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Experimental analysis of whiplash injury with hybrid III 50 percentile test dummy

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Abstract. In this study, the effects of sitting position of the driver on the whiplash neck injury have been analyzed experimentally by using hybrid III series 50 percentile male crash test dummy. A testing platform consisting of vehicle ground, driver foot rest, driver seat and a 3-point seatbelt has been prepared. This testing platform and the instrumented crash test dummy are prepared for tests according to the Euro NCAP whiplash testing protocol. The prepared test set-up has been exposed to 3 different acceleration-time loading curves defined in the Euro NCAP whiplash testing protocol by performing sled tests. 9 different sled tests have been performed with the combinations of 3 different seating positions of the crash test dummy and 3 different acceleration-time loading curves. The sensor data obtained from the crash test dummy and high-speed videos taken are analyzed according to the injury assessments criteria defined in the Euro NCAP whiplash testing protocol and the criticality of the whiplash injury is defined. It is seen that the backset distance of the driver head with the headrest and the height difference of the top of the head of the driver with the headrest have a great importance on whiplash injuries.

Keywords: whiplash; neck soft tissue injury; crash test dummy; rear crash; sled tests

1. Introduction

Neck injury in vehicle collisions, often referred to as "whiplash injury", is one of the most common traffic related safety problems, resulting in serious implications for the society (Yoganandan and Pintar 2000). Although these injuries are typically considered minor, their high incidence rate and often long-term consequences lead to significant costs. Many accident studies and claims statistics coming from the insurance industry (Ono and Kanno 1993, Wismans and Huijskens 1994, Aspen Insurance UK 2004) clearly indicate that low severity rear crash may lead to injuries causing long-term disablement and discomfort. The medical and economical costs of such injuries are very high.

Although the whiplash was firstly defined in 1928 by Crowe as neck injury caused by

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acceleration forces, the precise definition of whiplash injury still remains controversial (Burton 2004, Crowe 1928, Evans 1992, Spitzer *et al.* 1995). A widely accepted definition that is formulated by the Quebec Task Force (QTF), a task force sponsored by the Société de l'assurance automobile du Québec, the public auto insurer in Quebec, Canada, in 1995 based on an extensive literature review is stated below (Spitzer *et al.* 1995):

"Whiplash is an acceleration-deceleration mechanism of energy transfer to the neck. It may result from rear end or other motor vehicle collisions, but can also occur during diving or other mishaps. The impact may result in bony or soft tissue injuries, which may lead to a variety of clinical manifestations which is Whiplash-Associated Disorders (WADs)".

As seen from this general definition, WADs may result from rear end or other motor vehicle collisions, or during diving or other mishaps, however, the whiplash injuries very predominantly occur in the rear end crashes of the vehicles (Horst 2002). In addition, crash analyses performed on whiplash studies reveal that these injuries usually occur at the velocity differences of 10 to 20 km/h. So, it can be understood that majority of whiplash injuries occur at low speed and low acceleration rear end crashes. In this study, whiplash-associated disorders resulting from low speed rear end crashes of the vehicles will be considered.

1.1 Phases of whiplash Injury

If the biological system deforms beyond a tolerable limit which results in damage to anatomical structures and/or alteration in normal function, physical injury will take place during the rear end collision (Wismans *et al.* 2000). The mechanism involved is called "injury mechanism". In the rear end collisions, the head and neck are exposed to the inertia and contact forces, which may load or deform the tissues in the neck beyond tolerable limits, resulting in injury.

During a rear end automobile collision, the occupant body goes through an extremely rapid and intense acceleration and deceleration. In fact, a whiplash injury during the rear end collision occurs in less than 500 milliseconds. This duration can be divided into four phases in which different forces acting on the body that contributes to the overall injury. In order to explain these phases clearly, some critical snapshots from the high-speed videos of whiplash tests performed during the study is presented in Fig. 1 and the phases are described as follows:

1.1.1 Phase 1 (retraction phase)

The snapshots shown as Instance 1 and Instance 2 in Fig. 1 are the starting and ending instances of retraction phase respectively. The vehicle is first pushed or accelerated forward and is essentially pushed out from under the occupant as occupant's back forces into the seat. The upper torso is pushed forward by the seat back while the occupant's head remains nearly stationary. As a result, an abnormal S-curve develops in the occupant cervical spine while the upper cervical spine gets into flexion and lower cervical spine gets into extension as occupant's seat back rebounds forward adding to the forward acceleration of the torso. This phase ends when the maximum relative translation of the head and torso is reached as shown in Instance 2 of Fig. 1.

