anti-whiplash car seat design since it can account for a wide rear-impact severity range where whiplash related injuries are common. This ΔV range covers the interval (9 to 20 kph) where whiplash related injury risk is high and also includes the interval (13 to 27 kph) where long-term whiplash related injury risk is significant (Eis et al., 2005, Krafft et al., 2002, 2005).

This paper presents reactive car-seat concepts which can absorb the crash energy effectively and mitigate whiplash related injuries optimally for crash severities ranging from 4.5 to 30 kph while remaining reusable after impact. The proposed car-seat concepts are developed using a relatively simple human model which was shown to be more biofidelic than the BioRID as described in the next section (Himmetoglu et al., 2009). The cervical spine of the human model was first separately developed and verified for rear impact, prior to its integration with the human model (Himmetoglu et al., 2007).

AN OVERVIEW OF EXISTING DESIGNS FOR WHIPLASH MITIGATION

A good anti-whiplash car seat should lower occupant acceleration, support the head effectively, reduce ramping and limit seatback rebound so that minimum neck internal motion and low neck forces are ensured throughout the impact.

There is a considerable number of seat and head restraint designs in the literature for whiplash mitigation (Himmetoglu, 2008). However, in principle, all of these designs can be classified into two main groups. In the first group, the emphasis is on absorbing the crash energy by controlled motion of the seat, hence lowering occupant acceleration. The most prominent and successful design on the market is the Volvo WHIPS system in which there is a plastically deformable, sacrificial link in the recliner mechanism which makes the seatback recline and absorb energy at the same time. The mechanism needs to be replaced following the impact, adding to the cost of repair.

The second group comprises active head restraint designs in which the emphasis is on providing early head support by automatically positioning the head restraint close to the head during the early stages of the rear impact. There are many variants of this design on the market and the most prominent one is the Saab Active Head Restraint (SAHR).

SAHR and WHIPS systems have consistently scored the highest points in the dynamic seat ratings (i.e. the IIWPG and EuroNCAP whiplash tests) (Avery et al., 2007). An analysis of real-world accident data by Kullgren et al. (2007) indicated that SAHR and WHIPS, along with some other similar systems, have been shown to have 50% lower risk of long-term whiplash symptoms in comparison to the typical seats introduced after 1997. Kullgren et al. (2007) also found a correlation between dynamic seat ratings and real-world injury outcome.

MODELLING OF A SEAT-OCCUPANT SYSTEM FOR REAR IMPACT SIMULATION

A biofidelic 50th percentile male multi-body human model for rear impact was developed by Himmetoglu et al. (2007, 2008, 2009) using MSC VisualNastran 4D with Matlab-Simulink and rigorously validated using the responses of seven healthy 50th percentile male volunteers from the Japan Automobile Research Institute (JARI) sled tests (Davidsson et al., 1999), which were performed at an impact speed of 8 kph with a rigid seat (i.e. a seat having all rigid surfaces and a fixed recliner), and without head restraint and seat-belt. The human model, as shown in Fig. 1, is composed of rigid bodies connected by rotational springs and dampers.

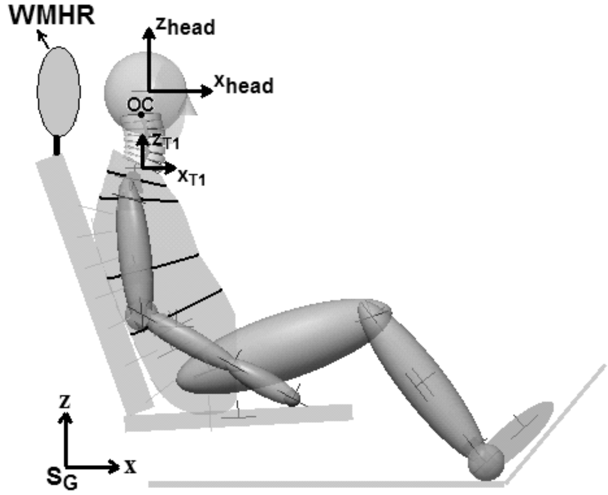

Fig. 1 - The Seat-Occupant System

It must be noted that the human model was rigorously validated to ensure that it behaves like an average volunteer in the JARI sled tests when subjected to the same rear impact conditions. In these tests, the head was allowed to extend due to the absence of head restraint and this helped to validate the mechanical properties of the joints for a larger range of joint rotations (Himmetoglu et al., 2007). The human model does not include soft tissue, such as the muscles, however the stiffness and time dependent damping characteristics of the joints is the novelty of this model which helps to mimic muscle activity and the increase in the resistance of the human body under dynamic conditions. For severities around the validation point (low-speed range), the human model is shown to be more biofidelic than the BioRID (Himmetoglu et al., 2009). In constructing the joint end limits for the joints to simulate severe cases, the static torque values of the stiffness functions were increased steeply in agreement with those of the mechanical and computational models of the BioRID. The developed human model helps to economically, efficiently and more accurately simulate different situations and enable what-if tests. It successfully satisfies the rear-impact dummy biofidelity evaluation criteria (Wismans, 2007) based on the head and upper-torso responses of the JARI volunteers.

In order to validate the human model, the rigid seat used in the JARI sled tests was modelled first and a contact model was developed to simulate the interaction of the human-body segments with the seat surfaces (Himmetoglu et al., 2009). A generic multi-body car seat model was also developed to implement various anti-whiplash devices, seatback and recliner properties. A head restraint, called WMHR, was then attached to the seatback as shown in Fig. 1. WMHR is a model of a typical head restraint whose mechanical properties were adapted from the results of head restraint impact tests by Viano (2002). Using the same driving posture as in the JARI sled tests and the rigid seat model as the basic configuration, several reactive car-seat concepts are developed for whiplash mitigation.

REACTIVE CAR-SEAT DESIGN CONCEPTS

A number of reactive car-seat concepts comprising anti-whiplash devices (AWDs) are developed to provide optimum whiplash mitigation at different crash severities. The AWDs are passive devices consisting of spring and damper units and they can be used to transform a typical car-seat from the market into a seat which can offer good protection against whiplash. The AWDs become operational only when the corresponding breakaway forces and/or torques are exceeded. The crash energy is absorbed by these devices in such a way that optimum protection is provided at different severities. The required characteristics of the AWDs were determined using a wide range (ΔV between 4.5 and 35 kph) and variety of crash pulses presented by Linder et al. (2001, 2003), Avery et al. (2007), and Viano (2002).

