An evaluation of passive head-restraints with different stiffness and energy dissipation properties for whiplash mitigation

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Abstract - This study investigates the protection offered by passive head-restraints with different stiffness and energy dissipation properties. For this purpose, computational multi-body models of a generic car seat and a biofidelic 50th-percentile male human for rear impact are used to study different seat designs and passive head-restraints. The validated seat-occupant model is also used in the design of two different car-seat models which are shown to effectively mitigate whiplash by utilising a crash-energy distribution technique. Five different passive head-restraints with varying stiffness (low-medium-high) and energy dissipation percentages (low-high) are successively attached to four different car-seat models. The simulation results indicate that the protection offered by head restraints is strongly dependent on the seat design. It has also been shown that the stiffness of the passive head-restraint has much more influence on whiplash-risk in comparison to its energy dissipation capacity.

NOTATION

AWD	anti-whiplash device
C i	i th cervical vertebra
E_a , E_d , E_r	energy absorbed, dissipated and returned respectively by HR
EDP	energy dissipation percentage
EMP	the medium severity crash pulse in EuroNCAP whiplash test
EuroNCAP	European New Car Assessment Programme
F_L , F_U	normal force generated by HR regarding the loading and unloading curves, respectively
$Fsh^{(-)}$, $Fsh^{(+)}$	largest negative and positive shear forces acting on the head respectively at the OC
Ftn	largest tension force acting on the head at the OC
g	gravitational acceleration
G	the inertial coordinate system
HR	typical passive head-restraint
*HR*1	HR with high stiffness and high EDP
*HR*2	HR with high stiffness and low EDP
*HR*3	HR with low stiffness and high EDP
*HR*4	HR with low stiffness and low EDP
HRB	baseline HR with medium stiffness and high EDP
IIWPG	International Insurance Whiplash Prevention Group
NDI	neck distortion index
NIC	neck injury criterion by Boström et al. [12]
N_{km}	neck injury criterion by Schmitt et al. [13]
OC	occipital condyles or upper neck
OF	the outer-seatback-frame in RFWMS
P	translational AWD
R	rotational AWD of ROWMS and WMS, at the recliner
R^+	rotational AWD of RFWMS, at the recliner
*R**	rotational AWD of RFWMS, connecting OF to the seatback
*R^*	the recliner joint of RONB
RFWMS	whiplash-mitigating car-seat model with the inner-frame
RONB	the car-seat model similar to a typical car-seat
ROWMS	a modified version of WMS
T1	the first thoracic vertebra
v_r	maximum resultant head rebound velocity
WMS	whiplash-mitigating car-seat model
x	deformation of HR
$\Delta\theta_{IV-UH}$	largest (+/-) intervertebral rotations in the upper half of the neck
$\Delta\theta_{IV-LH}$	largest (+/-) intervertebral rotations in the lower half of the neck
ΔV	change in the velocity of a vehicle subjected to a crash pulse
$\theta_{OC/C1}$	intervertebral rotation between OC and C1
$\theta_{C7/T1}$	intervertebral rotation between C7 and T1

INTRODUCTION

The term “whiplash” is used to describe neck injuries (or disorders) in which the sudden differential movement between the head and torso, leads to damage of soft tissue in the neck. The highest risk of sustaining whiplash injury has been found to occur in rear-end crashes [1,2]. A head restraint with good stiffness and energy absorbing characteristics, positioned at the right height and with an appropriate (small) backset distance, can decrease whiplash risk in rear-end crashes. However, research has shown that seats with good static head-restraint geometry do not always offer good protection dynamically [3,4]. Whiplash can be mitigated by car seats which can reduce occupant acceleration, support the head effectively, reduce ramping and limit seatback rebound [4]. The seat and the head restraint must work in unison to absorb the crash energy effectively so that neck internal motion and neck forces are reduced throughout the impact [4].

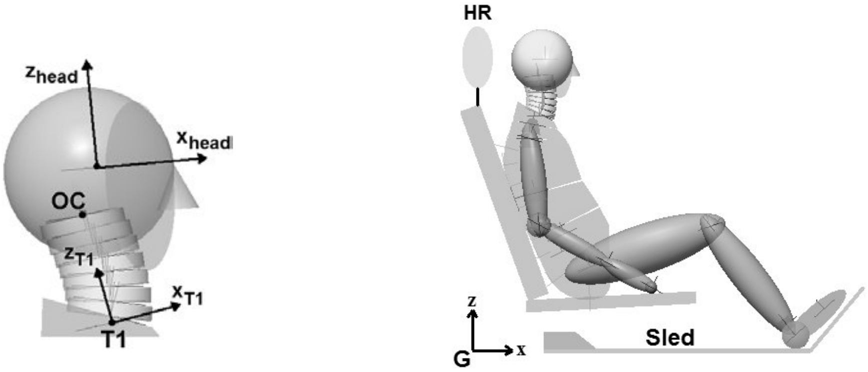
Head restraints are an essential part of car seats but there are a few detailed studies on the mechanical properties of typical passive head-restraints. Jakobsson et al. [5] showed an increase in head linear and angular acceleration, neck shear and tensile forces with a stiffer and less energy absorbing head restraint in their computer simulations. Viano [6] evaluated the energy absorption properties of head restraints by conducting tests in which the back cap of a Hybrid III dummy head was impacted vertically on different head restraints using a hydraulic material-testing machine. A high stiffness of the head restraint was considered good because it can limit head displacement and thus neck extension and shear. A high percentage of energy absorption by foam deformation was also favoured since this would reduce rebound velocity. Similarly, a high percentage of energy absorption by metal deformation and a relatively small peak metal displacement was considered good for the same reasons. It was emphasised that a stiff head restraint with good energy absorption properties can provide low head rebound velocity and reduce the differential rebound of the head and torso [6].

In this study, four different car-seat models with different structural characteristics are used. Two of these car-seat models are anti-whiplash seats possessing whiplash-mitigating features. Five different passive head-restraints with varying stiffness (low-medium-high) and energy dissipation percentages (low-high) are successively attached to each of these four different car-seat models. The mechanical properties of the head restraints are derived from the impact tests by Viano [6]. The seat-occupant models are then subjected to the EuroNCAP medium severity crash pulse. It is shown that the performances of the head restraints depend strongly on the dynamic behaviour of seats with different structural characteristics.

A SEAT-OCCUPANT SYSTEM FOR REAR IMPACT SIMULATION

A biofidelic 50th-percentile male multi-body human model, as shown in Figure 1, was developed using MSC VisualNastran-4D with Matlab-Simulink; and validated using the responses of seven healthy 50th-percentile male volunteers from the Japan Automobile Research Institute (JARI) sled tests [7]. The human model is composed of rigid bodies connected by rotational springs and dampers. The initial configuration of the human model, as shown in Figure 1(b), corresponds to the normal driving posture of a 50th-percentile male who is relaxed and unaware of the timing of the impact.