1.1.2 Phase 2 (extension phase)

The snapshots shown as Instance 2 and Instance 3 in Fig. 1 are the starting and ending instances of extension phase respectively. This phase starts after the head reaches the maximum translation with respect to the torso and then head rotates rearwards. During this phase, occupant's head moves backward into extension, creating a powerful shearing force in the neck. This shearing, combined with the compression of the spine in the neck may cause substantial injury. As a result of this rotation some extensive orientations between the upper and lower motion segments of the spine occur. This phase ends when the head touches to the head restraint.

1.1.3 Phase 3 (rebound phase)

The snapshots shown as Instance 3 and Instance 4 in Fig. 1 are the starting and ending instances of rebound phase respectively. This is probably the most damaging phase of the whiplash phenomenon. This phase starts after the head touches the head restraint and then the head bounds to the front. This bounce from the head restraint may cause the maximum head translational acceleration occurring through all phases. This phase ends when the torso of the dummy is stopped by the seat belt.

1.1.4 Phase 4 (protraction phase)

The snapshots shown as Instance 4 and Instance 5 in Fig. 1 are the starting and ending instances of protraction phase respectively. The protraction phase occurs when differential motion between the head and torso are reversed. In this fourth phase, occupant's torso is stopped by the seat belt and the head is free to move forward without any restraint. This results in a violent forward-bending motion of the neck, straining the muscles and ligaments, tearing fibers in the spinal discs, and forcing vertebrae out of their normal position. Occupant’s spinal cord and nerve roots get stretched and irritated, and the brain can strike the inside of the skull. When head reaches the maximum translational distance with respect to torso, the phase ends.

Several previous studies have been conducted about whiplash related subjects. Some of these studies have been concentrated mainly on the biomechanical part of it such as finding new whiplash injury criteria, creating a new cervical spine model for whiplash and so on. However, there are also other studies concentrated more on the mechanical part of whiplash like a new seat design against whiplash, finding the effects of whiplash on different crash test dummy types and so on.

In the study of Davidsson *et al.* (2001), a comparison between BioRID P3 and Hybrid III performance in rear impacts is presented. The BioRID P3 was compared with human volunteer test data in a rigid and a standard seat without head restraints. The dummy kinematics performance, pressure distribution between subject and seatback, neck loads and accelerations were compared with those of ten human volunteers and a Hybrid III. The BioRID P3 provided repeatable test results and its response was very similar to that of the average volunteer in rear impacts at velocity difference of 9 km/h.

Linder *et al.* (2002) evaluated the BioRID P3 and the Hybrid III in pendulum impacts to the back with respect to the human subject test data. This study evaluates both BioRID P3 dummy for rear impacts and the Hybrid III dummy by means of a recently available set of human subject data [12]. The BioRID P3 and the Hybrid III were evaluated by means of pendulum impacts to the back and compared with the data from previously run cadaver tests. Seated dummies were struck with a pendulum with a mass of 23 kg and an impact velocity of 4.6 m/s at the level of the 6^{th} thoracic vertebra. The results showed that peak values and temporal responses of the BioRID P3 was closer to that of the corridor of the cadavers than the Hybrid III in terms of horizontal, vertical, and angular displacement of the head and of the head relative to first vertebra of thoracic spine (T1).

Philippens *et al.* (2002) compared the biofidelity of BioRID II and RID 2 crash test dummies in low speed rear end impacts with respect to each other also compared both of them with respect to Hybrid III dummy.