Fig. 2 shows the schematic drawings of the reactive car-seat concepts (WMS and RFWMS) and a simplified model of a typical car seat (TYPS). The abbreviations used in describing the car-seat concepts are listed in Table 2. For all seats, the masses of the individual seat components are the same and they are representative of typical car seats (Verver, 2004).

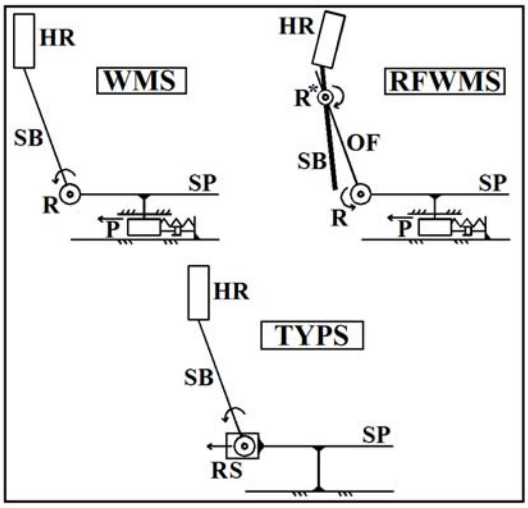

Fig. 2 - Schematic Drawings of the Seats

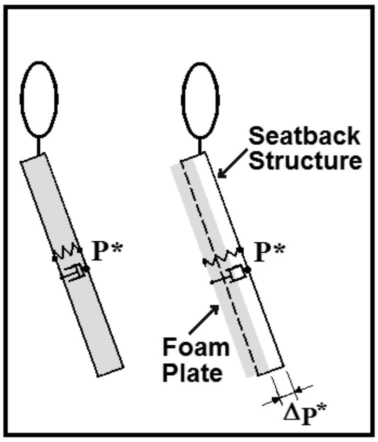

Fig. 3 - Construction of the Foam-plate

Table 2. List of Abbreviations for the Seat Concepts

AWD: anti-whiplash device	**WMHR:** the attached head restraint for all seats
WMS, RFWMS: reactive car-seat concepts	**R:** rotational AWD
WMS-H: WMS with the stronger recliner	**R*:** rotational AWD in RFWMS
WMS-S: WMS with the softer recliner	**P:** translational AWD
TYPS: typical seat model	**P*:** foam-plate AWD
TYPS-B1: typical seat model - version B1	**RS:** the recliner structure of TYPS
TYPS-G2: typical seat model - version G2	**OF:** the outer seatback frame in RFWMS

The typical seat TYPS consists of a head restraint (HR), a seatback (SB), a seat-pan (SP) and a recliner structure (RS). When the recliner structure deforms under rear impact, the SB rotates and horizontally translates with respect to the SP. The typical seat TYPS is then modified to become WMS and RFWMS as shown in Fig. 2. In WMS, the rotational anti-whiplash device denoted by **R** enables the SB to rotate with respect to the SP and the translational anti-whiplash device denoted by **P** permits the whole seat to translate backwards. The difference between RFWMS and WMS is that in RFWMS, the seatback (SB) now acts as an inner seatback frame which is pivoted about an outer seatback frame (OF) with the aid of another rotational anti-whiplash device denoted by **R***. In RFWMS, the outer seatback frame (OF) is connected to the seat-pan (SP) by the rotational anti-whiplash device **R**. But when the breakaway torque at **R*** is overcome due to the pressure applied by the torso on the seatback (SB), a rotation at **R*** occurs which is in the opposite direction to the rotation at **R**.

In order to imitate the function of seatback foam and suspension, a rigid plate which is of the same size as the seatback, was connected to the seatback structure by a translational AWD denoted by **P*** as shown in Fig. 3. This rigid plate is called “foam-plate” and during impact, it allows the torso to penetrate into the seatback structure by approximately 3 cm in addition to the static deformation caused by the occupant weight. Foam-plate displacement is denoted by Δ_{P*}. Fig. 4(a) shows the stiffness and damping functions for the translational anti-whiplash device **P*** which were derived by making use of the differences in the responses of JARI volunteers who were subjected to sled tests using both a rigid and a standard (i.e. typical) seat (Davidsson et al., 1999). The stiffness function of **P*** does not involve any breakaway force and the mass of the foam-plate is taken as 1 kg. The foam-plate is integrated into the seatbacks of all seats i.e. TYPS, WMS and RFWMS. Consequently, all seats have rigid surfaces throughout (except the head restraint) since they are the transformed versions of the JARI rigid seat used in the validation of the human model. Using multi-body seat models with rigid surfaces can be considered as an economical approach in developing seats for rear impact whiplash mitigation, since the seat surfaces stay rigid for all conditions, while in the case of an actual commercial seat with a degree of frame compliance, foam stiffness and suspension movement, the mechanical properties need to be correctly estimated for all impact speeds through extensive dynamic testing of seat components. Thus, having already developed a successfully validated seat-occupant system in which the human model interacts with rigid seat surfaces, the feasibility of seat design concepts and whiplash mitigation techniques can be readily tested through simulations.

Two different versions of WMS are considered. WMS-H has a stronger (or harder) recliner, whereas WMS-S has a softer one as shown by the stiffness functions of the rotational anti-whiplash device **R** given in Fig. 4(b). The recliner of RFWMS is softer than that of WMS-S on the whole. The three reactive car-seat concepts WMS-H, WMS-S and RFWMS have breakaway torques of 1100 Nm, 1000 Nm and 1000 Nm respectively. For rearward rotation at **R**, a constant damping coefficient of 1 Nms/deg is used for all three reactive car-seat concepts. This is an estimation of the rotational damping coefficient for the recliner structure of typical car seats (Eriksson, 2002). The rotational anti-whiplash device **R** applies high damping (150 Nms/deg) when the seatback (SB) starts rotating forward (rebound motion), hence minimising seatback rebound.

Fig. 4(c) shows the stiffness and damping functions of the rotational anti-whiplash device **R*** which has a breakaway torque of 1350 Nm. **R*** applies high damping (400 Nms/deg) for the reverse (rebound) motion. Fig. 4(d) presents the stiffness and damping functions of the translational anti-whiplash device **P** which are the same for all reactive car-seat concepts, however the breakaway forces are 5000 N, 4500 N and 4250 N for WMS-H, WMS-S and RFWMS respectively. For the reverse (forward) motion, **P** applies high damping (30 kNs/m) to limit forceful rebound of the seat-pan (SP).