In validating 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 rigid seat surfaces [7]. Based on the JARI rigid-seat, a generic multi-body car-seat model was developed at the same time to implement various energy absorbing devices, seatback, head restraint and recliner properties [4]. A typical passive head-restraint (HR), attached to the seatback as shown in Figure 1(b), is also included in the seat-occupant system model. The seat model is able to simulate the mechanical function of a typical seatback foam and suspension. The developed seat-occupant system model helps to economically simulate different rear-impact scenarios.



(a) (b)

Figure 1. (a) Head-and-neck model in S-shape-like deformation, (b) The seat-occupant system model

WHIPLASH MITIGATING CAR-SEAT MODELS

A typical car-seat is composed of a passive head-restraint (HR), a seatback, and a seat-pan, as shown in Figure 2. In a typical car-seat, the recliner attaches the seatback to the seat-pan. The recliner is a mechanism that remains locked during normal daily use. When a rear impact occurs, the structure of the recliner mechanism deforms and this causes the seatback to rotate backwards with respect to the seat-pan. The rotation of the seatback can be coupled with some translational deformation at the recliner and at the base of the seat-pan. However, the dominant or typical mode of deformation is the rotation of the seatback around the rotation-centre of the recliner mechanism.

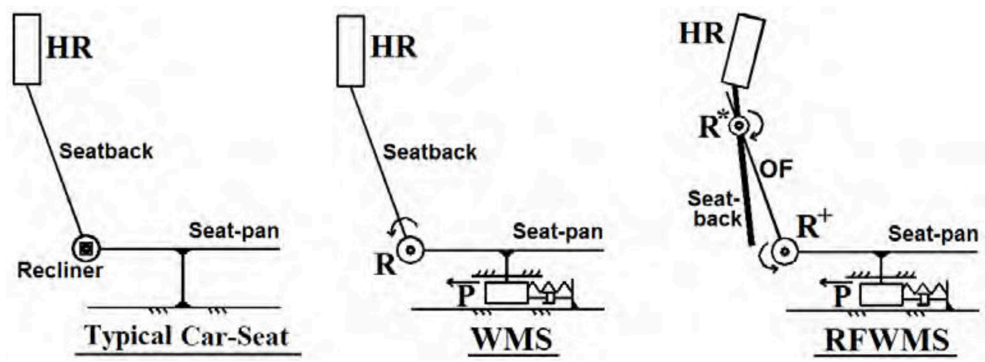


Figure 2. Schematic drawings of car-seat models

Using the seat-occupant system model shown in Figure 1(b), two different whiplash-mitigating car-seat models, namely WMS and RFWMS, were developed [4]. As shown in Figure 2, WMS and RFWMS are different than a typical car-seat as they employ anti-whiplash devices (AWDs) which control the relative motion between the structural members of the seat, to provide effective whiplash mitigation for a wide range of crash severity. Using these AWDs, a typical car-seat can be transformed into a seat which can offer improved protection in rear impacts. The AWDs, which are denoted by R, R*, R^+ and P, are passive energy-absorbing devices composed of nonlinear spring-and-damper units and they become operational, only when the corresponding breakaway forces and/or torques are exceeded. The AWDs enable the crash energy to be distributed and absorbed effectively.

In WMS, the rotational anti-whiplash denoted by R is positioned at the recliner and it enables the seatback to rotate with respect to the seat-pan. The translational anti-whiplash device denoted by P is placed under the seat-pan and it permits the whole seat to translate backwards a short distance during rear impact. The main difference between RFWMS and WMS is that in RFWMS, the seatback (which the torso directly interacts with) functions as an inner-frame and it is pivoted to the outer-seatback-frame (OF) using another rotational anti-whiplash denoted by R*. Besides, OF is connected to the seat-pan by the rotational anti-whiplash device R^+. When the breakaway torque at R* is overcome due to the pressure applied by the torso on the seatback, a rotation at R* occurs in the opposite direction to the rotation at R^+.

The mechanical properties of the AWDs were determined using a variety of crash pulses with a wide range of ΔV (between 4.5 and 35 km/h) [4]. The applied set of crash pulses also included the low, medium and high-severity crash pulses employed in the EuroNCAP whiplash test [8]. As shown in Table 1, the AWDs become operational in succession, according to the severity of the rear impact. No AWD becomes operational for a ΔV value less than 7 km/h to prevent activation during normal daily use.

Table 1. Operational ranges of the anti-whiplash devices

	7 km/h ≤ ΔV < 10 km/h	10 km/h ≤ ΔV ≤ 13 km/h	ΔV > 13 km/h
WMS	R	R , P	R , P
RFWMS	R^+	R^+ , P	R^+ , P , R*

Himmetoglu et al. [4] demonstrated that the whiplash-mitigating car-seat models WMS and RFWMS could successfully mitigate whiplash injuries for a wide range of crash severity (between 4.5 and 30 km/h of ΔV) through coordinated motion of seat components. For the highest severity considered, the seat-pan displacement and seatback rotational displacement were limited to 6.4 cm and 32 deg, respectively. This helped to limit the ramping of the unbelted occupant and the rearward displacement of the seat. RFWMS performed better than WMS at all severities, since the rotational AWD denoted by R* controls the rotation of the seatback more effectively and provides relatively earlier head-restraint contact. The performances of the whiplash-mitigating car-seat models were also compared with those of the typical car-seat models without any whiplash-mitigating feature. The numerical simulations indicated that both WMS and RFWMS represented a significant improvement over the typical-car-seat models although all of the seats had the same head restraint with the same static geometry (as shown in Figure 1(b), with a backset distance of 60 mm) prior to impact. For example, for WMS and RFWMS, the neck shear-forces were about three times lower in comparison to the typical-car-seat models.

CAR-SEAT MODELS FOR HEAD-RESTRAINT EVALUATION

In order to investigate the influence of head-restraint mechanical properties on seat-occupant response, four different car-seat models (RONB, ROWMS, WMS, RFWMS) are considered, as shown in Figure 3. The mechanical properties of these car-seat models are given in Figure 4. The dimensions and masses of the individual seat components are the same for all the car-seat models, and they are representative of the typical car-seats on the market [9].

Mechanical properties of WMS and RFWMS

WMS and RFWMS are whiplash-mitigating car-seat models as described previously. The stiffness and damping characteristics of the translational anti-whiplash device P, as shown in Figure 4(c), are the same for these two car-seat models; but the breakaway forces are 5 kN and 4.25 kN for WMS and

RFWMS respectively. For the rebound (forward) motion, P applies high damping (30 kNs/m) to limit forceful rebound of the seat-pan.

WMS and RFWMS have some differences regarding the stiffnesses of the rotational AWDs situated at the recliner, as shown in Figures 4(a) and 4(b). It can be seen that R^+ of RFWMS is softer than R of WMS. RFWMS performs better than WMS at all crash severities [4] since R^+ is used in conjunction with R* as indicated in Table 1.