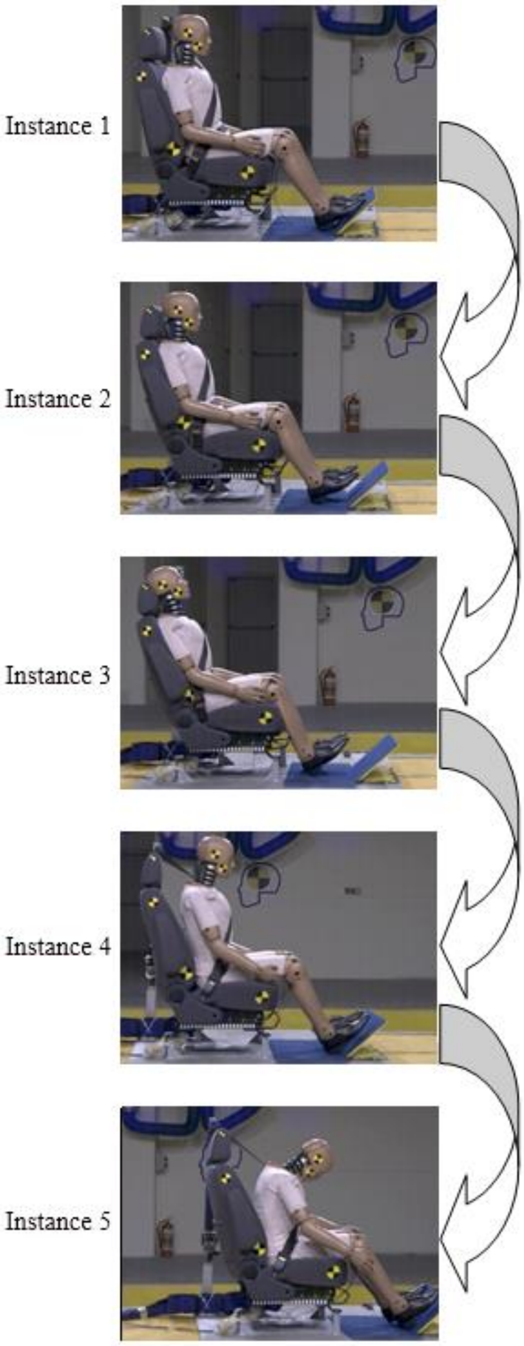

Fig. 1 Phases of whiplash injury

Viano and Davidsson (2002) have proposed a new whiplash injury criterion by evaluating neck displacements of 10 volunteers, BioRID P3 and Hybrid III from sled tests at 8.6 km/h with a standard seat and 9.3 km/h with a rigid seat in their study [14]. They have used the film analysis method to determine the rotation, and x and z displacements of the occipital condyles (OC), the base of the skull, with respect to first thoracic vertebrae (T1). For the volunteers, average and standard deviations were determined and cross-plotted as OC rotation versus x-displacement, and z-displacement versus x-displacement of OC-T1. These responses have provided corridors for the natural range of neck motion in rear impacts. For these parameters, BioRID P3 and Hybrid III have closely simulated the volunteer neck kinematics. Tests of the Saab SAHR (SAAB Active Head Restraint) and standard head restraints showed differences in neck displacements that are consistent with field whiplash rates. A Neck Displacement Criterion (NDC) has been proposed to assess whiplash risks. By using the BioRID P3 and Hybrid III responses in sled tests and knowing the whiplash rates for the Saab SAHR and standard head restraints, initial working targets for NDC are proposed for consideration.

Kim *et al.* (2005) from Rear Impact Dummy Evaluation Task Group of the Occupant Safety Research Partnership/USCAR (United States Council for Automotive Research) have made a comparison of the BioRID II, Hybrid III and RID2 in low-severity rear impacts. The BioRID II, 50th percentile Hybrid III and RID2 crash test dummies, all representing a mid-size adult male, were subjected to the rear impact sled tests. Their measured and calculated responses were used to evaluate their sensitivity to sled velocity, head restraint position, and other test setup parameters. Three test series were conducted using different sled acceleration pulses and different types of seats. For conditions where three identical tests were conducted, repeatability was evaluated.

In the study of Kuppa *et al.* (2005) a new whiplash injury criterion is proposed by performing some rear impact sled tests using Hybrid III dummy for “FMVSS No 202 Head Restraints” regulation tests. The injury risk curve, based on the head-to-torso rotation of the Hybrid III dummy, was developed using insurance claims data, and the rear impact sled tests with the Hybrid III dummy. The feasibility of the application of this injury criterion in rear impact vehicle crash tests and sled tests has also been performed. The sled test results indicate that the developed whiplash injury criterion correctly predicts improved performance of head restraint and seat systems.

Zuby and Lund (2010) offered a historical review of vehicle design measures which have been implemented to reduce the risk of neck injuries to the occupants of a vehicle having a rear crash case. The literature on regulations, consumer information programs and efforts by vehicle manufacturers to address the whiplash injuries are summarized along with the studies evaluating the efficacy of the resulting vehicle design change. They showed that the vehicle design including the seat and headrest design have changed considerably over last 40 years. The results of those design changes on the whiplash injuries are also presented.

Ivancic and Xiao (2011) have used a human model of the neck called “HUMON” to determine the neck load and motion responses during simulated low speed rear crashes and to investigate the whiplash injury and prevention mechanisms. The neck specimen was mounted to BioRID II crash test dummy and low speed rear crash simulations performed. The neck load and motion responses of HUMON compared favorably with in vivo data. The shear, compression and flexion moment were shown as the neck loads. It was shown that the whiplash injuries may be reduced by refinement of injury prevention systems.

Ivancic and Sha (2010) have studied on different whiplash injury criteria and evaluated and compared the whiplash injury criteria (IV-NIC, NIC, N_{km}, N_{ij}, and NDC) during simulated rear impacts of a new Human Model of the Neck (HUMON) with and without an active head restraint (AHR). HUMON was seated and secured in a car seat with AHR on a sled. Rear impacts (7.1 and 11.1 g) were simulated with the AHR in five different positions followed by an impact with no

HR. According to the test results, a correlation was observed between IV-NIC and NIC, N_{km}, N_{ij}, and NDC. Extrapolation using the present correlations and the IV-NIC injury thresholds suggests neck injuries may occur at peak NIC of 14.4 m^2/s^2, N_{km} of 0.33, or N_{ij} of 0.09. Nonphysiologic spinal rotation at one or more spinal levels may occur even if head/T1 motions are small.