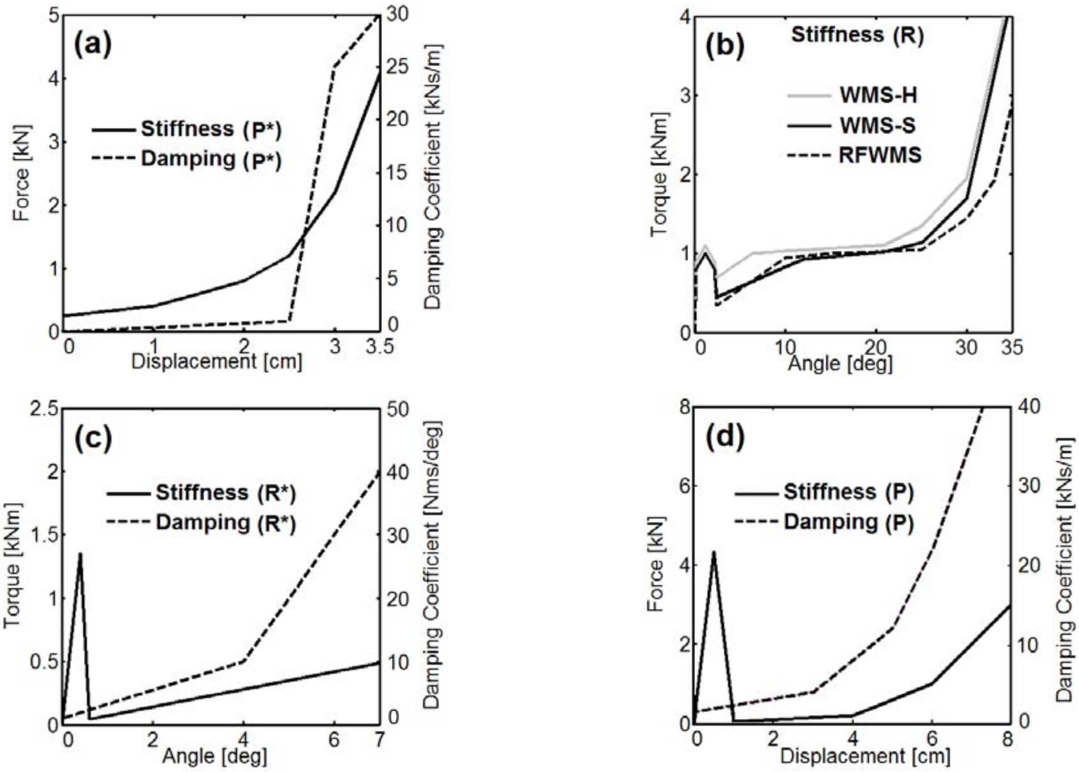

Fig. 4 - The Mechanical Properties of the AWDs

The operational ranges of the anti-whiplash devices are presented in tabulated form in Table 3. For all three reactive car-seat concepts, the anti-whiplash devices, **R** and **P** become operational when ΔV≥7 kph and ΔV>10 kph respectively. In RFWMS, **R*** becomes operational when ΔV>13 kph. For all three reactive car-seat concepts, no anti-whiplash device becomes operational for values of ΔV's less than 7 kph in order to prevent activation during normal daily use. This can easily be achieved in practice by using a sacrificial shear element, spring loaded latch or through active control. So, it is possible to reinstate the AWDs to their original positions after the impact. Therefore, for ΔV's less than 7 kph, the foam-plate and the head restraint are fully responsible for protection against whiplash.

The AWDs are passive units consisting of a nonlinear spring and a damper. They are modelled in such a way that spring and damper forces are produced in proportion to the displacement within the device. For instance, the translational anti-whiplash device **P** has damping coefficients which are nonlinear functions of the displacement as shown in Fig. 4(d). In practice, this can be achieved by designing a damper in which the size of the orifice can be narrowed as the seat-pan (SP) moves back. This action will force the fluid in the damper to flow through a narrower orifice, hence increasing the effective damping coefficient of the device.

Table 3. Operational Ranges of the AWDs

	ΔV< 7 kph	7 kph ≤ ΔV<10 kph	10 kph ≤ ΔV<13 kph	ΔV ≥ 13 kph
WMS-H	—	**R**	**R, P**	**R, P**
WMS-S	—	**R**	**R, P**	**R, P**
RFWMS	—	**R**	**R, P**	**R, P, R***

The mechanical properties of the recliner structure (RS) of the typical seat TYPS were derived from the work of Eriksson (2002) in which the validation of a number of typical car seat models were performed by subjecting typical car seats from the earlier decades to rear impact sled tests using two crash pulses with the same ΔV but with different acceleration profiles. From this study, two typical seats, namely TYPS-B1 and TYPS-G2 were selected. Eriksson (2002) indicated that TYPS-B1 had a higher whiplash risk than TYPS-G2. For both seats, Figs. 5(a) and 5(b) present the stiffness and damping characteristics for the rotational deformation at RS, whereas the stiffness and damping characteristics for the translational deformation at RS are given in Fig. 5(c). In the stiffness functions of RS, as shown in Figs. 5(a) and 5(c), the load increases in proportion to the deformation until the peak torque or force value is reached. For further deformations, there is a drop in torque or force which is associated with the failure of structural hardware at the recliner (i.e. plastic deformation).

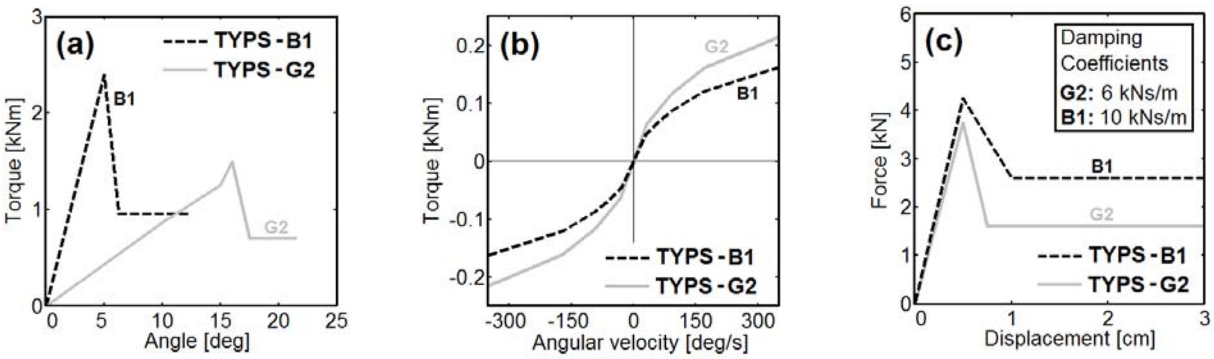

Fig. 5 - The Mechanical Properties of the Recliner Structure (RS)

