

Driving Position Field Study, Differences with the Whiplash Protocol and Biomechanics Experimental Responses

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ABSTRACT – Rear-impact collisions at low speed are a leading cause of economic costs among motor vehicle accidents. Recently, EuroNCAP has incorporated in its protocol the whiplash test, to reproduce a low-speed rear impact. This paper presents a field driving study to assess the potential differences between the EuroNCAP dummy tests and actual drivers in the field, focusing on occupant position and biomechanics experimental results. A total of 182 drivers were randomly selected in two geographical areas in Spain. The driving position of each driver was recorded with a focus on the most relevant measurements for rear impact. Statistical analysis was performed to obtain means, standard deviations and density functions to compare observational seating position with that of the EuroNCAP testing protocol. The observational data showed a similar seatback angle to that used in the EuroNCAP protocol (24° in front of 25° for the protocol), a greater distance between the head vertex and the top of the head restraint (53mm compared to 39.5mm), and less distance between the occipital bone of the head and the headrest (67.9 compared to 89.3mm). Based on these data, 4 dummy tests were conducted using the dummy BioRID IIg. The baseline test was designed to reproduce the dummy position according to EuroNCAP 3.0 whiplash protocol. Three different additional tests were defined to reproduce the actual observed driving position as well as to assess a “worst case” scenario in terms of reduced seatback angle. These variations in initial driver position, comparing the EuroNCAP protocol to the observational study results, were not observed to cause significant differences in the biomechanical values measured in the BioRID IIg. The T1 acceleration was reduced less than 8%, the NIC was increased about 8%, and the Nkm presented a reduction of 20%. Reducing the seat angle was observed to be more harmful in terms of NIC.

INTRODUCTION

Rear-impact collisions at low speed are a leading cause of economic costs among motor vehicle accidents and are also the topic of substantial investigation. The biomechanical literature is currently replete with publications on the topic of “whiplash”, a term that has been used describe the head and neck motion during a rear impact since the early 1950s [Bowman 1952, Gay and Abbot 1955]. Recently, EuroNCAP has incorporated in its protocol the whiplash test to reproduce a low-speed rear impact. During a rear-impact collision, the struck vehicle is accelerated forward and therefore the seatback loads the posterior aspect of the occupant’s thorax. This seatback force, in turn, accelerates the occupant’s thorax leading to a change in velocity of the thoracic spine. However, the head, according to Newton’s first law of motion, will remain in its pre-

impact position since no forces act on it directly. This, consequently, sets up a relative movement between the thoracic spine and the head. This relative motion can produce a complex S-shaped motion of the neck followed by hyperflexion depending on the vehicle or seat stiffness, headrest location, and other geometric parameters that are assessed in this study [Svensson, 2000]. Test data show that this motion, often referred to as “whiplash”, takes place in approximately 200 ms. Field data on rear-impact collisions indicate that the majority of reported whiplash injuries occur at ΔV s (Delta V) below 4.4 m/s (16 km/h). Conversely, insurance data indicates that these injuries are reported over a range of ΔV s both above and below 4.4 m/s (Sendur, 2005).

An array of injury mechanisms associated with whiplash are described throughout the literature. For example, Severy and colleagues in 1955 relied on

laboratory tests to postulate that the injury mechanism was extension followed by flexion. In 1964, based on animal tests, Macnab et al. pointed toward hyperextension as the main responsible injury mechanism. In 1975, based on radiographic research, the importance of shear displacement between vertebrae was considered [Aufdermaur 1975]. Aldman *et al.* in 1986, hypothesized that the injury could be induced in the spinal nerve root during the complex extension-flexion motion. Penning *et al.* in 1992, identified hypertranslation of the head as a potential injury mechanism. Panjabi et al. in 1999, suggested the intervertebral rotation during the initial shear phase as primary mechanism of injury and Yoganandan *et al.* 1998 and 1999 among others, indicated that a posterior stretch in the suboccipital region may be responsible for altering the mechanics and electrical activity of suboccipital muscles, leading to headaches, and that pinching of the facet joints of the lower cervical spine as injury mechanism for neck pain.