The whiplash injuries in the upper cervical spine investigated using a detailed neck model by Fice and Cronin (2012). A detailed and validated explicit finite element model of a 50th percentile male cervical spine in a seated posture was used to investigate upper cervical spine response and the potential for whiplash injury resulting from vehicle crash scenarios. The model predicted increasing upper cervical spine ligament strain with increasing impact severity. Considering all upper cervical spine ligaments, the distractions in the apical and alar ligaments were the largest relative to their failure strains, in agreement with the clinical findings. The model predicted the potential for injury to the apical ligament for 15.2 g frontal or 11.7 g rear impacts, and to the alar ligament for a 20.7 g frontal or 14.4 g rear impact based on the ligament distractions.

A finite element head and neck model of a 50th percentile female was validated in rear impacts by Östh *et al.* (2017). A previously validated ligamentous cervical spine model was complemented with a rigid body head, soft tissues and muscles. In both physiological flexion-extension motions and simulated rear impacts, the kinematic response at segment level was comparable to that of human subjects. Evaluation of ligament stress levels in simulations with varied initial cervical curvature revealed that if an individual assumes a more lordotic posture than the neutral, a higher risk of whiplash associated disorder might occur in rear impact. The female head and neck model, together with a kinematical whole-body model which was under development, addressed a need for tools for assessment of automotive protection systems for the group which is at the highest risk to sustain whiplash associated disorder.

Vazquez *et al.* (2016) studied the importance of the impact biomechanics on the assessment of whiplash injury. They worked on the previous whiplash injury assessment studies and recommend using delta *v* and mean acceleration as intensity criteria in the study of the medico-legal causality of post-traumatic cervical syndrome, keeping in mind, however, that mean acceleration is more sensitive. Although these two are not good predictors of the severity and prognosis of the pathology, they are good indicators of the likelihood of injury or onset of symptoms, with high specificity in very low-speed collisions.

In this study, the effect of three different head restraint positions with respect to the head of the occupant at three different impact velocities, totally nine configurations will be examined by performing the sled crash tests using the crash simulation system available in METU-BILTIR Center Vehicle Safety Unit Sled Test Facility. In order to perform these sled crash tests a test sample consisting of a particular seat, a three-point generic seat belt, a hybrid III family 50 percentile male crash test dummy, has been prepared according to the Euro NCAP Whiplash Test Protocol.

First of all, low speed rear impact test protocols used in the world are investigated and the differences of those protocols with the one used in this study is defined. Preparation of the test sample, positioning of the crash test dummy in the test sample, preparation of the required test pulses and so the test procedure based on the Euro NCAP Whiplash Test Protocol is done and the sled test are performed as the second step. Finally, the test data obtained from the crash test dummy sensors and the high-speed videos taken during the tests and their assessments are done by using the defined whiplash injury criteria. It has been shown that the position of the driver in the seat has a significant affect in terms of the whiplash injury occurrence.

2. Test sample preparation according to euro NCAP whiplash test protocol

The test sample is prepared according to the Euro NCAP Whiplash Test Protocol. Main elements of this test sample are;

• A "steel plate" which simulates the floor of the vehicle.

• A "toe board" which is a small board oriented 45° from the horizontal on which dummy's feet rest when dummy sits in the seat.

• A "seat" on which the dummy sits during test.

• A "3 point generic seat belt" which holds the dummy on seat during the test.

The steel plate used is a simple steel plate whose main purpose to simulate the vehicle ground and to create a connection interface with the sled test system used.

The toe board is a simple steel plate too. However, it is covered with a short-piled carpet as in the case of real cars.

The seat used in this this study is the driver (front left) seat of a light commercial vehicle as in Fig. 2. This seat has the adjustment mechanisms of seat track, seatback tilt, cushion tilt, lumbar support and arm rest.

Fig. 2 Seat used in the thesis study

A generic three-point lap-shoulder seat belt equipped with an inertia reel (i.e., rotating locking mechanism) shown in Fig. 3 is used during the tests. Bolt-nut and weld connections are used during the preparation of the test sample and all the sample elements are shown in Fig. 4.

