Preventing Pediatric Out-of-Position in Frontal Crashes: Impact Assessment of a Head Support System

Francisco J. Lopez-Valdes, Oscar Juste Lorente, Juan J. Alba

Abstract Head injuries are the most frequent and severe injuries sustained by children in motor vehicle crashes regardless of age, restraint type and direction of impact force. Recent investigations have shown that these injuries are likely related to the direct contact of the head with the interior components of the vehicle. The present study evaluates the impact performance of a device intended to provide head support to children with problems to control the position of the head. Twenty-three crash tests with a nominal impact speed of 50 km/h were performed in a decelerator sled according to European regulation ECE R44/04. Two different sizes of dummies (P3, P6) were used in the evaluation. Three different CRS were considered: a forward-facing seat with ISOFIX and top tether (P3 dummy), a high-back booster seat with ISOFIX (P3 and P6 dummies) and a high-back booster seat (P3). It was observed that the use of the device did not influence significantly the kinematics of the dummies. Even if the system modified slightly the trajectory of the head, it did not cause substantial changes in the magnitude of the head and chest accelerations. All the dummy parameters fell well within the limits established by the regulation. Thus, given that other studies have shown that the head support system is effective preventing out-of-position, the results presented here suggest that the use of the system can contribute to improve the overall safety of pediatric occupants by diminishing the incidence of out-of-position events without altering the protection given by the CRS in frontal impacts.

Keywords ECE-R44, frontal impacts, head support system, pediatric out-of-position.

I. INTRODUCTION

WHO estimates about 10 million children injured or disabled each year as a result or road traffic crashes worldwide. Head and limbs are the most commonly injured body regions among children [1]. A study combining hospital discharge data from 10 European countries showed that traumatic brain injuries and fractures to the limbs, followed by injuries to the abdominal and thoracic organs, were the most frequent types of injuries sustained by children younger than 12 years old [2, 3]. In the United States, traumatic brain and skull injuries are the most common severe injuries sustained by pediatric occupants in road traffic crashes, regardless of age, crash direction and restraint type [4]. Head injuries are responsible for one third of all pediatric injury deaths [5, 6].

Regulation FMVSS 213 (Child restraint systems) in the US and ECE-R44 (Uniform provisions concerning the approval of restraining devices for child occupants of power-driven vehicles) in Europe limit the maximum horizontal displacement of the head of pediatric-sized Anthropomorphic Test Devices (ATD) or dummies in a simulated frontal impact, and yet there is a high incidence of pediatric contact head injuries in the field. The misuse of child restraint systems and the presence of lateral force components in the collision are likely associated with an increased risk of pediatric head injuries. A relatively low number of studies have attempted to describe the factors leading to the occurrence of pediatric head injuries. Recent studies have suggested that intrusion was a major cause of pediatric head injuries in crashes with lateral components [7] and that large head side wings could contribute to the prevention of head contacts against the interior of the vehicle [8]. In frontal impacts, even when children were appropriately restrained there was a substantial forward head motion that resulted in contact of the head/face against the back of the front seat or the B-pillar [9]. AIS 2+ head injuries

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were associated with head contact with the interior of the car in 60% of the cases [10]. Children's posture also affects injury risk, modifying the interaction between the occupant with the restraints and its kinematics [11].

Due to the existing lack of information on the impact response of pediatric occupants, observational studies have gained importance over the last years as they provide qualitative information about the behavior, restraint fit and children postures during real trips [12, 13, 14]. Forman et al. exposed 30 children to an in-transit study during night-time driving. Children were rear-seated and adequately restrained according to their anthropometry [15]. The study showed that the group using a high-back booster seat reduced significantly ($p<0.05$) the mean frequency of poor shoulder belt fit and the 90th percentile of the absolute value of the relative lateral motion of the head compared to the group using no booster. The group using a low-back booster seat also exhibited a reduction in both magnitudes in comparison with the no-booster group, but the differences were not statistically significant in this case.