INJURY MEASURES AND SEAT DESIGN PARAMETERS

First, it is ensured that the head restraint WMHR which is attached to all seats, satisfies the minimum height requirement by the European standard (UN-ECE Regulation No.17; Edwards et al., 2005). Nonetheless, an additional vertical height of 35mm is added for WMHR in order to compensate for spine straightening. This value corresponds to the average upward displacement of T1 (the first thoracic vertebra) as obtained in the JARI volunteer sled tests (Davidsson et al., 1999). Hence, the top of WMHR becomes level with the top of the head (see Fig.1). Avery and Weekes (2006) suggested that backset values less than 45 mm could cause discomfort. Therefore, the backset of WMHR is set to

60 mm to allow head comfort and this backset value is within the range of a good head restraint geometry as specified by IIWPG (2008).

In order to evaluate the dynamic performance of the seat concepts, the seven assessment criteria of the EuroNCAP dynamic whiplash test are considered which are the head restraint contact time, T1 forward acceleration, head rebound velocity, NIC (Neck Injury Criterion), N_{km}, upper neck (rearward) shear force and upper neck tension force. In order to rate the upper neck i.e. OC (occipital condyles) forces, the neck force classification specified by IIWPG (2008), is used. However, it must be noted that this classification is a statistical but not a biomechanical interpretation of upper neck forces. These criteria were determined by studying the distribution of upper neck forces based on the tests done with the BioRID II dummy using 2004 model year car seats with good geometry. In these tests by the IIWPG, the 2004 model year car seats were subjected to the IIWPG standard crash pulse (ΔV=16 kph, a_{mean}=5g, a_{peak}=10g) only. Although BioRID II's resistance to loading by the seatback and the head restraint will differ to some extent in comparison with the human model used in this study, these specifications can still be used for comparison purposes.

IIWPG (2008) recommends a head restraint contact time of 70 ms and a T1 forward acceleration limit of 9.5g for energy absorbing seats at the IIWPG standard crash pulse. The suggested injury threshold value for N_{km} is 1 (Schmitt et al., 2001) and the proposed injury threshold value for NIC is 15 m^2/s^2 (Boström et al. 1996). For head rebound velocity (v_r), there is no commonly accepted limit but in this study, the classification by Krafft et al. (2004) is used in which there is low risk if $v_r \leq 4.5$ m/s, medium risk if 4.5 m/s < $v_r \leq 6$ m/s and high risk if $v_r > 6$ m/s.

The maximum allowable rearward displacements of the seat components are selected considering the suggested values for other energy-absorbing car-seat designs in the literature (Lundell et al., 1998; Zellmer et al., 2001; Viano, 2002; Schmitt et al., 2003). Therefore, for the highest severity studied, the rotation at **R*** (i.e. the inner seatback frame rotation in RFWMS) and the seat-pan (SP) displacement are limited to 6.5 deg and 6.4 cm respectively. The recliner rotation at **R** and the change in seatback angle, are restricted to 30 deg to limit ramping and rearward displacement of the seatback (SB).

The formation of S-shape (or head retraction relative to the upper torso) during rear impact, can cause abnormal segmental motions in the neck, causing unfavourable loading of the soft tissues and even pressure alterations (Boström et al., 1996) inside the cervical spinal canal. NIC is associated with the formation of S-shape and is based on the relative acceleration and velocity between the OC and T1. While NIC can address the spinal ganglion injuries associated with S-shape formation, it does not explicitly indicate the amount of distortion in the neck in terms of relative displacements. Therefore, in addition to the EuroNCAP whiplash assessment criteria, an injury measure called the Neck Deformation Index (NDI) is proposed to practically quantify neck internal motion by monitoring the neck intervertebral angles (see Fig. 1) of the human model. Such a kinematics based injury measure is missing in the whiplash consumer tests.

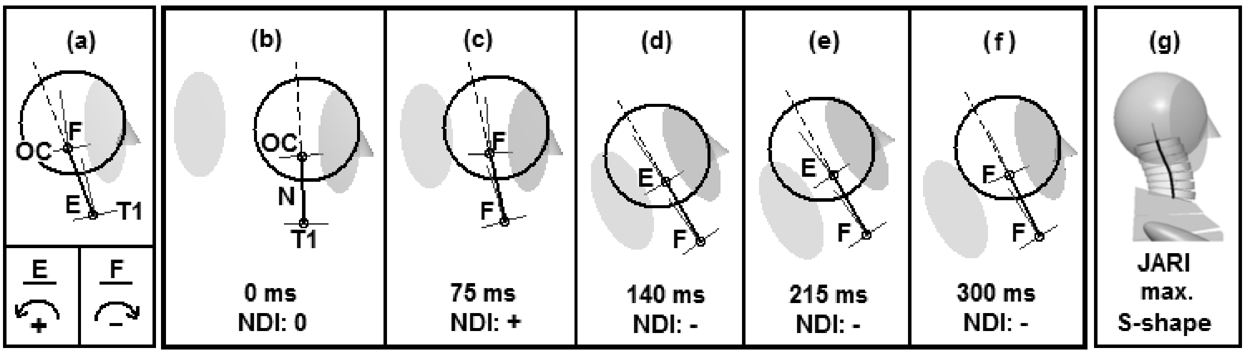

Fig. 6 - Motion Phases of the Head-and-neck

NDI is expressed as ($-\theta_{OC/C1} + \theta_{C7/T1}$), where C1 and C7 represent the first and seventh cervical vertebrae respectively. $\theta_{OC/C1}$ and $\theta_{C7/T1}$ represent the intervertebral angle changes between OC and C1, and, C7 and T1, respectively. $\theta_{OC/C1}$ and $\theta_{C7/T1}$ can be considered to represent the state (i.e. either flexion (-) or extension (+)) of the upper and lower neck respectively. It should be noted that NDI is specifically defined for whiplash type loadings in the sagittal plane. Fig. 6 presents a schematic sketch of the neck deformation phases in a typical interaction of the head with the head restraint. Figs. 6(b) to 6(f) also represent the head-and-neck responses when the human model is seated in WMS-S and the highest severity pulse of the EuroNCAP whiplash test is applied. In Fig. 6, **F** and **E** represent flexion or extension respectively of either the lower or upper neck. There are two coordinate systems attached to the head and the upper torso at the OC and T1 respectively. The origins of these two coordinate systems are connected by the link **N**, which represents the neck.