After the preparation of the test sample, the crash test dummy positioning process is done. In order to sit Hybrid III 50 percentile crash test dummy on the seat, two important equipment are required. First and the most important one is the "H-Point Manikin". This device is a metal dummy consisting of a body, legs and metal weights. This manikin has adjustable body parts in different dimensions and masses. The required dimensions and masses of this manikin is adjusted according to the test regulation or protocol used. In this study it is adjusted as defined in Euro NCAP Whiplash Test Protocol and the required steps of installation of the manikin in the seat is

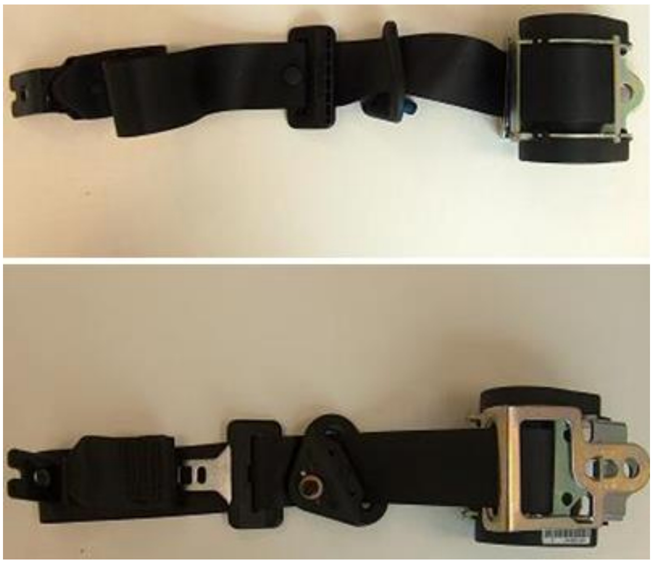

Fig. 3 Seatbelt used in the thesis study

Fig. 4 Test sample elements

performed. After it is seated another device called "Head Restraint Measuring Device (HRMD)" which is a metal head form is used. This device can be connected to the H-Point Manikin as the head of it and it is used to measure the dimensions between the head of the dummy and the head restraint of the seat. When both devices are connected and seated, the H-Point locations of the seat are measured from the H-Point marks of the H-Point Manikin by using a mobile coordinate measuring machine (CMM). This process is shown in Fig. 5.

2.1 Head restraint positions and dummy positioning

There are two parameters that define the head restraint position with respect to the dummy

Fig. 5 H-Point location measuring (left) and HRMD installation (right)

head. These are “distance from top of the head, h,” and “backset, b,” “Distance from top of the head” is defined as the vertical measurement between height probe of the HRMD and the top of the head restraint as seen in Fig. 6. “Backset” is defined as the horizontal measurement between the back surface of the HRMD head and the front surface of the head restraint as measured by the backset probe of the HRMD as seen in Fig. 6.

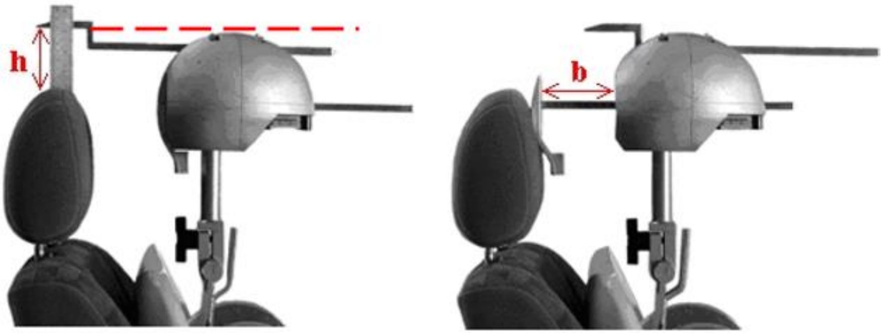

Fig. 6 Distance from top of the head (h) and backset (b)

Although the head of the dummy has a specific position with respect to the head restraint of the seat after performing the positioning procedures defined in the test protocol, it is aimed to see how head restraint position affects the whiplash injury with different test pulses. So, three different head restraint positions have been used in the tests. The nearest position is taken as “Position 1”, the standard position obtained according to the positioning procedure of the Euro NCAP Whiplash Test Protocol is taken as “Position 2” and the furthest position is taken as “Position 3”. Positions used are given in “cm” as below;

• Position 1:
- Distance from top of the head, h, is 1 cm (above dummy head).
- Backset, b, is 2 cm.

• Position 2:

- Distance from top of the head, h, is -4 cm (below dummy head).
- Backset, b, is 4 cm.

• Position 3:

- Distance from top of the head, h, is -7 cm (below dummy head).
- Backset, b, is 7 cm.

After the selection of head restraint position, the crash test dummy is positioned as defined in the test protocol. A positioned dummy in the seat is given in Fig. 7.