Forman's study suggested an association between head position and shoulder belt fit: a correct head position would impact positively the position of the belt on the torso of the occupant. In 2012 and 2013, a prototype of a flexible head support system was shown to prevent out-of-position (OOP) during normal driving both in pediatric and adult occupants [16, 17]. The support system was designed to control the position and attitude of the head in circumstances in which the head-torso alignment might be compromised due to the lack of cervical muscle activity (i.e. when the occupant is sleeping or presents some sort of disability). A follow-up of Forman's study [17] (designed to be a case crossover observational study) showed that a head support system reduced significantly the 90th percentile value of the lateral motion of the head regardless of the child restraint system used and also reduced the maximum downward position of the sternal notch within the low-back booster and the no booster groups, preventing the pediatric occupants to adopt a slouch posture that could increase the risk of submarining. It was found that the use of a head support improved significantly the positioning of the shoulder belt on the torso of the occupants. The prototype of the head support system used in the previous study evolved into a commercial system (www.headpod.com) available as an orthopedic device for children with deficient head control due to mental or physical disability.

Despite the previous evaluations and to the knowledge of the authors, there is no study assessing the performance of such a device in case of impact. By design, the HSS was never intended to act as an additional restraint to arrest the motion of the occupant but only to reduce the frequency of OOP. Thus, the ultimate goal of this study was to assess if the commercially available version of the HSS caused changes in the performance of child restraint systems complying with regulation ECE R44/04. The assessment included three different types of child restraint systems and two dummy sizes (3-year-old, 6-year-old).

II. METHODS

Test matrix

The test matrix was designed to assess the performance of the head support system (HSS) in three different types of child restraint systems (forward-facing seat with ISOFIX and top-tether, high-back booster seat with ISOFIX and high-back booster seat) and using two different dummy sizes. Three repeats were done per each condition. Tests that included the use of the HSS were compared to those in which the HSS was not present, within the same restraint group and dummy size. This test matrix would have resulted in a total of 24 tests, but the malfunctioning of the instrumentation in one of the tests with the P6 dummy reduced the total number of tests to 23. Table I summarizes the conditions and the associated test numbers.

Test setup, instrumentation and data analysis

The tests were performed at TESSA-I3A, the crash test facility of the University of Zaragoza. The controlled deceleration of the rubber-band powered sled was achieved using a set of steel bars that penetrated into polyurethane tubes. The test buck was accelerated up to a nominal impact speed of 50 km/h and then decelerated as shown in Fig. 1, meeting the requirements of regulation ECE-R44. A rigid seat and a deformable cushion in compliance with regulation ECE-R44 was used to place the child restraint system (CRS) on the sled. A conventional three-point seatbelt (no retractor, no force-limited, no pre-tensioned) was used to restrain the occupants in the booster seats. Belt anchors were positioned according to regulation ECE R44/04. The belt was replaced after each test.

Three-axial acceleration was measured at the center of gravity of the head and at the thorax of the ATD at 10 kHz. The components of these accelerations were obtained in a local coordinate system that moved synchronously with the ATD head and torso, and that was oriented according to the SAE recommendations. Occupant acceleration data were filtered using a low-pass CFC-180 filter. An additional accelerometer measured the deceleration of the sled (filtered at CFC-60). High-speed video recorded the displacement of the occupant in the sagittal plane at 1 kHZ.

TABLE I
TEST MATRIX

Child restraint system	ATD	Occupant Restraint	HSS?	Test numbers
Booster seat	P3	3 pt seat belt	No	496 497 498
Booster seat	P3	3 pt seat belt	Yes	495 511 512
Booster seat (ISOFIX)	P3	3 pt seat belt	No	499 500 501
Booster seat (ISOFIX)	P3	3 pt seatbelt	Yes	508 509 510
Forward-facing seat (ISOFIX, Top Tether)	P3	Harness	No	502 503 504
Forward-facing seat (ISOFIX, Top Tether)	P3	Harness	Yes	505 506 507
Booster seat (ISOFIX)	P6	3 pt seat belt	No	513 514
Booster seat (ISOFIX)	P6	3 pt seat belt	Yes	515 516 517