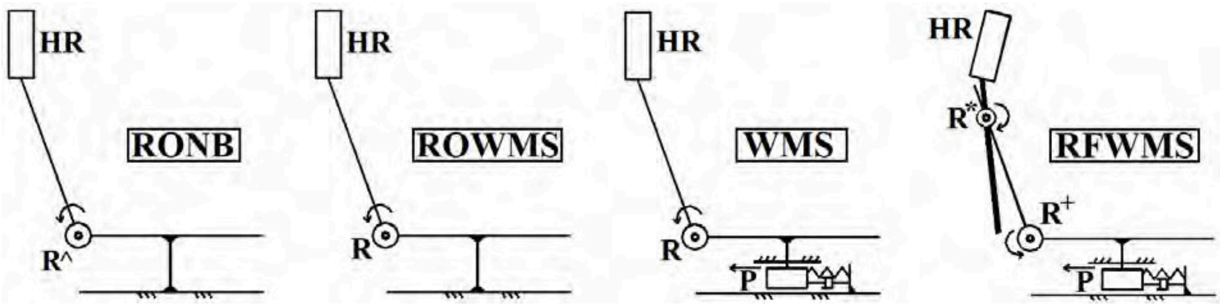


Figure 3. The car-seat models used in head-restraint evaluation

For rearward rotations at R and R^+, a constant damping coefficient of 1 Nms/deg is used. This is an estimation of the rotational damping coefficient for the deformation of the recliner-mechanism in typical car-seats [4]. R and R^+ apply high damping (15 Nms/deg) when the seatback (in WMS) and OF (in RFWMS) start rotating forward (rebound motion), hence limiting rebound.

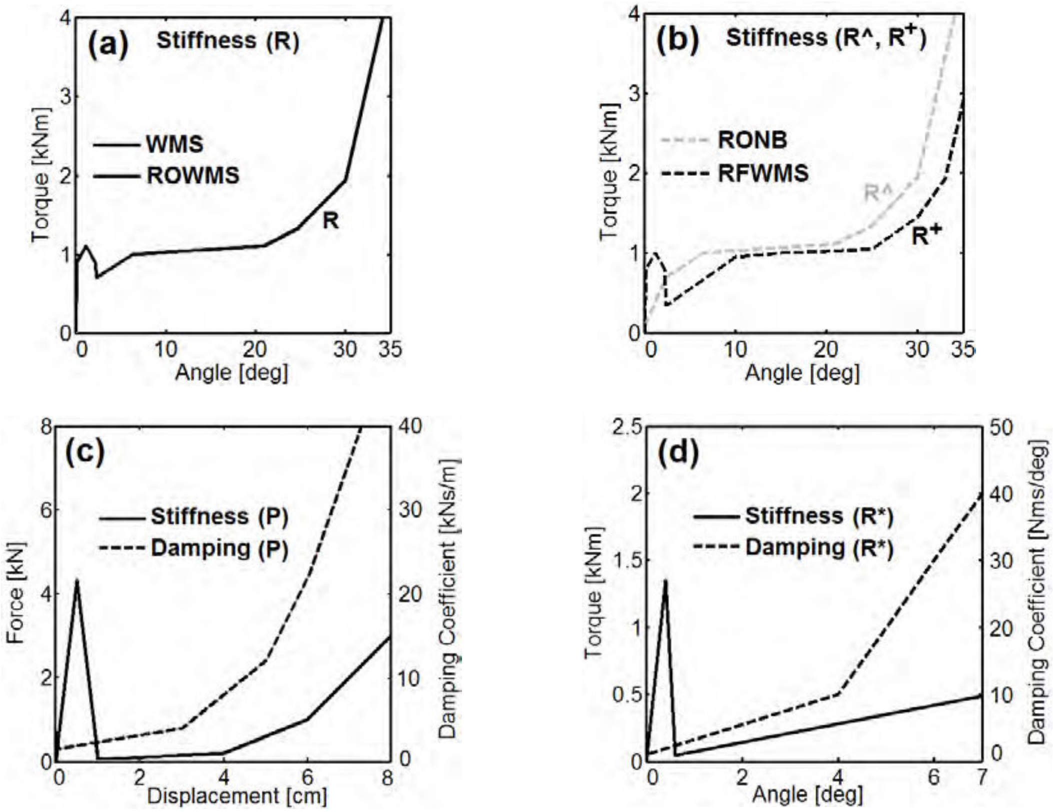


Figure 4. The mechanical properties of the car-seat models

Figure 4(d) shows the stiffness and damping characteristics of the rotational anti-whiplash device R* which has a breakaway torque of 1.35 kNm. A damping coefficient of 0.1 Nms/deg is applied by R* for the reverse (rebound) motion.

Mechanical properties of ROWMS and RONB

ROWMS is a modified version of WMS; they both have the same anti-whiplash device R, but in ROWMS the seat-pan is rigidly fixed to the floor (or sled - see Figure 1(b)). The car-seat model RONB is a modified version of ROWMS and it has got a recliner joint denoted by R^. As shown in Figures 4(a) and 4(b), the only difference between RONB and ROWMS is that in RONB, R^ does not incorporate any breakaway torque. The damping characteristics of R^ are the same as R and R^+.

In RONB, the stiffness characteristics of R^ are very similar to the deformation characteristics (i.e. static-torque versus seatback-rotation) of typical car-seat recliners as obtained in the quasistatic seat-tests conducted by Viano [6]. Therefore, RONB can be considered as a model of a typical car-seat without any particular whiplash-mitigating feature. In the quasistatic tests by Viano [6], the torque values increased up to 25-to-30 deg (on average) of seatback-rotation and for further rotational deformations, there were drops in torque, associated with the failure of the structure of the recliner mechanism (i.e. plastic deformation). On the other hand, in RONB and the other car-seat models, the torque values increase rapidly at around 25 deg as shown in Figures 4(a) and 4(b); this helps to limit ramping of the unbelted occupant in high severity rear impacts.

MECHANICAL PROPERTIES OF THE PASSIVE HEAD-RESTRAINTS

Five different passive head-restraints with varying stiffness and energy dissipation percentages are successively attached to each of the four different car-seat models described in the previous section. The mechanical properties of these passive head-restraints are given in Table 2 and, Figures 5 and 6. These mechanical properties are derived from the impact tests by Viano [6] in which the back cap of a Hybrid III dummy head was impacted vertically on different head restraints using a hydraulic material-testing machine, at an impact speed of 1.1 m/s. In these impact tests, the displacement of the dummy head and the normal force generated by the head restraints were recorded.