In order to quantify the most prominent S-shape (or retraction), NDI is calculated at the instant when the upper neck attains the largest flexion during lower neck extension. Fig. 6(a) depicts a typical S-shape deformation of the neck, in which **F** and **E** show the flexion and extension at the upper and lower neck respectively. The mathematical definition of NDI indicates a positive value during a typical S-shape formation in which the head retracts with respect to the upper torso or T1.

NDI can also account for situations where the neck is, for instance, completely in flexion but the flexion in the upper neck is more than that of the lower neck as shown in Fig. 6(c). In such a case, the neck still undergoes an S-shape like deformation since NDI takes a positive value. Therefore, NDI can quantify whether there is relative flexion or extension of the upper neck with respect to the lower neck. Negative values of NDI correspond to protraction type deformation of the neck.

In the JARI volunteer sled tests, a rigid seat without head restraint was used and the simulation of these tests using the human model, produced an NDI value of 4.5 deg when the most prominent S-shape occurred as shown in Fig. 6(g). Considering this, an NDI value of 4.5 deg can be taken as a reference value for the maximum allowable S-shape deformation (or retraction) in the neck.

TEST PROCEDURE AND SIMULATION OVERVIEW

In order to evaluate the performance of the reactive car-seat concepts using the human model, the hands and arms are positioned as shown in Fig. 1 to adopt a posture practiced in whiplash dynamic tests (IIWPG, 2008). The initial seatback angle is set to 20 deg from the vertical and the human model represents a relaxed and unaware occupant as in the JARI sled tests. In order to simulate the frictional resistance between a typical car occupant and a typical car-seat upholstery, a friction coefficient of 0.35 is used in the simulations for all contacts between the human and seat models. This value is derived from the work of Verver (2004) who conducted experiments to estimate an average friction-coefficient value to be used in modelling the interaction between an occupant and a typical car seat.

Table 4. Crash Pulse List

Pulse	ΔV [kph]	a_{mean} [g]	a_{peak} [g]	Ref. No		Pulse	ΔV [kph]	a_{mean} [g]	a_{peak} [g]	Ref. No
SN(4.5)	4.5	1.86	4.5	[1]		TR(16)	16	4.5	5	[3]
SN(8.4)	8.4	3.3	8.7	[1]		SN(16)	16	5	10	[3]
SN(9.4)	9.4	3.1	11.7	[1]		SN(20.5)	20.5	5.2	10.6	[2]
SN(11)	11	4.4	9.6	[1]		TR(24)	24	6.5	7.5	[3]
SN(13)	13	4.7	10.3	[1]		HS(30)	30	6.8	26.5	[4]
[1]: Linder et al. (2001), [2]: Linder et al. (2003), [3]: Avery et al. (2007), [4]: Saunders et al. (2001)										

The EuroNCAP dynamic whiplash test employs three different crash pulses, a low severity trapezoidal pulse (ΔV=16 kph, a_{mean}=4.5g, a_{peak}=5g), a medium severity triangular (or sinusoidal) pulse (ΔV=16 kph, a_{mean}=5g, a_{peak}=10g) and a high severity trapezoidal pulse (ΔV=24 kph, a_{mean}=6.5g, a_{peak}=7.5g) (Avery et al., 2007). In this study, the simulations are run for a much wider range of crash pulses as indicated in Table 4, in which sinusoidal and trapezoidal type pulses are denoted by SN and TR respectively and the highest severity pulse is represented by HS. Table 4 also includes the low, medium and high severity EuroNCAP crash pulses which are denoted by TR(16), SN(16) and TR(24) respectively. Sinusoidal type pulses are mostly included in the list since trapezoidal pulses are not found to be representative of the typical crash pulses that develop between current production cars engaged in rear impact within the crash severity range where the majority of rear-end collisions occur. For the same reason, when specifying the operational range of an anti-whiplash device (AWD) in terms of ΔV, it is actually meant that the AWD becomes operational when a sinusoidal pulse of a certain ΔV is reached.

The performance of the reactive car-seat concepts are also compared with those of the typical seat models TYPS-B1 and TYPS-G2. However, for this case, the simulations are run only for the crash pulse SN(16) since the properties of the recliner structure in the TYPS seats were derived from the work of Eriksson (2002) in which the models of typical car seats were tuned to the validation sled tests using two crash pulses of DV≈17 kph and the severity of SN(16) is similar to those of the two pulses.

In the simulations, the maximum T1 forward acceleration is taken as the highest acceleration of T1 in the x-direction, as expressed in the inertial coordinate system S_G (see Fig. 1). For the head rebound velocity, the maximum resultant head velocity with respect to the sled is taken during the period in which the head starts to rebound from the head restraint and also moves in the forward (+x) direction relative to the sled. This definition is in accordance with the rebound velocity measurement procedure used in dynamic whiplash tests (Bortenschlager et al., 2007). In the human model, the OC loads on the head are expressed in the head coordinate system located at the head centre of gravity as shown in Fig. 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 crash test dummies, these forces are assumed to be acting at the OC. The negative OC-shear force on the head of the human model is taken as the upper neck rearward shear force as defined by the IIWPG upper neck (OC) force classification (IIWPG, 2008).

RESULTS

The performance of the three reactive car-seat concepts have been evaluated by simulating rear impact sled tests at severities ranging from 4.5 to 30 kph of ΔV. Some selected results are given in Fig. 9 which include upper neck rearward shear force ($Fsh^{(-)}$), head restraint contact time (HrCt) and maximum T1 forward acceleration ($T1_{x\text{-}acc}$). In order to give an insight into the behaviour of the seat components, the responses of the anti-whiplash devices of RFWMS, when subjected to the crash pulse SN(16), are presented in Fig. 7(a). The corresponding time histories of the injury measures and the responses of the human model are shown in Figs. 7(b) and 8 respectively.