While biomechanical studies are critical in better understanding how whiplash injuries may occur, identifying these injuries can be difficult and typically requires computed tomography (CT) or magnetic resonance imaging (MRI), which unfortunately are not always completely irrefutable in identifying the damaged structures and the specific nature of the injury. The difficulty to objectively find an injury commonly leads to litigation and high societal costs. While “whiplash” is not specifically identified as such, it could be included under “Spinal cord injury without radiological abnormalities” and graded as an Abbreviated Injury Scale (AIS) of 1 (i.e., minor injury (AIS 2005 – update 2008)). It is the most frequently reported injury occurring from automobile accidents. The costs in Europe have been estimated between 5-10 billion Euros each year [Castro, 1997], and this number increases annually. Insurance data suggest that only 10% of all whiplash injuries are long term and only 1% of whiplash injuries are associated with permanent impairment. Currently the most comprehensive assessment of car seat performance relative to neck injury protection is included in the EuroNCAP program [EuroNCAP, 2010] which integrates experience from many research centers such as Folksam, the Swedish Transport Authority, the IIHS (Insurance Institute of Highway Safety) and Thatcham. In recent times, the tests have also been influenced from IPWPG (International Insurance Whiplash prevention group) input and RCAR (Research Council for Automobile Repairs) discussions.

The aim of this study is to 1) compare the dummy seated position in the EuroNCAP protocol to that of actual drivers obtained from an observational study in Spain, and 2) assess the effect of variation in seating position on the measured biomechanical measurements in the EuroNCAP whiplash test based on best practice.

METHODS

The study was comprised of two parts 1) an observational analysis of the driving position assumed by drivers relative to the EuroNCAP whiplash protocol, and 2) a set of rear impact dummy tests to explore the effect of variations in driver seating position obtained in the observational study

Observational study of driver seating position.

The goal of this study was to assess the actual driving position assumed by of a convenient sample of drivers in two geographic areas in Spain, Three geometric measures were recorded for each driver in addition to other vehicular and anthropomorphic data: seatback angle as well as vertical and horizontal distance between the head and the headrest.

The two selected data collection sites were in the surroundings of the IDIADA facilities located in L’Albornar (Tarragona) and the “Instituto de Investigación sobre Reparación de Vehículos”, also known as “Centro Zaragoza” (Zaragoza), this terminology will be used from here on in this paper.

Two data collection teams (one per each site) were trained together and a common protocol was utilized for both groups to minimize differences in measurement methodology. The volunteers were to be approached by researchers in gas stations and carwash areas located in their respective geographical areas. To the advantage of researchers, both research companies are well known in their areas, which facilitated the introductory phases of the approaching to the drivers. After an unambiguous explanation of the project’s goal, drivers were asked permission to have their position measurements taken. No information was provided that could affect the head position relative to the headrest and no changes in the seatback angle were permitted.

To select participants, a randomized protocol was implemented, no selection criteria in terms of age, heights, weights or gender was established. The selection criterion was to select one of every ten customers and once a verbal agreement was obtained from each potential volunteer, the measurements

were obtained. Once a given volunteer agreed to participate, the measurements were recorded with the driver in his or her own vehicle.

To determine the driving position two direct measurements were taken a) horizontal distance between the headrest and the posterior aspect of the head at the level of the occipital condyle and b) the vertical distance between the head vertex and the most superior aspect of the headrest as illustrated in Figure 1.

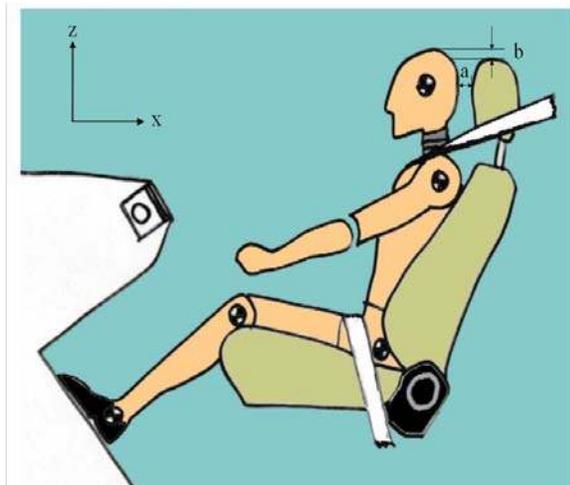


Figure 1. Direct measurements from the volunteers.