Table 2 classifies the selected passive head-restraints according to their stiffnesses and energy dissipation percentages. The stiffnesses of the passive head-restraints can be seen in Figures 5 and 6 which show the normal force generated by the head-restraint versus deformation (x) of the head-restraint. In Figures 5 and 6, the loading and unloading curves are drawn in black and grey colours, respectively. The energy dissipation percentage (EDP) is calculated using Equation [1] in which the energy absorbed, energy returned and energy dissipated by the head-restraint are denoted by E_a, E_r and E_d, respectively. In Equation [1], F_L and F_U represent the normal forces (generated by the head-restraint) along the loading and unloading curves, respectively.

$$E_a = \int F_L dx \quad , \quad E_r = \int F_U dx \quad , \quad E_d = E_a - E_r \quad , \quad EDP = \frac{E_d}{E_a} \cdot 100 \qquad [1]$$

Table 2. Stiffnesses and energy dissipation percentages (EDP) of the head-restraints

Head-restraint	Stiffness	EDP
HRB	medium	high (58%)
HR1	high	high (51%)
HR2	high	low (32%)
HR3	low	high (54%)
HR4	low	low (35%)

The loading curves of HR1 and HR2 are identical. Similarly, the loading curves of HR3 and HR4 are identical. In all of the passive head-restraint models, a hysteresis model, as shown in Figure 5, is applied. In this model, when the deformation rate changes sign, the human head loads and unloads the head-restraint along the hysteresis slope until the corresponding loading and unloading curves are reached.

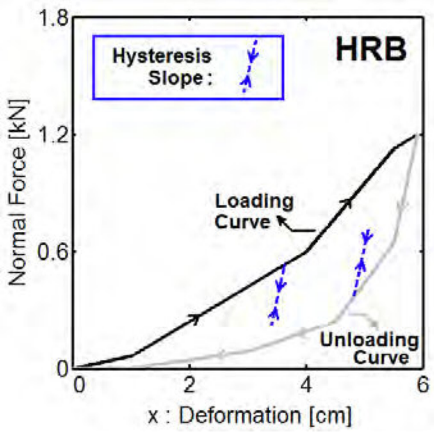


Figure 5. The mechanical properties of the baseline head-restraint (HRB)

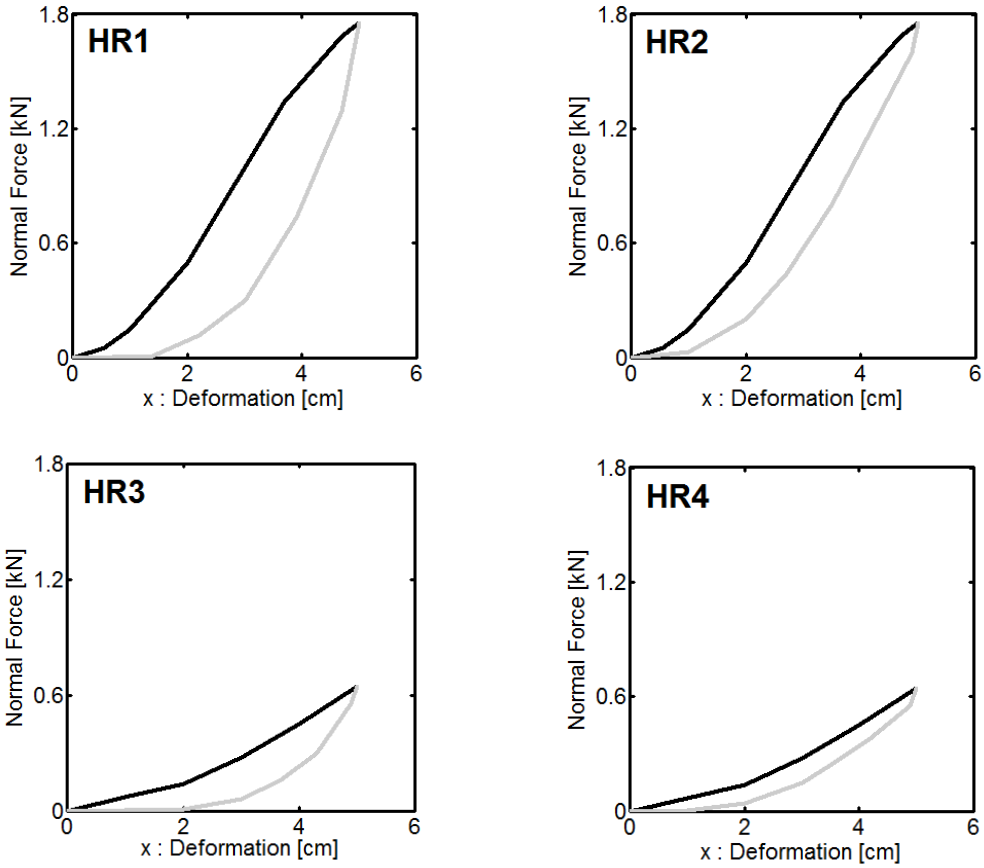


Figure 6. The mechanical properties of the head-restraints HR1, HR2, HR3, HR4

TEST PROCEDURE

The five passive head-restraints (HRB, HR1, HR2, HR3, HR4) are successively attached to the four car-seat models (RONB, ROWMS, WMS, RFWMS). Prior to rear impact, the human model is positioned as shown in Figure 1(b) to adopt a posture similar to the one practiced in dynamic whiplash sled-tests [10]. The initial seatback angle is set to 20 deg from the vertical and no seatbelt is used. For all head-restraints, the height and backset distances before the impact are the same. The top of the head-restraints is level with the top of the head and the backset is set to 60 mm; this pre-impact geometrical setting of the head-restraints is within the range of a good head-restraint geometry as specified by IIWPG [11]. As performed in the EuroNCAP whiplash test, the stationary seat-occupant models are accelerated in the +x direction of the inertial coordinate system G by subjecting the sled (see Figure 1(b)) to the EuroNCAP medium severity crash pulse (EMP) which has a ΔV of 16 km/h, peak acceleration of 5 g and mean acceleration of 4.5 g.

In order to evaluate the dynamic performance of the seats and head-restraints, some of the assessment criteria of the EuroNCAP whiplash test [8] are selected which are the upper-neck rearward shear force ($Fsh^{(-)}$), upper-neck tension force (Ftn), head rebound velocity (v_r), N_{km} , and neck injury criterion (NIC). NIC is associated with the formation of S-shape-like deformation in the neck and is based on the relative acceleration and velocity between the OC and the first thoracic vertebra T1 (see Figure 1(a)). OC is the occipital condyles which can be called as the junction between the head and the upper neck. The proposed injury threshold value for *NIC* is 15 m^2/s^2 [12]. N_{km} is an injury criterion which uses a combination of the shear force and moment acting at the OC. The proposed injury threshold value for N_{km} is 1 [13]. v_r is the maximum resultant head velocity with respect to the sled 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 (see Figure 1(b)).