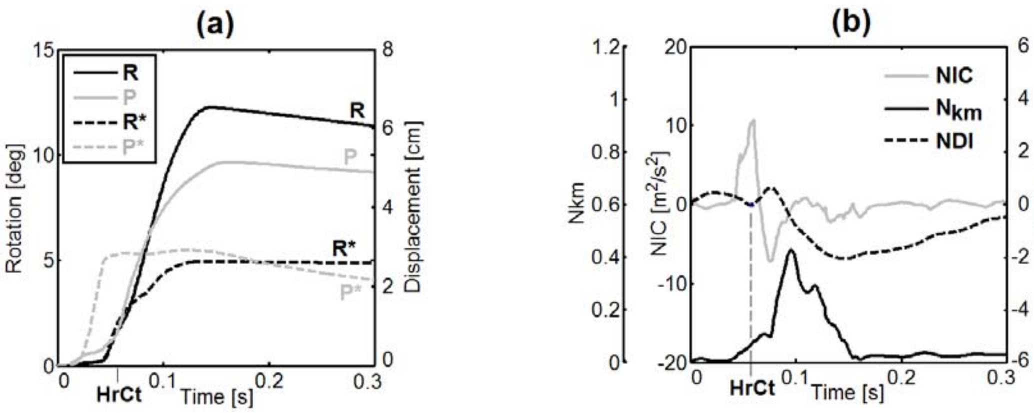

Fig. 7 - Time Histories of AWD Responses (a), and Injury Measures (b). (Seat: RFWMS, Pulse: SN(16))

Fig. 7(a) indicates that during the first 50 ms of the impact, the foam-plate, with the aid of **P***, allows the human model to sink into the seatback structure by 2.8 cm without any rotation of the seatback. Thus, between 0 to 50 ms, the seat-pan starts to move backwards slowly relative to the sled and **P** becomes fully operational by the end of this period while **R** (recliner) and **R*** are still not operational. At around 50 ms, the foam-plate bottoms out. Starting from 50 ms, the seat-pan starts to move backwards rapidly and at around 55 ms, **R** and **R*** both become operational. At 70 ms, the seat-pan reaches a displacement of 2.2 cm. Between 50 to 70 ms, the rotations at **R** and **R*** are of the same magnitude, but they cancel each other. Thus, the seat moves backwards initially without considerable seatback (SB) rotation. After 70 ms, the displacement rates are rapid for all the AWDs (except **P***) until the maximum displacements are reached. For the seats WMS-H and WMS-S, the AWDs behave in a very similar way.

As indicated by Fig. 7(b) and Fig. 8, head restraint contact (HrCt) occurs at 58 ms, followed by the formation of the most prominent S-shape (i.e. head retraction) at 75 ms. The neck deformation is insignificant throughout the impact as observed from the simulations. At around 120 ms, the normal force applied by the head restraint on the head becomes maximum, hence the shear force at the OC attains its largest value. From then on, the head unloads the head restraint until it completely loses contact with it at 225 ms. There is a rise in the compression force at around 225 ms, because of the fact that the pelvis slides down the seatback in the latter half of the impact until it hits the seat-pan gently. The peak compression force at the OC occurs at around 50 ms as a consequence of spine straightening. The foam-plate also bottoms-out around this time as the torso has fully sunk into the seatback structure. This causes a temporary increase in the normal force applied by the seatback on the torso, causing spine straightening and a peak in the compression force. It should be noted that for all the reactive car-seat concepts and at all severities, the values of the peak compression force (resulting from spine straightening) are within the range of the peak compression forces sustained by the volunteers in the JARI sled tests (Davidsson et al., 1999).

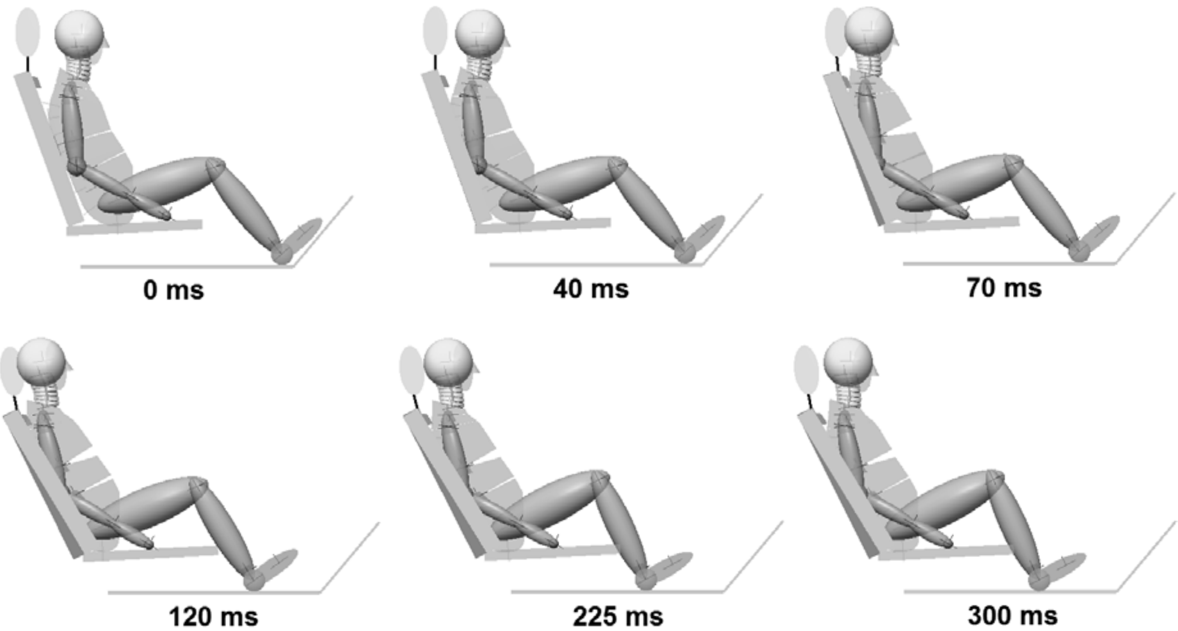

Fig. 8 - Response of the Human Model and RFWMS to the Crash Pulse SN(16)

DISCUSSION

For all the reactive car-seat concepts and at all severities, the results indicate that the maximum T1 forward accelerations ($T1_{x\text{-}acc}$) are less than the recommended IIWPG limit (9.5g) specified for energy absorbing seats. The maximum values of the NIC are less than 11 m^2/s^2 which is lower than the proposed injury threshold value of 15 m^2/s^2. Early head to head restraint contact times (HrCt $\leq$ 75 ms) are achieved considering that the suggested contact time at the IIWPG standard crash pulse is 70 ms. The only exception happens at the pulse SN(4.5) for which HrCt is 87 ms. This is due to the fact that the pulse is weak, but it is not injurious. For ΔV>13 kph, RFWMS has significantly earlier contact times than WMS-H and WMS-S (see Fig. 9) since the counter-rotation of the inner seatback (SB) frame at **R*** reduces the dynamic backset and the effective seatback angle.