An additional measurement was taken indirectly, the seatback angle in driving position. To measure this angle we used the 3D-H point machine, also known as OSCAR, which is the procedure followed in ISO 6549. The process consisted in:

1. OSCAR in position in the seat
2. Weight in place
3. Legs in position
4. Move the back forwards
5. Three 5° displacements are made left and
6. Keeping the back forwards, a Force of 100N is applied to the basis of the Oscar.
7. The back is pushed against the seat with a Force of 25 N.
8. Record the measured angle.

Figure 2 reproduces the OSCAR positioning.



Figure 2. 3D H-point machine (OSCAR).

In addition to the measurements related to seating position, the age, weight, and height of each driver were obtained as well as the model year of the vehicle.

The protocol for data collection of volunteer drivers was approved by the Universidad de Navarra Ethics Committee (Protocol No. 086/2009).

To compare the measured values to the values used in the EuroNCAP whiplash protocol, a probability density function was calculated for each variable according to the Equation 1. This Equation was used with the assumption that the measured variables followed the normal distribution.

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\frac{x-\mu}{\sigma}} \quad (1)$$

Where: μ is the average and σ (sigma) is the standard deviation.

Dummy rear impact test.

Based on the statistical results from the volunteer data, four dummy tests were performed using the BIORID IIg, which is used in EuroNCAP protocol version 3.0 to dynamically assess car seats during rear impact.

The test matrix was defined after comparing the observational measurements with a reference test using the BIORID IIg following the EuroNCAP protocol, from the 3 proposed by EuroNCAP, the medium severity sled pulse requirements were selected for measurement. Figure 3 illustrates the mandatory corridor.

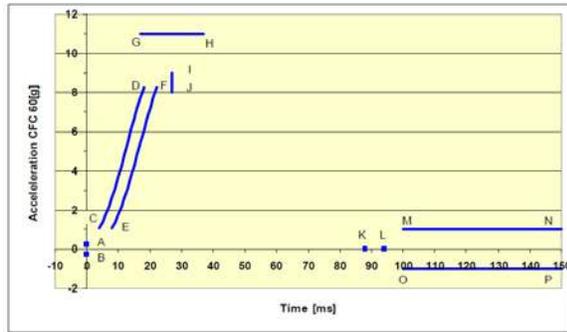


Figure 3. Medium severity pulse corridor according to EuroNCAP protocol. Source EuroNCAP.

Figure 4 provides the experimental baseline for the first test (Test #109). All the package measurements were obtained either from the EuroNCAP protocol or from the vehicle manufacturer. A standard vehicle seat with a EuroNCAP score of 2.0 using passive measures was selected. The same type of seat was used for all tests. A new and identical seat was used for each test.



Figure 4. General and detailed view of the baseline condition. SEAT and dummy positioned according the whiplash protocol. The experiments were performed in CTAG-IDIADA in a hydraulic inverse acceleration catapult, CTAG-IDIADA is a certified EuroNCAP laboratory for rear impact. Figure 5 provides the pulse of the three subsequent tests (tests 201, 202 and 203) showing reasonably good repeatability across tests. All the pulses were able to fulfill properly the required corridor presented in Figure 3.

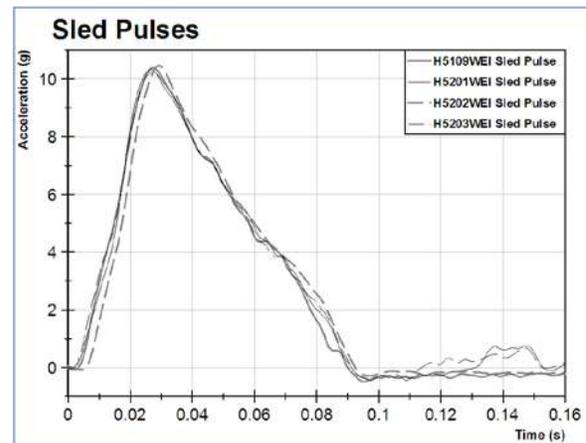


Figure 5. Medium severity pulse corridor and obtained repeatability in the hydraulic inverse acceleration catapult.