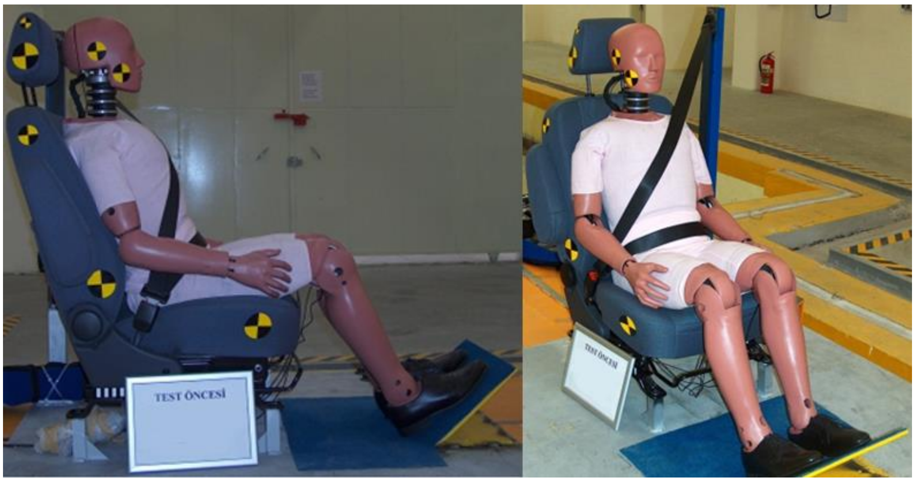

Fig. 7 Positioned dummy in the seat

2.2 Test pulses

As it is stated previously, three different test pulses are used in this study. Those pulses are "low severity pulse", "medium severity pulse" and "high severity pulse" of the Euro NCAP Whiplash Test Protocol.

The low severity pulse of the Euro NCAP Whiplash Test Protocol is the red curve in Fig. 8 and its acceptance corridors are the blue curves in Fig. 8.

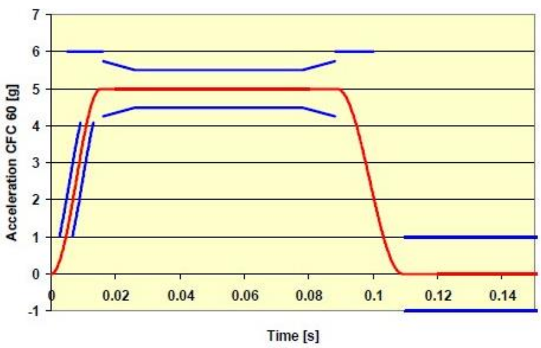

Fig. 8 Low severity pulse of the euro NCAP whiplash test protocol

The medium severity pulse of the Euro NCAP Whiplash Test Protocol is the red curve in Fig. 9 and its acceptance corridors are the blue curves in Fig. 9.

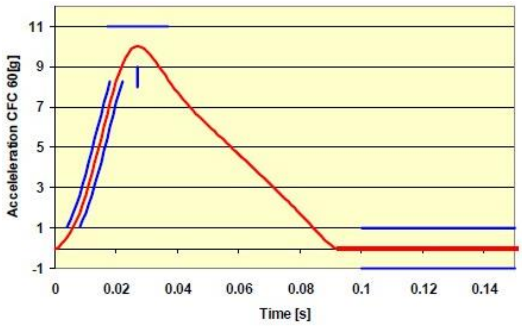

Fig. 9 Medium severity pulse of the euro NCAP whiplash test protocol

The high severity pulse of the Euro NCAP Whiplash Test Protocol is the red curve in Fig. 10 and its acceptance corridors are the blue curves in Fig. 10.

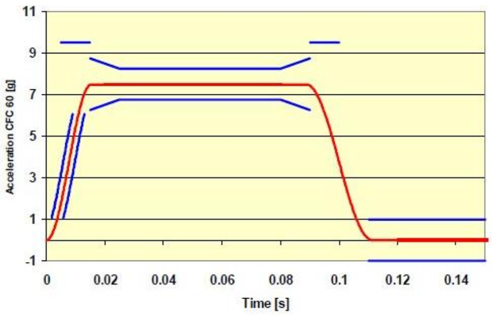

Fig. 10 High severity pulse of the euro NCAP whiplash test protocol

Those 3 pulses are used with the 3 different head restraint positions and totally 9 test combinations are defined.

These three different test pulses correspond to the different impact velocities. The velocity and mean acceleration requirements of the test pulses according to the Euro NCAP Whiplash Test Protocol are shown in Table 1.

Table 1 Velocity and mean acceleration requirements of the test pulses

Test Type	Mean Acceleration (m/s^2)	Velocity Difference (km/h)
Low Severity	42.35 ± 4.50	16.10 ± 0.80
Medium Severity	47.85 ± 4.00	15.65 ± 0.80
High Severity	63.15 ± 4.85	24.45 1.20

3. Tests performed

Nine tests, which correspond to three different head restraint positions and three different test pulses are performed during this study. Table 2 shows these test parameters.