In rating the forces at the upper-neck (i.e. at the OC), the IIWPG neck force classification [11], as shown in Figure 7, is used. The head coordinate system is located at the head centre of gravity as shown in Figure 1(a). In the human model, the positive shear and the positive normal forces acting on the head at the OC (i.e. upper neck) are defined in the directions of +x and +z axes of the head coordinate system respectively. Hence, the upper-neck tension force acting on the head (Ftn) is negative by definition, and the upper-neck rearward shear force (defined by the IIWPG force classification) is taken as the negative shear force acting on the head at the OC. Thus, the positive shear force acting on the head at the OC is in the +x direction of the head coordinate system and it is denoted by $Fsh^{(+)}$.

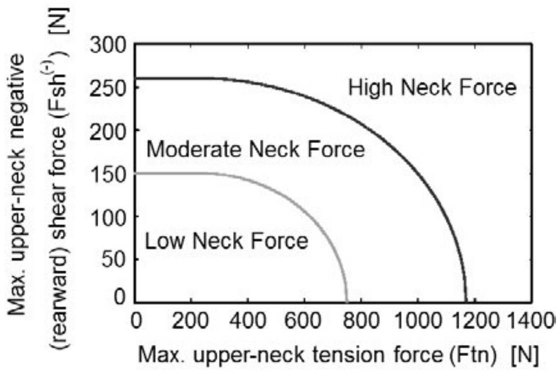


Figure 7. IIWPG neck force classification (adapted from [11])

Additionally, neck intervertebral rotations are monitored to check the neck internal motion of the human model. Based on the changes in the upper and lower-neck intervertebral rotations, an injury measure called the Neck Distortion Index (NDI) is proposed as shown in Equation [2]

$$NDI = -\theta_{OC/C1} + \theta_{C7/T1} \quad [2]$$

where $\theta_{OC/C1}$ is the intervertebral rotation between OC and C1; $\theta_{C7/T1}$ is the intervertebral rotation between C7 and T1. C1 and C7 represent the first and seventh cervical vertebrae, respectively. $\theta_{OC/C1}$ and $\theta_{C7/T1}$ can be considered to represent the state (i.e. either flexion (-) or extension (+)) of the upper-half and the lower-half of the neck, respectively. NDI quantifies the amount of retraction and protraction type deformations in the neck in a typical interaction of the head with the head restraint. NDI indicates a positive value during a typical S-shape-like deformation in which the head retracts with respect to T1, thus there is flexion in the upper neck and extension in the lower neck as shown in Figure 1(a). Negative values of NDI correspond to protraction type deformation of the neck.

Figure 8 shows the variation of intervertebral rotations and NDI when the seat model WMS with the head restraint HRB is subjected to the EuroNCAP medium severity crash pulse (EMP). It can be seen that the neck is almost completely in flexion throughout its motion. At around 80 ms, the most prominent retraction type deformation takes place; at this instant the neck is completely in flexion but the flexion in the upper half of the neck is more than that of the lower half hence NDI attains the maximum value. At 300 ms, NDI attains the minimum value since there is the most prominent protraction type deformation; at this instant the flexion in the lower half of the neck is more than the flexion in the upper half of the neck.

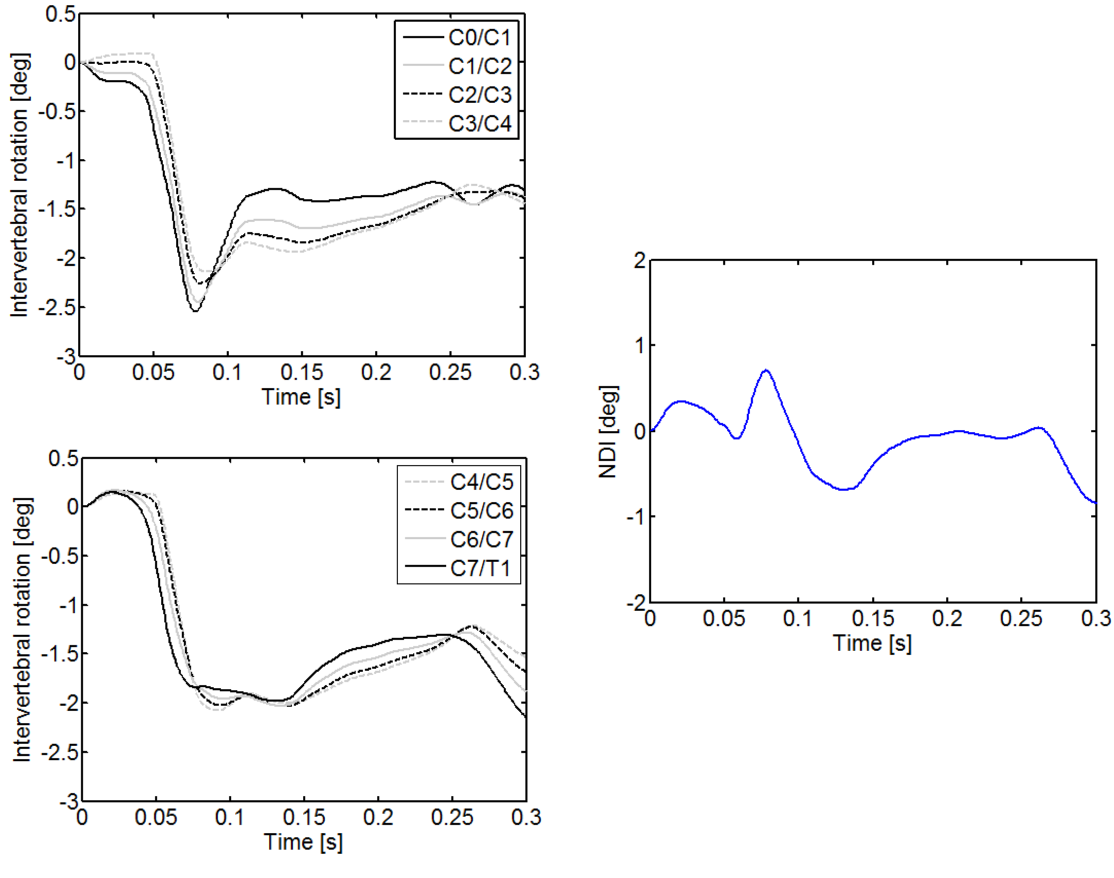


Figure 8. Intervertebral rotations and NDI (seat: WMS, head-restraint: HRB, crash pulse: EMP)

RESULTS

The responses of the seats (with the aforementioned head-restraints) and the human model to the crash pulse EMP are given in Tables 3, 4, 5 and 6. In these tables, the minimum (-) and the maximum (+) values of NDI are presented which correspond to the most prominent protraction and retraction type deformations in the neck. These tables also present the values of $\Delta\theta_{IV-UH}$ and $\Delta\theta_{IV-LH}$ which involve the maximum (i.e. largest (+)) and minimum (i.e. largest (-)) values of the intervertebral rotations in the upper half and lower half of the neck, respectively. In order to see the effects of head-restraint contact on neck internal motion, the maximum and minimum values of NDI, $\Delta\theta_{IV-UH}$ and $\Delta\theta_{IV-LH}$ are recorded before the pelvis contacts the seat-pan in the rebound phase.