The second test (test #201) was defined with a seatback angle $\mu - \sigma$. The average seatback angle from the observational study was found to be only one degree less than that used in the EuroNCAP protocol. In order to explore a greater portion of the range of this parameter observed in the field, the authors selected to reduce the angle further to observe its effect on the biomechanical response.

The third test (test #202) was performed with BIORID IIg with the head positioned to the average value b obtained in the observational study.

The fourth test (test #203) was performed with BIORID IIg with the head positioned to the average a value from the observational study.

All other geometric parameters were held constant although minor variation was unavoidable due to the interrelation between parameters. All final 3-D positions were recorded in using a FARO ARM (FARO Gage Plus TM, accuracy $\pm 0.05\text{mm}$).

The following biomechanical-response parameters were recorded during the rear impact event: T1 x-acceleration, Neck Injury Criteria, Mkm criterion, the upper neck shear (+Fx) and the upper neck tension (+Fz). The time of initial head contact with the headrest and the rebound velocity of the head relative to the sled were also recorded.

RESULTS

In the observational study, approximately 80% of those approached agreed to participate. Observational driver seating position measurements were taken from 182 drivers (82 from IDIADA and 100 from Centro Zaragoza researchers).

The measurements obtained through the observational study carried out in the Centro Zaragoza and IDIADA locations were reasonably similar as seen in Table 1. However, substantial dispersion was observed in the sample in terms of headrest height and headrest distance. Conversely, the measured seatback angle was most consistent and exhibited the least variation of all collected measures.

Table 1 summarizes the measured parameters and provides the mean, standard deviation, maxima and minima values for both samples, including the values for the volunteer’s anthropometry, age, and vehicle model year.

Table 1. Observational measurements (n=182)

		Age	Weight	Height	Age	Headrest	Headrest	
		(years)	(kg)	(cm)	(years)	height	Distance	OSCAR
		(years)	(kg)	(cm)	(years)	(mm)	(mm)	angle (°)
CZ	mean	38.0	71.8	170.2	7.0	59.2	73.9	25.1
	sd	13.1	14.9	8.3	4.6	45.3	40.3	5.4
	Max.	72.0	150.0	190.0	20.0	230.0	154.0	42.0
	Min.	19.0	48.0	152.0	0	0	0	7.0
IDIADA	mean	32.1	75.8	174.6	6.3	46.6	60.5	22.8
	sd	6.7	16.1	7.8	4.2	28.9	42.9	4.0
	Max.	50.0	128.0	193.0	17.0	155.0	200.0	33.4
	Min.	21.0	49.0	157.0	0	-98.0	0	13.5
TOTAL	mean	35.3	73.6	172.1	6.7	53.0	67.9	24.0
	sd	11.1	15.6	8.3	4.4	47.4	41.9	4.9
	Max.	72.0	150.0	193.0	20.0	230.0	200.0	42.0
	Min.	19.0	48.0	152.0	0	-98.0	0	7.0

sd: standard deviation

Negative headrest height indicates headrest above the head z

Figures 6 - 8 provide the calculated density function of the aggregated samples for OSCAR angle, headrest height and headrest distance. In the headrest distance density function the negative distance has been removed from the curve to include only physically meaningful values.