Table 2 Test parameters

	Impact Type	Distance from Top of the Head (cm)	Backset (cm)
Test 1	High Severity	1	2
Test 2	High Severity	-4	4
Test 3	High Severity	-7	7
Test 4	Medium Severity	1	2
Test 5	Medium Severity	-4	4
Test 6	Medium Severity	-7	7
Test 7	Low Severity	1	2
Test 8	Low Severity	-4	4
Test 9	Low Severity	-7	7

Tests are performed with a sled test system capable of producing low speed test pulses with a good repeatability in METU-BILTIR Center Vehicle Safety Unit Sled Test Facility. Apart from this acceleration sled system, other important elements of the tests are instrumented Hybrid III 50 percentile male crash test dummy, high speed cameras and data acquisition systems.

The crash test dummy used in the tests was an instrumented dummy. The sensor data is taken over all of the sensor channels of the crash test dummy from -200 ms to+500 ms time with the sampling rate of 10 kHz during the test by using the data acquisition system. This data is evaluated with a special software called “EVAluation” and the required calculations for whiplash injury criteria are performed with this software. In addition to this data taken, a high-speed camera is used to take the high-speed video of test instance. This camera is used with 1000 frames/second as defined in the Euro NCAP Whiplash Test Protocol with a solution of 1536×1024 pixels. An example of the high-speed camera frames of the tests performed is given in Fig. 11.

All of the tests performed are analyzed using some of the selected whiplash assessment criteria. The ones used in this study are head restraint contact time, chest x-acceleration, upper neck shear force (F_x) and upper neck tension (F_z), head rebound velocity and N_{km} injury criterion. However, NIC (Neck Injury Criterion) and T1 x-acceleration have not been used in this study since the required data to calculate these criteria is not available on the Hybrid III 50th percentile male crash test dummies.

The head restraint contact time is calculated from the high-speed video taken during the tests. The starting of head restraint contact time, T-HRC $_{(start)}$, is defined as the time of the first contact between the rear of the dummy head and the head restraint, where the subsequent continuous contact duration exceeds 40 ms. For the purposes of assessment, T-HRC $_{(start)}$ is rounded to the nearest millisecond. Minor breaks in the contact time (up to 1ms) are permissible if it can be proven that these are not due to biomechanical phenomena such as dummy ramping, head restraint or seatback collapse, or ‘bounce’ of the head during non-structural contact with the head restraint. For the subsequent criteria, the end of head restraint contact is also found; T-HRC $_{(end)}$. This is defined as the time at which the head first loses contact with the head restraint, where the subsequent continuous loss of contact duration exceeds 40 ms.

Hybrid III 50^{th} percentile male crash test dummy is fitted with a three-channel accelerometer on the chest. Like this accelerometer, all of the sensor channels of the crash test dummy are filtered after the data is taken over them. The most common filters used in the vehicle safety area from the family of channel frequency class (CFC) filters. Similarly, Euro NCAP Whiplash Test Protocol uses this family of filters and the technical details of these filters are given in SAE J211 standard. The data channel acquired from chest accelerometer is filtered to channel frequency class (CFC) 60 as defined by SAE J211. The maximum acceleration is generated from the chest acceleration in the x-direction, considering only the portion of data from T-zero which is defined as the time before the CFC 60 filtered sled acceleration reached 1.0g level until T-HRC $_{(end)}$.

The upper neck load cell of the Hybrid III 50th percentile male crash test dummy records both shear and tensile forces. Since the instrumentation is configured in accordance with SAE J211, positive shear is indicative of a head-rearwards motion and positive tension is associated with pulling the head upwards, generating a tensile force in the neck as shown in Fig. 4.4. Firstly, both the upper neck shear force, F_x, and the upper neck tension force, Fz, channels are filtered at CFC 1000. The peak values, F_{xmax} and F_{zmax}, are then determined for each of the forces, considering only the portion of data from T-zero until T-HRC $_{(end)}$ as done for the chest acceleration.

The head rebound velocity in the horizontal (i.e., x direction) is calculated using high speed videos and the head accelerometer data in the x direction and the sled accelerometer. Theoretically, the peak rebound velocity should occur due to the elastic energy release from the seat assembly, after the peak sled acceleration has occurred. In the case of usage of the acceleration sled, this should also be prior to the sled braking, which at the earliest should occur from 300 ms. The rebound velocity of the crash test dummy is usually generated due to the release of stored elastic energy within the seat structure, suspension and foam. The time of occurrence of peak rebound velocity is the maximum horizontal component of head rebound velocity calculated between T-zero and T=300ms. By parallel assessment of high speed videos and the head accelerometer data, the time when this rebound occurs is determined. The rebound velocity of the head which is the relative velocity of the head with respect to the sled velocity is calculated by using this occurrence time.

The N_{km} criterion is based on a combination of moment and shear forces, using critical intercept values for the load and moment. This criterion includes different mathematical expressions and its details can be found in Euro NCAP Whiplash Test Protocol.