The injury criteria $Fsh^{(-)}$, N_{km} , NIC, NDI and v_r in Tables 3-6 are especially chosen since these are considered to be sufficient in differentiating between the dynamic performance of the seats and head restraints. Schmitt and Muser [14] made a sensitivity analysis of the criteria in the EuroNCAP dynamic whiplash test and they demonstrated that N_{km}, NIC and v_r formed a sufficient set of criteria that was able to rate the rear-impact performance of seats accurately.

Table 3. Response of the seat-occupant system with different head-restraints (seat: WMS)

HR	$Fsh^{(-)}$ [N]	$Fsh^{(+)}$ [N]	Ftn [N]	N_{km}	NDI [deg]	$\Delta\theta_{IV-UH}$ [deg]	$\Delta\theta_{IV-LH}$ [deg]	NIC [m^2/s^2]	v_r [m/s]
HRB	-166	21.8	-147	0.40	0.71 -0.69	0.09 -2.55	0.17 -2.15	9.90	1.29
HR1	-205	25.2	-81.3	0.47	0.44 -2.79	0.09 -2.32	0.17 -2.87	9.90	1.1
HR2	-205	17.3	-81.3	0.47	0.44 -2.8	0.09 -2.32	0.17 -2.89	9.90	1.2
HR3	-142	17.3	-223	0.33	0.87 -0.09	0.09 -2.65	0.17 -2.19	9.90	1.27
HR4	-142	17.3	-223	0.325	0.87 -0.41	0.09 -2.65	0.17 -2.19	9.90	1.39

Table 4. Response of the seat-occupant system with different head-restraints (seat: RFWMS)

HR	$Fsh^{(-)}$ [N]	$Fsh^{(+)}$ [N]	Ftn [N]	N_{km}	NDI [deg]	$\Delta\theta_{IV-UH}$ [deg]	$\Delta\theta_{IV-LH}$ [deg]	NIC [m^2/s^2]	v_r [m/s]
HRB	-136	17.1	0	0.43	0.51 -2.1	0.39 -2.02	0.17 -1.72	11.1	0.99
HR1	-145	20.6	0	0.36	0.35 -3.21	0.76 -1.63	0.17 -2.47	9.76	0.90
HR2	-145	14.6	0	0.36	0.35 -3.21	0.76 -1.64	0.17 -2.47	9.76	0.94
HR3	-130	14.6	0	0.44	1.03 -1.12	0.12 -2.26	0.17 -1.60	10.9	1.01
HR4	-130	14.6	0	0.44	1.03 -1.64	0.27 -2.26	0.17 -1.67	10.9	1.08

Table 5. Response of the seat-occupant system with different head-restraints (seat: ROWMS)

HR	$Fsh^{(-)}$ [N]	$Fsh^{(+)}$ [N]	Ftn [N]	N_{km}	NDI [deg]	$\Delta\theta_{IV-UH}$ [deg]	$\Delta\theta_{IV-LH}$ [deg]	NIC [m^2/s^2]	v_r [m/s]
HRB	-232	8.3	-207	0.61	0.28 -1.73	0.08 -3.18	0.13 -3.31	8.88	1.52
HR1	-273	24.5	-124	0.65	0.28 -3.67	0.08 -2.90	0.13 -3.74	8.88	1.24
HR2	-273	8.3	-124	0.65	0.28 -3.68	0.08 -2.90	0.13 -3.75	8.88	1.42
HR3	-247	12.1	-287	0.68	0.28 -1.62	0.08 -3.37	0.13 -3.39	8.88	1.44
HR4	-246	8.3	-287	0.68	0.28 -1.95	0.08 -3.37	0.13 -3.39	8.88	1.55

Table 6. Response of the seat-occupant system with different head-restraints (seat: RONB)

HR	***Fsh***$^{(-)}$ [N]	***Fsh***$^{(+)}$ [N]	***Ftn*** [N]	N_{km}	**NDI** [deg]	$\Delta\theta_{IV-UH}$ [deg]	$\Delta\theta_{IV-LH}$ [deg]	**NIC** [m^2/s^2]	v_r [m/s]
HRB	-244	29.4	-412.7	0.75	0.28 -3.11	0.07 -3.85	0.14 -4.23	15.8	1.51
HR1	-333	28.4	-185	0.89	0.28 -3.16	0.07 -3.67	0.14 -4.23	15.8	1.27
HR2	-333	28.4	-186	0.89	0.28 -3.58	0.07 -3.67	0.14 -4.23	15.8	1.31
HR3	-347	40.6	-478	0.75	0.28 -3.11	0.07 -3.84	0.14 -4.23	15.8	1.40
HR4	-347	40.6	-478	0.77	0.28 -3.11	0.07 -3.84	0.14 -4.23	15.8	1.54

DISCUSSION

Whiplash injury mechanisms are not completely understood and the injury criteria used in the EuroNCAP whiplash test are not completely proven by biomechanical research [2,8]. Hence, EuroNCAP takes into consideration every plausible injury-mechanism and criterion (or measure) that have been suggested [2,8]. Considering these facts, minimising neck internal motion by monitoring the values of NDI should be considered as a reasonable and supplementary approach. It should be noted that NDI can be an indication of relative injury-risk, but not absolute injury-risk therefore NDI should be used to assess the relative performance of car seats and head restraints in rear impacts.

Performance of different passive-head-restraints (HRs) for seat WMS

HR1 and HR2 are stiffer HRs. HR1 and HR3 have higher EDP. In comparison to the baseline head-restraint HRB, the following outcomes are obtained: *Fsh*$^{(-)}$ is 40 N higher for stiffer HRs whereas *Fsh*$^{(-)}$ is 25 N lower for softer HRs. Stiffer HRs produce 0.07 more N_{km} whereas softer HRs results in 0.07 less N_{km}. *Ftn* is 65 N lower for stiffer HRs whereas it is 75 N higher for softer HRs. *Ftn* values are all in the low neck-force region for all HRs. Softer HRs reduce the protraction type deformation (as indicated by the negative NDI value) by allowing some additional but much smaller amounts of retraction type deformation as indicated by the positive NDI value.

For HRs with the same stiffness, the differences in EDP do not affect *Fsh*$^{(-)}$, *Ftn* and N_{km}. Maximum NIC values are the same for all HRs and they occur before head-restraint contact for all HRs. The neck is predominantly in flexion (i.e. intervertebral rotations are negative) for all HRs. Positive intervertebral rotations (i.e. extension of the cervical vertebrae) are highly insignificant and they occur in the lower half of the neck before head-restraint contact in the first 40 ms of the impact; this extension of the vertebrae and the resulting retraction type deformation is indistinct. As expected, v_r values are lower for HRs with higher EDP. Softer HRs have higher v_r in comparison to stiffer HRs but the differences in v_r values are insignificant.