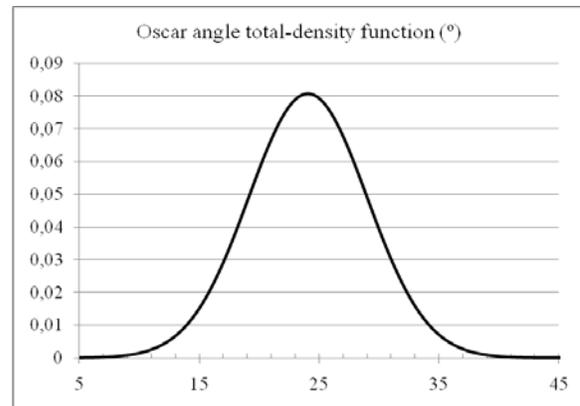


Figure 6. OSCAR angle density function for Centro Zaragoza and IDIADA study.

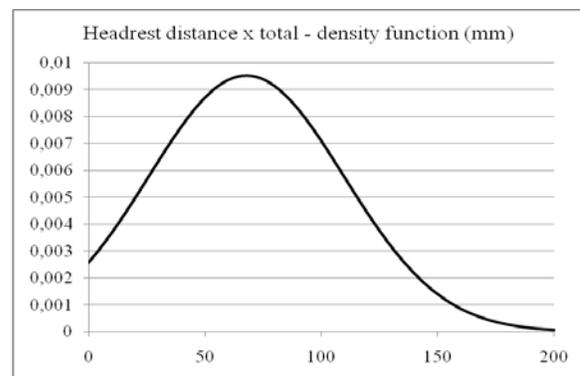


Figure 7. Headrest distance density function for Centro Zaragoza and IDIADA study.

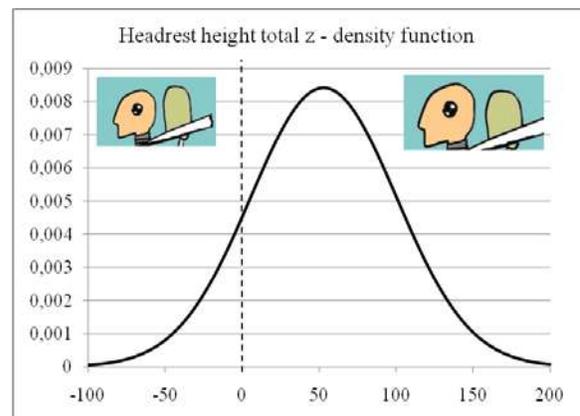


Figure 8. Headrest height density function for Centro Zaragoza and IDIADA study. Negative value headrest higher than the top of the head, positive value head rest lower than the head.

To compare measurements with the selected seat, three measurements with the BIORID II were performed with three different seats. The average of each measurement was used for presented tests. The

average measurements and the associated standard deviations were: OSCAR angle: $24.9 \pm 0.1^\circ$, headrest distance 89.3 ± 4.5 mm and, headrest height 39.5 ± 2.1 mm.

The closest measure obtained in the observational study to the dummy measure was the backseat angle, which differed less than 1° . Distance between the head and the headrest was on average 21 mm closer in the volunteers than in the BIORID II when positioned for the EuroNCAP protocol. The distance between the top of the head and the top of the headrest indicated that the actual drivers placed the headrest 15 mm lower than the relative position measured in the dummy for EuroNCAP tests.

Related to these observational results, four experimental tests using the BIORID IIg dummy were conducted as explained in the methods section. Table 2 provides a summary of the observational measurements and the experimental dummy test matrix.

Table 2. Summary of the test observational measurements compared to the text matrix.

	Observational measurements (n=182)					
	μ	σ	$\mu + \sigma$	μ	μ	σ
Head restrain distance Z (mm)	53.0	47.4	100.4	5.7		
Head restrain distance X (mm)	67.9	41.9	109.8	25.9		
Backseat angle ($^\circ$)	24.0	4.9	29.0	19.1		
Dummy tests						
	H5109WEI Reference test	H5201WEI modifying angle	H5202WEI modifying height	H5203WEI modifying distance		
Head restrain distance Z (mm)	39.5	19.0	56.0	39.5		
Head restrain distance X (mm)	89.3	89.3	89.3	67.9		
Backseat angle ($^\circ$)	25.0	19.0	25.0	25.0		

μ = mean
 σ = standard deviation
 $\mu \pm \sigma$ accounts for 68.2% of the population

Figures 9 to 14 provide time-histories for selected parameters for all tests. These include: T1 acceleration, maximum Neck injury criteria, Nkm, rebound head velocity, upper neck shear, and upper neck tension.