3.1 Test results

In order to define the analysis intervals of the whiplash assessment criteria, the T-HRC $_{(start)}$, T-HRC $_{(end)}$ and T-zero are used. Definitions of T-HRC $_{(start)}$ and T-HRC $_{(end)}$ was given in the previous section. However, T-zero is defined as the time before the filtered sled acceleration reaches 1.0 g and the relevant times for the low, medium and high severity pulses are 4.6 ms, 5.8 ms and 3.7 ms.

Results of the tests are calculated according to the Euro NCAP Whiplash Test Protocol and discussions about the test results are given as follows:

• It has been seen that increasing the impact velocity during the tests creates earlier T-HRC $_{(start)}$ times for the same head restraint position. However, T-HRC $_{(end)}$ times have different trends. The medium severity tests have the earliest T-HRC $_{(end)}$ times for the same head restraint position. However, T-HRC $_{(end)}$ times of the low and high severity tests are close to each other but later than

Fig. 11 High speed video frames

the T-HRC $_{(end)}$ times of the medium severity tests for the same head restraint position. The high severity and low severity signals creates longer and very close total contact times (i.e., T-HRC $_{(end)}$ - T-HRC $_{(start)}$) to each other with respect to the medium severity signal. This is a result of triangular shape of the medium severity signal whereas the others have trapezoidal shapes. Since the medium severity signal has a single peak acceleration while the others keep the peak accelerations continuously for a while, such total contact times have been occurred.

• There seems a 3-4 ms delay in the T-HRC $_{(start)}$ times from the first head restraint position in tests 1, 4, 7 to the second head restraint position in tests 2, 5, 8. However, this delay reaches the 15-20 ms level when the head restraint position changes from the second position to the third position in tests 3, 6, 9.

• Increasing the impact velocity creates higher maximum chest accelerations in the x-direction for the same head restraint position. However, it is seen that this increase is more from the low to medium severity impacts and less from medium to high severity impacts respectively.

• When the first head restraint position is changed to the second one, the maximum chest acceleration in the x-direction increases for the same impact velocities. Similarly, the same effect has been seen from the second position to the third position. This increase gets more when the severity of the test pulse gets harder.

• The maximum chest acceleration occurs at 95, 93 and 105 milliseconds for high, medium and low severity signals respectively.

• The maximum upper neck shear force, F_x, obtained in the entire tests has negative sign that means it occurs during the forward motion of the head.

• There is an increasing trend in the upper neck shear force when impact velocities are the same and the head restraint positions are changing from the first to the second and the second to the third positions.

• The maximum upper neck tensile force, F_z, obtained in the tests has positive sign that means it occurs during the upwards pulling of the head.

• The maximum head rebound velocity increases from the first to the second and the second to the third head restraint positions for the same impact velocities.

• The maximum head rebound velocity increases with the increasing impact velocities for the same head restraint positions.

• Occurrence times of the maximum head rebound velocity are the earliest for the medium severity and the latest for the low severity pulses. This is a result of the triangular shape of the medium severity pulse.

• The maximum of all of the four parts of the N_{km} has been the neck flexion posterior (N_{fp}) in the tests. So, the N_{km} is taken as the N_{fp} which is the combined negative-going portions of the shear force channel (F_{xp}) and positive-going portions of the moment channel around y axis (M_{yf}) as described in Euro NCAP Whiplash Test Protocol.

• N_{fp} value is increasing from the first to the second and the second to the third head restraint positions for the same impact velocities.

4. Conclusions

In this study, effects of the relative head restraint position with respect to the head of the occupant changing in both vertical and longitudinal directions and impact pulse on whiplash injury have been analyzed by performing the sled crash tests. The test sample used in the tests has been prepared according to the Euro NCAP Whiplash Test Protocol. The sled tests are performed for three different head restraint positions and three different impact pulses in the METU-BILTIR Center Vehicle Safety Unit Sled Test Facility. During these tests an acceleration sled, a Hybrid III 50^{th} percentile instrumented adult male dummy, a three-point generic seat belt and a driver seat are used as the main parts of the test sample. The test data are obtained from the high-speed video and the sensors of the crash test dummy through the data acquisition system.

Results of the tests are calculated according to the Euro NCAP Whiplash Test Protocol and conclusions about the tests and their results are given as follows:

• It has been shown that increasing the impact severity for the first and third head restraint positions, decreases the possibility of having the whiplash injury for the occupant. However, there is not such clear trend for the second head restraint position.

• It has also been shown that a seating position where the head of the passenger is closer to the head restraint in both vertical and longitudinal directions decreases the possibility to have the whiplash injury for the same test pulses.

• It is shown that maximum N_{km} is obtained for the combined negative-going portions of the shear force channel and positive-going portions of the moment channel around y axis.

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Note

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