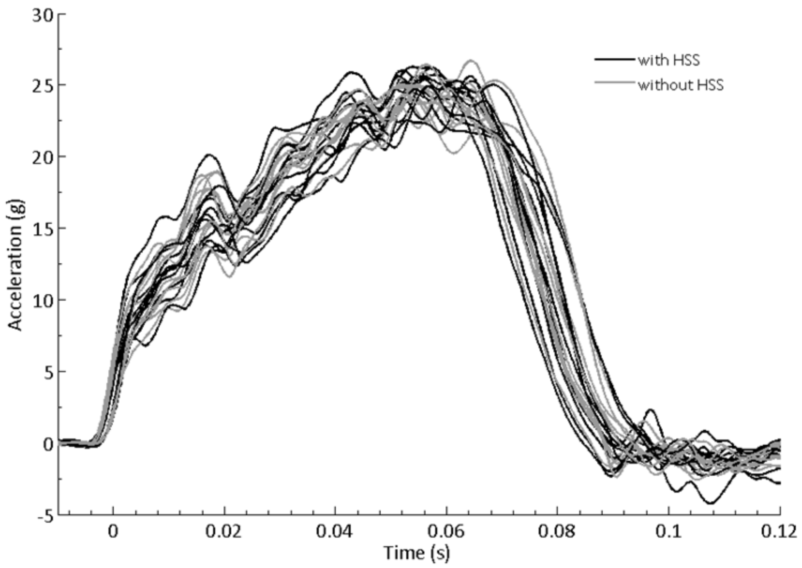


Fig. 1. Time-history plot of the deceleration of the test buck. All tests fell within the corridor required by regulation ECE R44/04.

Child restraint systems used in the tests

Three different CRS were used to assess the HSS. The selection was made to cover a broad range of restraining solutions and more than one dummy size. The three CRS were commercial systems that satisfied the requirements of regulation ECE-R44 and they were chosen after checking that the attachment of the HSS to the back rest of the CRS was solid and did not exhibit any looseness that could have influenced the outcome of the assessment.

The first system was a certified Group I (recommended for children weighting between 9 and 18 kg) forward-facing seat with ISOFIX and top-tether. The occupant in this system was restrained by the five point harness of the CRS. The two other CRS were essentially the same model of high-back booster seat and they differentiated in the presence of ISOFIX. These two booster seats were certified as Group II-III, recommended for children between 15 and 36 kg. The occupant was restrained by the three point belt installed on the test buck.

Fig. 2. The three CRS used in this study: forward facing seat (ISOFIX, top-tether), high-back booster seat (ISOFIX) and high-back booster seat without ISOFIX.

TABLE II

SLED TEST CRITERIA (FRONTAL IMPACT) IN REGULATION ECE R44/04

Test speed	50 km/h
Maximum head forward movement horizontal:	
• Groups I, II, III	550 mm
• Group I ISOFIX with Top Tether	500 mm
Maximum head forward movement vertical (all groups)	800 mm
Maximum chest deceleration	
• Resultant acceleration	55 g
• Vertical acceleration	30 g

ECE R44/04

Version 04 is the current version of regulation ECE R44 and every child seat sold in Europe must comply with this standard safety requirement. This version of the regulation will be in place until 2018, although it will run in parallel with the newly proposed i-Size regulation from June 2013.

ECE R44/04 establishes operating and using criteria such as specific buckle opening forces or the absence of sharp edges, and also sled test criteria. The regulation requires both a frontal (at 50 km/h) and a rear (at 30 km/h) impact. This study focused on the assessment of the head support system in frontal impacts. The regulation requires using a dummy of the P-series and establishes several performance criteria including the maximum head forward movement and the resulting and vertical acceleration of the ATD chest. These criteria are summarized in Table II.

The three CRS were certified under regulation ECE R44/04 and therefore satisfied the criteria included in Table II.

The head support system

The head support system assessed in this study was a commercially available orthopedic device intended to provide support to the head in children with deficient head control due to physical or mental disability and no spasmodic motions. The system consists of a posterior elastic band that is placed under the occipital region. Anteriorly, another band runs over the frontal cranial bone and joins the posterior band bilaterally. A third piece connects the two flexible bands to a vertical elastic strip that attaches to a support fixed to the child restraint system or to the headrest of the vehicle. A schematic of the system and a lateral pre-test view showing how the system was incorporated to one of the CRS are included in Fig. 3.

The head support system assessed in this study was a prototype that modified the interface between the vertical strip and the support to facilitate that the strip would slide smoothly over the horizontal part of the support in case of a sudden deceleration. The system was placed on the ATD head following the recommendations provided by the manufacturer. The anterior band was fitted tightly to the head front of the ATD and the adjustable vertical strip was placed to hold the head without pulling upwards.