Performance of different passive-head-restraints (HRs) for seat RFWMS

In comparison to the baseline head-restraint HRB, the following outcomes are obtained: *Fsh*$^{(-)}$ is 9 N higher for stiffer HRs whereas *Fsh*$^{(-)}$ is 6 N lower for softer HRs. Stiffer HRs produce 0.07 less N_{km} whereas softer HRs results in 0.01 more N_{km}. Softer HRs reduce the protraction type deformation by allowing some additional but smaller amounts of retraction type deformation. The maximum NIC values occur at initial head to head-restraint contact. The insignificant differences in maximum NIC values are due to the initial stiffnesses of the HRs.

Ftn is zero for all HRs. For HRs with the same stiffness, the differences in EDP do not affect $Fsh^{(-)}$, *Ftn*, N_{km} and NIC. The neck is predominantly in flexion for all HRs. Maximum positive intervertebral rotation occurs at the OC/C1 joint at around maximum HR deformation during the rebound of the head from the HR for all HRs. v_r values are lower for HRs with higher EDP and softer HRs have higher v_r in comparison to stiffer HRs. The differences in $Fsh^{(-)}$, N_{km} , NIC and v_r are quite insignificant.

Performance of different passive-head-restraints (HRs) for seat ROWMS

HR3 and HR4 bottom-out and the head loads the HR structure directly as a result of this. Consequently, the following outcomes are obtained in comparison to the baseline head-restraint HRB: $Fsh^{(-)}$ is 40 N higher for stiffer HRs whereas $Fsh^{(-)}$ is 15 N higher for softer HRs. Stiffer HRs produce 0.04 more N_{km} whereas softer HRs results in 0.07 more N_{km}. *Ftn* is 83 N lower for stiffer HRs whereas it is 80 N higher for softer HRs. *Ftn* values are all in the low neck-force region for all HRs. Softer HRs reduce the protraction type deformation while the insignificant amount of retraction type of deformation is the same for all HRs.

For HRs with the same stiffness, the differences in EDP do not affect $Fsh^{(-)}$, *Ftn*, N_{km} and NIC. Maximum NIC values are the same for all HRs and they occur before head-restraint contact for all HRs. The neck is predominantly in flexion for all HRs. Extension of the cervical vertebrae are highly insignificant and they occur in the lower half of the neck before head-restraint contact in the first 40 ms of the impact; this extension of the vertebrae and the resulting retraction type deformation is indistinct. v_r values are lower for HRs with higher EDP and softer HRs have higher v_r in comparison to stiffer HRs but these differences are insignificant.

Performance of different passive-head-restraints (HRs) for seat RONB

HR3 and HR4 bottom-out. Therefore in comparison to the baseline head-restraint HRB, the following outcomes are obtained: $Fsh^{(-)}$ is 90 N higher for stiffer HRs whereas $Fsh^{(-)}$ is 100 N higher for softer HRs. Stiffer HRs produce 0.14 more N_{km} whereas softer HRs have almost the same N_{km} as HRB. *Ftn* is 230 N lower for stiffer HRs whereas it is 65 N higher for softer HRs. Softer HRs reduce slightly the protraction type deformation while the insignificant amount of retraction type of deformation is the same for all HRs.

For HRs with the same stiffness, the differences in EDP do not affect $Fsh^{(-)}$, *Ftn*, N_{km} and NIC. Maximum NIC values are the same for all HRs and they occur before head-restraint contact for all HRs. The neck is predominantly in flexion for all HRs. Similar to seats ROWMS and WMS, Extension of the cervical vertebrae are highly insignificant and indistinct. v_r values are lower for HRs with higher EDP and softer HRs have higher v_r in comparison to stiffer HRs but these differences are insignificant.

Comparison of the performances of seats WMS, RFWMS, ROWMS and RONB

RONB produces the highest risk of whiplash since it results in the largest neck internal motion, and the largest OC forces and moments. The poor performance of RONB stems from the fact that the seatback of RONB begins to rotate early and rapidly after the onset of the impact, leading to poor support of the head and torso throughout the impact. This excessive rotation of the seatback during the first 90 ms causes the head to flex significantly relative to the upper torso; thus head restraint contact time is extended excessively. Consequently, the head interacts with the head restraint severely. RONB does not have any particular whiplash-mitigating feature. The recliner-joint R^ is only involved in energy absorption and since R^ is not strong enough by itself, the seatback yields quite easily and ineffectively. Another shortcoming of RONB is the lack of breakaway torque in the mechanical properties of R^. A relatively small breakaway torque at the recliner can enable the torso to sink into the seatback structure without excessive rotation of the seatback at the start of the impact. RONB also shows the highest sensitivity to differences in the stiffness of HRs regarding $Fsh^{(-)}$, N_{km} and *Ftn* values. On the other hand, RONB shows the least sensitivity to differences in the stiffness and energy absorption capacity of HRs regarding NDI values and the intervertebral rotations; thus neck internal motion cannot be reduced by RONB no matter which HR is used.

The only difference between RONB and ROWMS is the breakaway torque that ROWMS has for the anti-whiplash device (R) at the recliner (see Figures 3 and 4). This relatively small breakaway torque improves seat performance appreciably (in comparison to RONB). For ROWMS, $Fsh^{(-)}$ values are in the high or moderate-force region for all HRs and this indicates a relatively higher risk of whiplash. Compared to WMS and RFWMS, ROWMS also produces larger *Ftn*, N_{km} values and larger intervertebral rotations. The reason is that the head and the torso are not supported effectively enough by ROWMS. On the other hand, WMS and RFWMS control the rotation of the seatback more effectively and provide earlier head-restraint contact.

RFWMS has three different anti-whiplash devices that control the motion of the seat components and it is the best performing car-seat model on the whole. RFWMS achieves this performance by utilising an inner-frame which controls the rotation of the seatback more effectively and provides relatively earlier head-restraint contact. In RFWMS, the seat-pan motion (at P) and the inner-frame rotation (at R*) prevent excessive rotation of the seatback and at the same time, provide early and more effective head-support. More information on WMS and RFWMS can be found in reference [4].