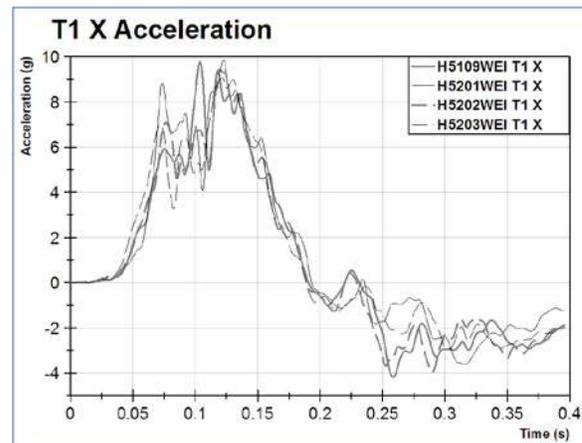


Figure 9: T1 X-axis acceleration time-history curves for tests 109, 201, 202 and 203.

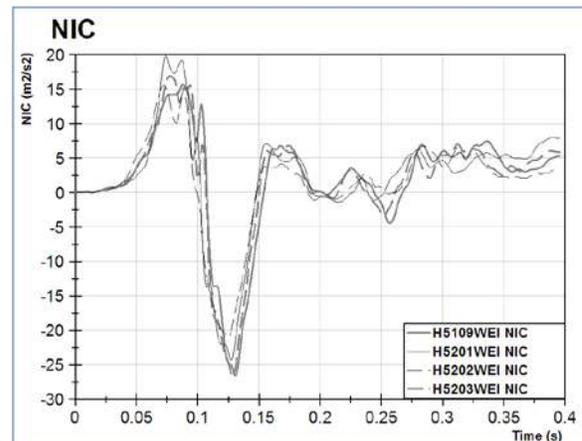


Figure 10: Neck injury criteria time-history curves for tests 109, 201, 202 and 203.

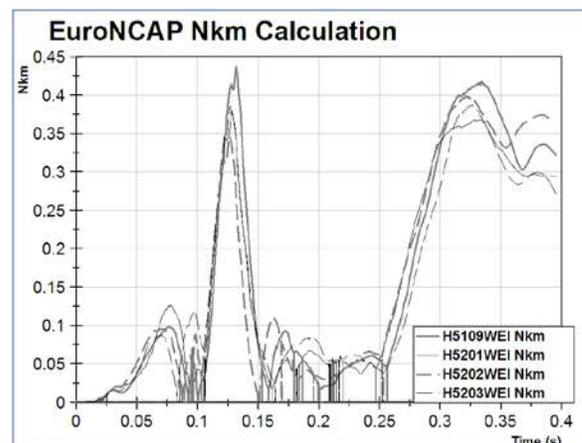


Figure 11: Nkm time-history curves for tests 109, 201, 202 and 203.

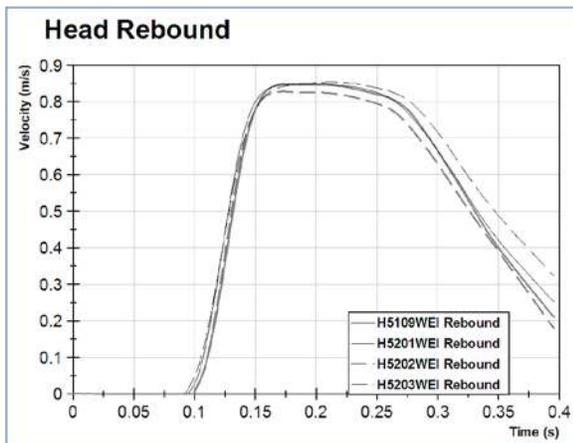


Figure 12: Rebound head velocity time-history curves for tests 109, 201, 202 and 203.