The results show that the rotation at **R*** (i.e. the inner seatback frame rotation in RFWMS) and the seat-pan (SP) displacement do not exceed the selected limits of 6.5 deg and 6.4 cm respectively. The recliner rotation at **R** and the change in seatback angle are also successfully limited to around 30 deg.

Foam-plate displacement, which is denoted by Δ_{P*} (see Fig.3), is around 3.2 cm at most. No seat-belt is used in the simulations but occupant retention is still provided. The head restraint WMHR is high enough and the ramping of the body has not caused hyperextension in the neck. As the forward rebound of the seat components is minimised, the rebound velocities of the head and torso is insignificant. In the EuroNCAP whiplash test, a head rebound velocity (v_r) of 3 m/s is regarded as a low risk value for the lower severity pulse (i.e. TR(16)) but for all the reactive car-seat concepts, v_r values are less than 1.3 m/s at all severities and hyperflexion is not observed in the simulations.

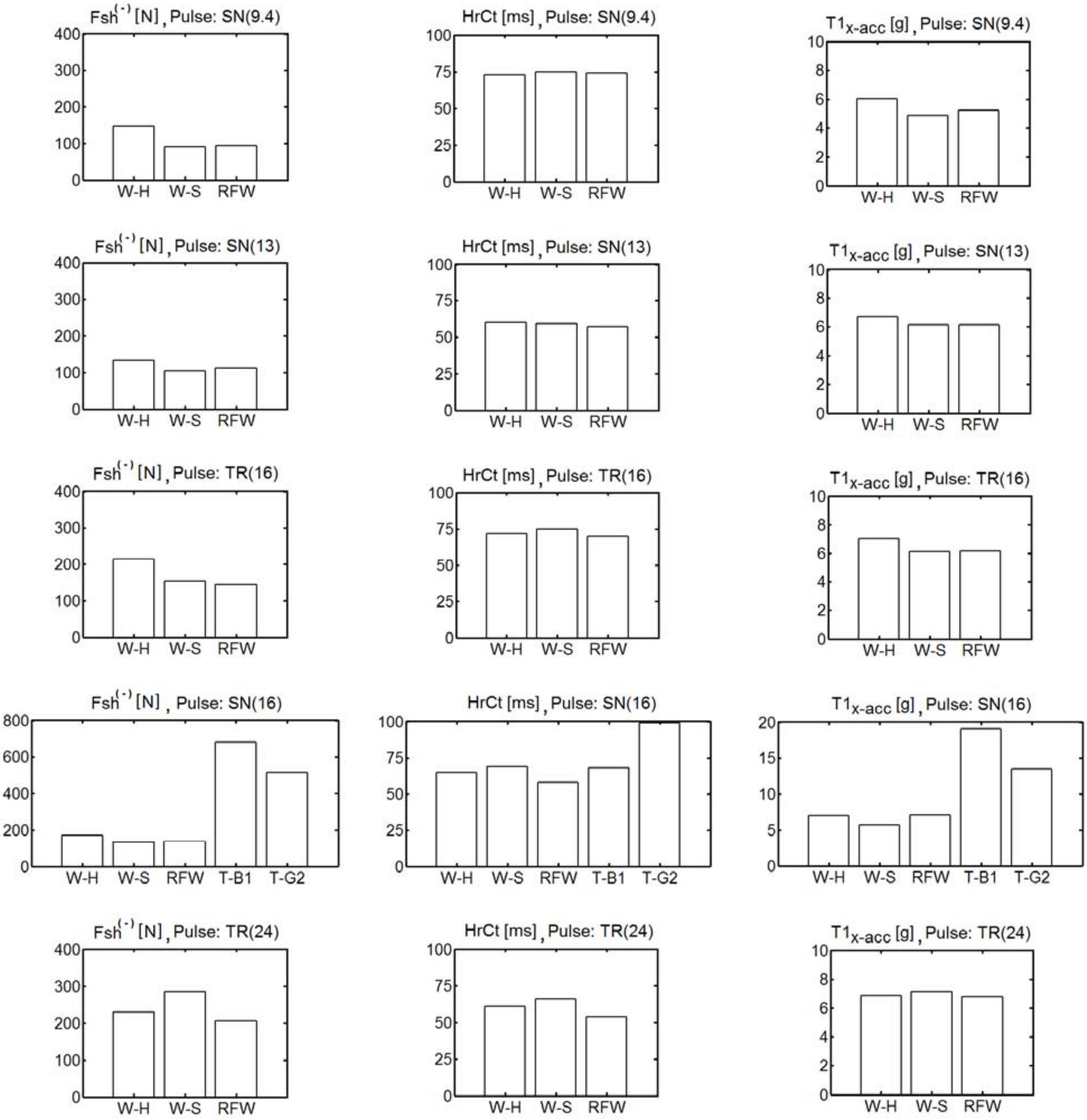

Fig. 9 - Comparison of Seat Performance at Selected Crash Severities

The NDI values are all less than 4.5 deg which is the suggested reference value in this study for the maximum allowable S-shape deformation. Hence, all the reactive car-seat concepts are able to limit the formation of S-shape (or head retraction). Fig. 10 shows the head-and-neck responses for the seat WMS-H at the highest severity of EuroNCAP whiplash test (i.e.TR(24)). The most prominent S-shape (or head retraction) occurs at 73 ms whereas the neck experiences the most prominent protraction type deformation at 200 ms. It should be noted that for all the reactive car-seat concepts and at all severities, the neck intervertebral angle changes are less than 4 deg (both flexion and extension) on average. Thus, the range-of-motions of the neck joints are not exceeded considering that the range-of-motion for each neck joint of the human model are 12.5 deg in extension and 6 deg in flexion (Himmetoglu et al., 2009).

Fig. 10 - Head-and-neck Responses (Seat: WMS-H, Pulse: TR(24))

At all severities and for all the reactive car-seat concepts, N_{km} values are less than the suggested injury threshold value of 1. The OC tensile forces are less than 260 N at all severities and this is considered to be low according to the IIWPG upper neck force classification. The positive OC-shear forces ($Fsh^{(+)}$) are also quite low (< 45 N) which indicates that head retraction is successfully limited. In general, the reactive car-seat concepts exhibit negative OC-shear forces ($Fsh^{(-)}$) which are either low (less than 150 N) or moderate (in between 150 N and 260 N). Fig. 9 shows the largest values of the negative OC-shear forces (i.e. upper neck rearward shear force) at selected crash severities.