For all seats, the maximum NIC values are not affected by the mechanical properties of HRs since this maximum value typically occurs before or at initial head to head restraint contact. For all seats, $Fsh^{(+)}$ values are very low but the occurrence of $Fsh^{(+)}$ is insignificant and not easy to interpret. For all seats, v_r values are low [15] but in comparison to WMS and RFWMS, ROWMS and RONB produce larger v_r since head interacts with the head restraint severely due to ineffective support of the seatback. RFWMS produces the lowest v_r values. Due to the larger deformations of softer HRs and the shape of the force versus deformation graphs of HRs, v_r values for softer HRs are slightly higher. For all seats and HRs, S-shape-like deformation (i.e. retraction type deformation) is not significant as observed visually in the simulations and as indicated by the amount of positive NDI values. For all seats (except RONB), stiffer HRs induce notable protraction type deformation (as indicated by the negative NDI values) which is still not pronounced as observed visually in the simulations. Except RFWMS, *Ftn* is higher for softer HRs since softer HRs produce lower normal forces which in turn lead to lower friction forces opposing the upward motion of the head along the head-restraint. A clear correlation between N_{km} and HR stiffness is not found but the relative percent change in N_{km} (with respect to the baseline HR) is below 18 % for all seats.

The relationship between neck forces/moments and NDI is worth investigating. If RONB (with HR2) is compared to WMS (with HR1), it can be seen that the seat-HR combination with larger negative NDI has larger neck forces/moments. If ROWMS (with HR3) is compared to RFWMS (with HR2), it can be seen that the seat-HR combination with smaller NDI has much larger neck forces/moments. If RFWMS (with HR1) is compared to WMS (with HR1), it can be seen that the seat-HR combination with larger NDI has smaller neck forces/moments. Hence, one should use NDI as a complementary injury measure together with injury measures involving neck forces/moments.

WMS (with HR3) and RFWMS (with HR3) are the two best seat-and-HR combinations as they provide lower neck forces/moments, and lower neck internal motion. However, RFWMS should be considered as the best performing seat since it shows the least sensitivity to differences in the stiffness and energy dissipation capacity of HRs. WMS and RFWMS perform better when they are used with softer HRs but the performance of these seats in high severity impacts should be tested to see whether the softer HRs bottom-out or not.

CONCLUSIONS

In this study, five different passive-head-restraints (HRs) with varying stiffness and energy dissipation percentages (i.e. capacities) are attached to four different car-seat models. The seat-occupant models are subjected to the EuroNCAP medium severity crash pulse. Among the car-seat models, there are two whiplash mitigating car-seats named WMS and RFWMS which utilise a crash-energy distribution technique. The results indicate that the protection offered by HRs is strongly dependent on seat design. It is shown that the stiffness of the HR has much more influence on whiplash-risk in comparison to its energy dissipation percentage (EDP). The influence of energy dissipation percentage of the HRs on neck protection is minimal. Softer HRs provide better neck protection than stiffer HRs unless they bottom-out. Hence, well-designed seats perform much better when softer HRs are used. An injury measure called Neck Distortion Index (NDI) is proposed which quantifies the amount of retraction and protraction type deformations in the neck. NDI should be used as a complementary injury measure in addition to the injury criteria (or measures) in the literature. It is shown that the seat-HR combinations which allow some small amounts of retraction, reduce $Fsh^{(-)}$ values unless HR bottoms-out. In general, softer HRs cause more flexion in the upper half of the neck but less flexion in the lower half of the neck. On the whole, stiffer HRs cause less flexion in the upper half of the neck but more flexion in the upper half of the neck. Poorly performing seats (ROWMS and RONB) cause much larger flexion of the cervical vertebrae. RFWMS which is one of the whiplash mitigating car-seats, shows a robust performance since it shows the least sensitivity to differences in the stiffness and energy dissipation capability of HRs. Hence, the results of this study can help to select or design an optimum passive head-restraint for whiplash mitigation.

REFERENCES

1 V Eis, P Fay, and R Sferco, 'A detailed analysis of the characteristics of European rear impacts', Proc of 19th ESV Conf, Washington DC, USA, National Highway Traffic Safety Administration, 2005, paper 05-0385-O.

2 M Avery, E Giblen, A M Weekes, and D S Zuby, 'Developments in dynamic whiplash assessment procedures', Int Conf on Neck Injuries in Road Traffic and Prevention Strategies, Munich, Germany, TÜV SÜD Akademie GmbH, 2007.

3 M Edwards, S Smith, D S Zuby, and A K Lund, 'Improved seat and head restraint evaluations', Proc of 19th ESV Conf, Washington DC, USA, National Highway Traffic Safety Administration, 2005, paper 05-0374-O.

4 S Himmetoglu, M Acar, K Bouazza-Marouf, and A J Taylor, 'Car-seat design to improve rear-impact protection', Proc of IMechE Part D: Journal of Automobile Engineering, 2011, Vol.225, 441-459.

5 L Jakobsson, H Norin, C Jernström, S E Svensson, P Johnsen, I Isaksson-Hellman, and M Y Svensson, 'Analysis of different head and neck responses in rear-end car collisions using a new humanlike mathematical model', Proc of the Int IRCOBI Conf, Lyon, France, International Research Council on Biomechanics of Injury, 1994.

6 D C Viano, Role of the seat in rear crash safety, Society of Automotive Engineers, Warrendale, PA, USA, 2002.

7 S Himmetoglu, M Acar, K Bouazza-Marouf, and A J Taylor, 'A multi-body human model for rear-impact simulation', Proc of IMechE Part D: Journal of Automobile Engineering, 2009, Vol.223, 623-638.

8 M van Ratingen, J Ellway, M Avery, P Gloyns, V Sandner, and T Versmissen, 'The EuroNCAP whiplash test', Proc of the 21st ESV Conf, Stuttgart, Germany, National Highway Traffic Safety Administration, 2009, paper 09-0231.

9 M M Verver, Numerical tools for comfort analyses of automotive seating, PhD Thesis, Eindhoven University of Technology, Eindhoven, The Netherlands, 2004.

10 The dynamic assessment of car seats for neck injury protection testing protocol, EuroNCAP, 2014.

11 RCAR-IIWPG seat/head restraint evaluation protocol, International Insurance Whiplash Prevention Group (IIWPG), 2008.

12 O Boström, M Y Svensson, B Aldman, H A Hansson, Y Håland, P Lövsund, T Seeman, A Suneson, A Säljö, and T Örtengren, 'A new neck injury criterion candidate-based on injury findings in the cervical spinal ganglia after experimental neck extension trauma', Proc of the Int IRCOBI Conf, Dublin, Ireland, IRCOBI, 1996.

13 K-U Schmitt, M H Muser, and P Niederer, 'A new neck injury criterion candidate for rear-end collisions taking into account shear forces and bending moments', Proc of 17th ESV Conf, Amsterdam, The Netherlands, National Highway Traffic Safety Administration, 2001, paper 124.

14 K-U Schmitt and M Muser, ‘Evaluating recent seat models in rear-end impacts according to currently discussed consumer test proposals’, Proc of 21st ESV Conf, Stuttgart, Germany, National Highway Traffic Safety Administration, 2009, paper 09-0116.

15 M Krafft, A Kullgren, and C Tingvall, ‘Assessment of whiplash protection in rear impacts - crash tests and real-life crashes’, Swedish National Road Administration, Stockholm, Sweden, 2004.