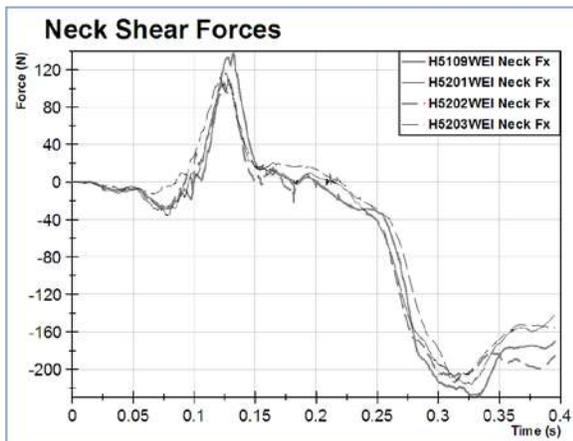


Figure 13: Upper Neck Shear time-history curves for tests 109, 201, 202 and 203.

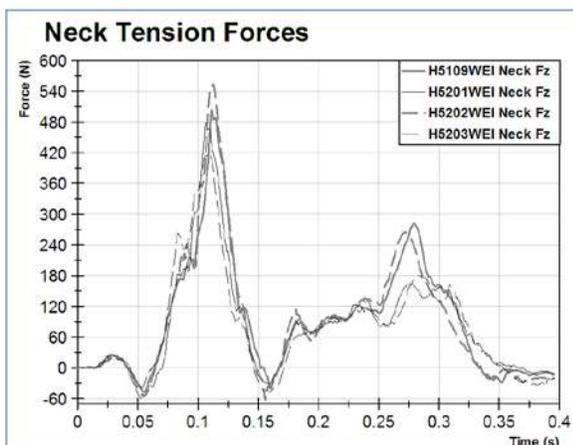


Figure 14: Upper Neck tension time-history curves for tests 109, 201, 202 and 203.

Table 3 summarizes the maximum values corresponding to the conducted tests.

	H5109WEI Reference	H5201WEI change in angle	H5202WEI change in height	H5203WEI change in distance
Head contact start (ms)	91.1	87.5	90.5	86.4
Total contact time (ms)	91	77	87	99
T1 acc (g)	9.77	9.85	9.44	9.07
Upper Neck Shear +Fx (N)	137.5	109.71	106.13	116.41
Upper Neck tension +Fz (N)	504.29	478.19	553.2	419.67
Rebound head vel (m/s)	4.01	3.82	3.94	3.55
NIC max (m2s2)	15.61	19.86	16.91	15.53
Nkm	0.44	0.38	0.35	0.39

The third test (202), in which the headrest was moved down compared with the baseline test, produced generally similar biomechanical responses and total time that the head was in contact with the headrest. Some substantial differences were observed, however, in the upper neck shear and the upper neck tension responses. These differences are likely related to the interaction between the headrest and the dummy head since in this test the headrest contact point was lower on the head, changing the head and neck kinematics (Figures 15 and 16)



Figure 15. Reference test H5109WEI at t= maximum upper neck tension +Fz

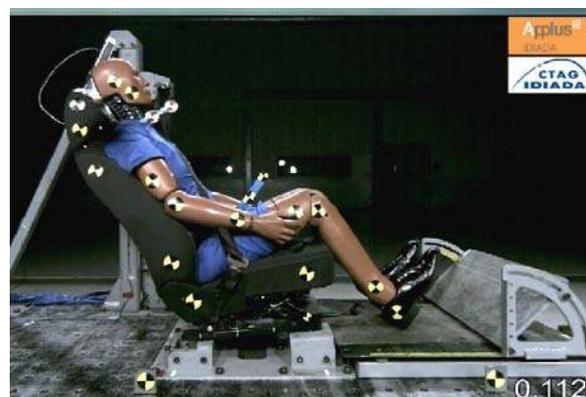


Figure 16. Change in height test H5202WEI at t= maximum upper neck tension +Fz

The fourth test (203) where the distance from the head to headrest was reduced by 21.4 mm as compared to the reference test, produced a reduction in the measured biomechanical response parameters, with the greatest reductions observed in the upper neck shear and the upper neck tension. This observation has been previously reported in the literature with two separate mechanisms: 1) relating the upper neck shear load (associated with an S-shape) to head-to-headrest separation distance (Garcia, 2003) and, 2) associating a reduction in this distance to a corresponding reduction in the peak neck shear and tension values.