It should be noted that for the seats WMS-H and RFWMS, the moderate $Fsh^{(-)}$ limit is reached at the highest severity pulse (i.e. HS(30)). But for the seat WMS-S, $Fsh^{(-)}$ values are slightly over the moderate $Fsh^{(-)}$ limit at the upper end of the severity range. In comparison with WMS-H, the seat WMS-S produces lower $Fsh^{(-)}$ for $\Delta V<20.5$ kph, but higher $Fsh^{(-)}$ for $\Delta V\geq 20.5$ kph. On the other hand, RFWMS achieves a more balanced and better perfomance with regard to $Fsh^{(-)}$ values. It can be shown that if the seatback was allowed to continue absorbing energy by rotating more at the higher severities (i.e. TR(24) and HS(30)), lower $Fsh^{(-)}$ values could be obtained. As seat-belt is not used, the occupant retention is solely provided by the seatback. This puts a limit on the seatback rotation considering that the interference with the rear seat and the rear occupant should be minimised at the same time.

As shown in Fig. 9, the simulations at the IIWPG standard crash pulse (SN(16)) indicate the effectiveness of the reactive car-seat concepts in comparison to the typical seats TYPS-B1 and TYPS-G2. The values of $Fsh^{(+)}$ (i.e. positive OC-shear force) and NDI indicate that head retraction is successfully limited by the TYPS seats due to the presence of a head restraint with good geometry. However, the remaining injury measures point to a high risk of whiplash. In the TYPS seats, the crash energy is not absorbed effectively, thus the head interacts with the head restraint severely, causing the head restraint to bottom-out. Although the reactive car-seat concepts and the TYPS seats have the same head restraint with the same geometry, their responses are quite different.

The anti-whiplash devices (AWDs) absorb the crash energy collaboratively as they successively become operational once the breakaway torques and/or forces are exceeded. These breakaway torques and forces correspond to the initial peaks in the stiffness functions of the AWDs as shown in Figs. 4(b), 4(c) and 4(d). The seatbacks of the reactive car-seat concepts are designed to be yielding but they become progressively stronger for larger rotations hence limiting the rearward displacements of the seat components. The breakaway torque at the recliner enables the torso to sink into the seatback structure without rotating the seatback excessively at the start of the impact. So, the seatback and the head restraint are not allowed to move away from the upper torso and the head during the initial stages of the impact. Therefore, the breakaway torque at the recliner is one of the design features that enables the head restraint to support the head effectively.

For all the reactive car-seat concepts, the foam-plate and the head restraint are fully responsible for protection against whiplash at ΔV's less than 7 kph. For all the reactive car-seat concepts, between 7 and 10 kph of ΔV, the AWD situated at the recliner (i.e. **R)** is operational only, hence all the crash energy is fed to **R**. This makes the seatback more compliant at lower severities. For the seats WMS-H and WMS-S, the translational AWD placed under the seat-pan, denoted by **P**, becomes operational after 10 kph of ΔV, hence the anti-whiplash devices **R** and **P** are both involved in energy absorption and this controls the rotation of the seatback (SB) effectively, preventing excessive rotation at the recliner.

For the seat RFWMS, **P** is also operational after 10 kph of ΔV, but after ΔV>13 kph, **R*** becomes operational as well. Noting that WMS-S and WMS-H are the seat concepts with softer and harder (i.e. stronger) recliners respectively, RFWMS combines the favourable properties of the seats WMS-S and WMS-H. Thus, RFWMS behaves like WMS-S for pulses up to SN(16) but then behaves more like WMS-H for the higher severity pulses. This can be seen in the $Fsh^{(-)}$ responses as shown in Fig.9. So, RFWMS is comparatively the better seat, as it shows a more balanced and better performance at all severities. RFWMS achieves this with the aid of the rotational anti-whiplash device **R*** which becomes operational for ΔV>13 kph. The rotation at **R*** helps RFWMS to obtain more reduction in dynamic backset while the torso conforms to the seatback. Early head contact is achieved without depending on the forward deployment of the head restraint relative to the top of the seatback as in the reactive and pro-active head restraint designs on the market. It must be noted that the characteristics of the AWD at R* must be adjusted properly so that the inner seatback (SB) frame rotation at R* must be accompanied by a sufficient amount of outer seatback frame (OF) rotation at R in order to avoid increasing the loading on the upper torso in any case.

LIMITATIONS OF THE STUDY

The seats are accelerated by applying crash pulses to the sled, hence the interaction of the seats with the rear occupant, the rear seat and the car interior is not modelled. In whiplash consumer tests, the BioRID II dummy is restrained by a seat-belt but in this study, no seat-belt is used, hence occupant retention is solely provided by the seatback. It is not possible to compare the seat concepts with the current systems on the market as they are concepts not physical systems that can be tested.

In designing the seat concepts through optimisation of the anti-whiplash devices, the rigid seat used in the JARI sled tests is modified and an unbelted 50th percentile male human model with a specific posture is used. A typical head restraint with a good geometry is used but it is the structural deformation of the seat which plays a pivotal role in whiplash mitigation. The design strategy, as described in this study, involves the application of anti-whiplash devices which effectively control the relative motion between the structural members of the seat. Therefore, using the proposed anti-whiplash devices, a typical car-seat from the market can be structurally modified to provide better protection against whiplash.

The optimised characteristics of the anti-whiplash devices also depend on the occupant weight. However, simulations of different gender, body sizes and proportions would be a large project on its own right considering that there is a lack of complete and reliable data on the mechanical properties of the human body. There is limited validation data on volunteer impact response and human cadaver testing has its own limitations including legal issues. The use of scaling methodology can help but that would possibly be the subject of another study.

CONCLUSIONS

This paper presents three reactive car-seat concepts, which achieve whiplash mitigation for a wide range of crash severities through collaborative motion of seat components. The effectiveness of the proposed concepts is evaluated using both kinematics and force based injury measures. This study demonstrates through simulations that the proposed car-seat concepts clearly represent a significant improvement over the typical seat models considering that they have the same head restraint with the same geometry. Unlike the energy absorbing car-seats on the market, the proposed car-seat concepts are reusable after a rear-end impact. It is also demonstrated that these reactive car-seat concepts can adapt themselves to different severities using passive anti-whiplash devices so that the seatback and the head restraint work together effectively. Among the proposed concepts, RFWMS provides the most optimum neck protection at all crash severities. RFWMS achieves this performance with the aid of an inner frame which controls the rotation of the seatback more effectively and provides relatively earlier head restraint contact. Hence, the developed reactive car-seat concepts can be considered to be promising designs for future whiplash-mitigating reusable car-seats which should be robust against uncontrolled factors in road-traffic accidents.

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