The head support was attached to the backrest of the child restraint system using the adaptors that are provided with the system. The whole system was replaced after each test.

ATD positioning and belt geometry

ATDs were positioned centered in the CRS and following the recommendations of ECE R44. The torso angle was adjusted so that the back of the dummy was initially in contact with the back rest of the CRS and therefore it was controlled by the geometry of the CRS. Table A.I in the Appendix show the measurement of the torso angle in each of the tests. Head angle was also measured prior to test and set to 0 degrees.

To ensure a repeatable position of the harness and the seat belt on the torso of the dummy, relative measurements were taken between ATD landmarks and the belt. These measurements are shown in Table A.II. ECE R44/04 procedure also fixes the level of pretest belt tension to ensure repeatability between tests.

Variables included in the study

This study focused on the influence of the HSS on the sled test criteria for frontal impacts required by regulation ECE R44/04 and showed in Table II. Thus, the maximum forward position of the head horizontally and the magnitudes of the resultant and vertical ATD chest accelerations were compared between the tests using the HSS and those in which the system was not present.

In addition to the parameters required by the regulation, the position of the center of gravity (CG) of the ATD head was tracked every 10 ms in the occupant's sagittal plane, up to its maximum forward displacement. The software Tracker© v4.80 was used to track the head motion. Due to the geometry of the CRS, the ATD head center of gravity marker was obscured during the initial phases of the impact in some of the analyzed tests. In these cases, the approximate position of the center of gravity of the head in the sagittal plane was estimated using two other points on the dummy head that were visible at all times and triangulating to obtain the position of the center of gravity. Displacement data of the head CG is shown as the average sagittal response within each restraint group and the corridor corresponding to plus/minus one standard deviation (SD) of the X and Z displacement of the head CG.

To further characterize the kinematics of the head, this study also includes the time history plots of the acceleration of the center of gravity of the ATD head.