DISCUSSION

The observational study showed good agreement with the EuroNCAP protocol with regards the seatback angle. The average measure in the observational data differed only one degree from that currently used in the EuroNCAP whiplash protocol (the protocol notes that if the manufacturer does not indicate any particular angle, then testing will be done at 25°). However, in this particular case of angle positioning, the standard deviation in seatback angle was approximately 20% of the mean value.

The vertical distance between the top of the head and the top of the headrest indicates that the actual drivers place the headrest 13.5 mm lower than that specified in the testing protocol, and also that the standard deviation is larger than anticipated, it being approximately 90% of the mean value.

The horizontal distance between the back of the head and the headrest shows that the actual drivers place their heads 21.4 mm closer to the headrest than for the dummy in the testing protocol. Also, the standard deviation indicates a substantial dispersion in the measures with the standard deviation being approximately 60% of the mean value.

Since it was reported in 1996 that only 10% of the drivers had the headrest in the most favorable position to prevent neck injuries (Viano, 1996), our convenient sample data collection shows an improvement, likely the result of instructing drivers about the headrest being a safety device, and not being a comfort device.

Compared with the reference test (test # 109), the second test (201) which reduced the backseat angle from 25° to 19° resulted in a moderate reduction across all measured biomechanical response parameters with the exception of T1acc and NIC, which was actually 27% greater. A possible explanation for this may lie in the NIC injury criteria

definition itself. During the retraction phase, the magnitude that the seatback pushes forward the upper torso forward (in the positive x direction) has been reported to affect this criterion (Sendur, 2005). With a reduced seatback angle, the z component of the seatback force acting on the posterior aspect of the subject is reduced; therefore the relative movement between the first and last cervical vertebrae is increased. The reduced seatback angle also affects the dummy kinematics and reduces in the tendency for the dummy to slide up the backseat.

The EuroNCAP protocol does not, however, take into account the vehicle stiffness; it is therefore a purely comparative test of a range of model seats. This manuscript, focusing on EuroNCAP protocol, presents data where this confounding variable has been eliminated by utilizing a repeatable test pulse and the same seat stiffness.

Our results are subject to several limitations: the observational study relies on a convenient sample of drivers meeting some inclusion/exclusion criteria that bear no intention to being representative from any particular driving population, no data for front passenger were included in the study; we collected observational in two separate sites and combined their data assuming there were no meaningful differences with regards to any of the parameters under study; the variables were assumed to follow a normal distribution, but can't be extrapolated to the EuroNCAP standard. The sample size and also the standard deviation are limitations.

Related to the dummy test, the seatback angle and head-to-headrest distance are interrelated to some degree. Additionally, only one test was carried out with each position. This study also used a single seat (with a determined stiffness) and one of the three proposed pulses from the EuroNCAP protocol.

CONCLUSION

Measurements in 182 volunteer drivers in Spain conveniently selected from two geographical sites regarding their average seatback angle and head-to-headrest distance were in good agreement with those currently used in the EuroNCAP whiplash testing protocol. However, headrest position was shown to have substantial dispersion, indicating that more work may be required to further educate drivers in most effectively positioning of their headrest as a countermeasure to reduce the potential for whiplash related injuries during rear impacts.

Reducing the seatback angle in the experimental setting was observed to produce the largest effect in

the Neck Injury Criteria (NIC) value. Lowering the headrest and increasing the distance to the top of the head were observed to change the head and neck kinematics and to increase the upper neck tension. Reducing the head-to-headrest distance produced a reduction in all measured biomechanical response parameters and calculated injury criteria.

Changes to the EuroNCAP protocol based on a convenient gathering of observational driver position data produced only minor biomechanical variations relative to those obtained using the current standard protocol. Thus, the currently used EuroNCAP positioning whiplash protocol appears reasonable based on the results of the current study.

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