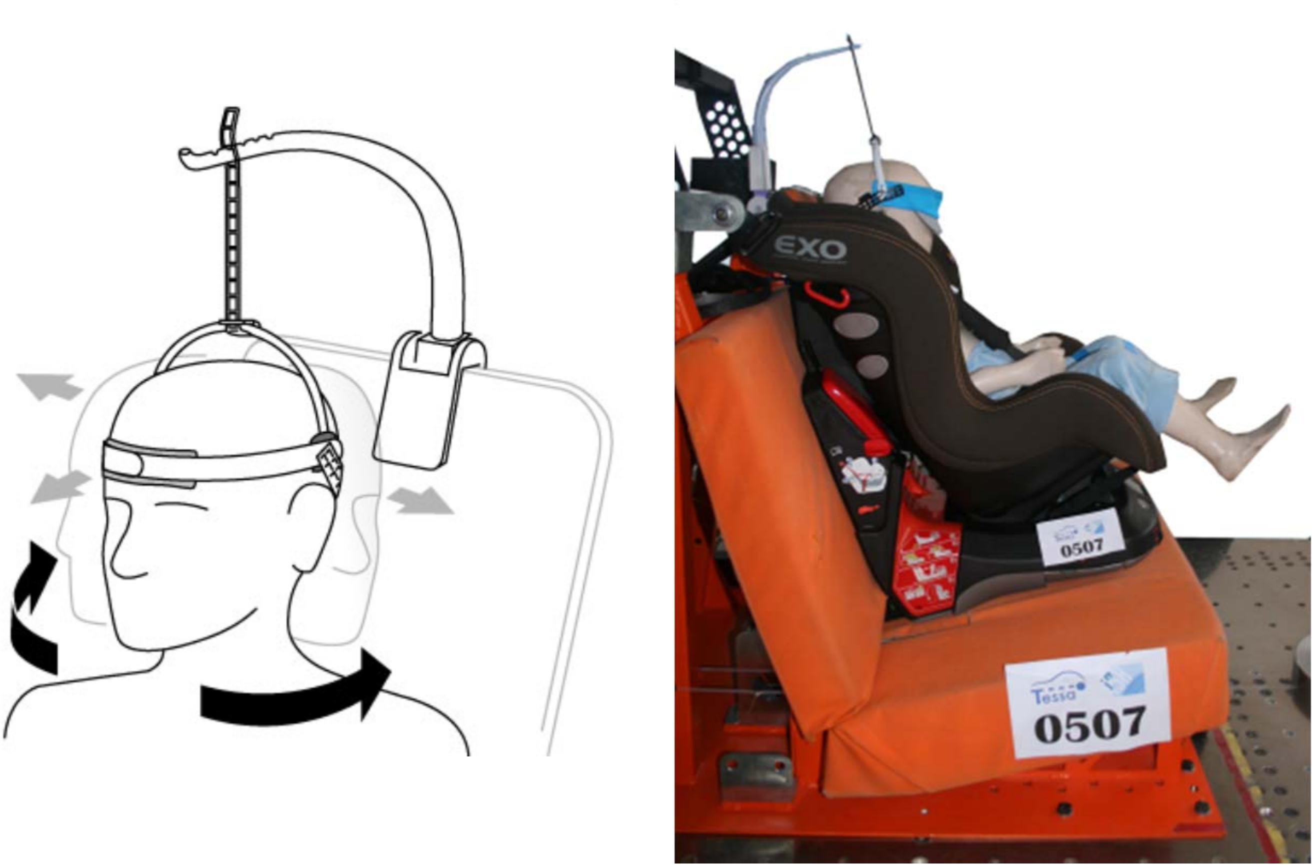
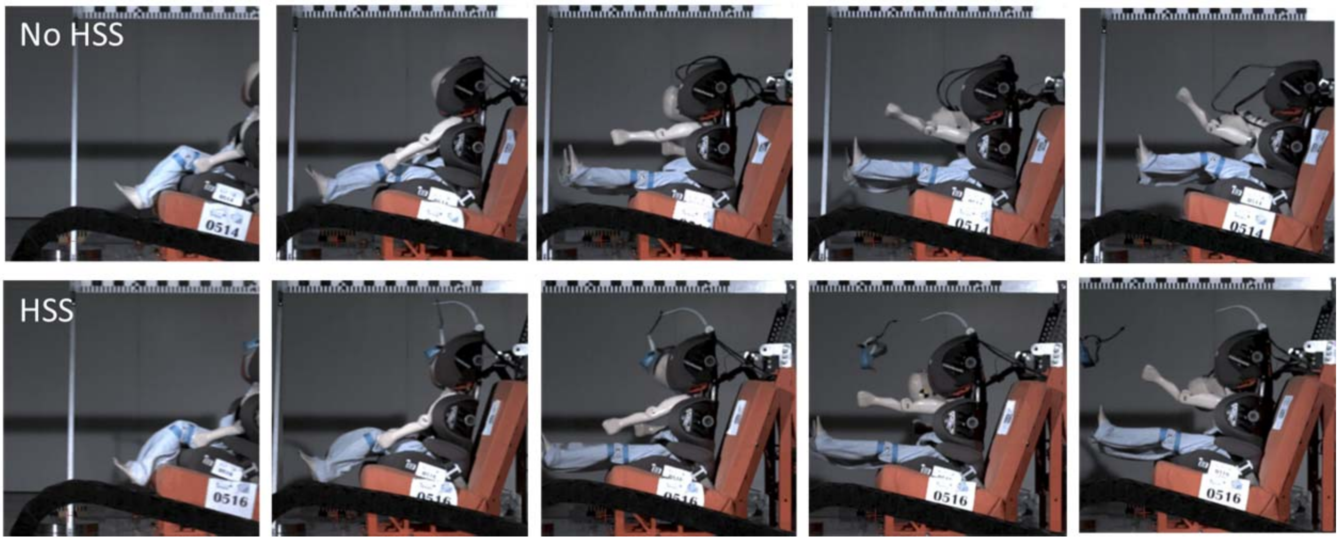


Fig. 3. Schematic of the HSS showing the head motions allowed by the system (left) and lateral view of Group I CRS incorporating the HSS (right).

III. RESULTS

General kinematics of the occupant

Figure 4 shows the kinematics of the pediatric surrogate at different time instants during the impact to illustrate how the dummy moved with and without using the HSS. The comparison of the high-speed video captures showed no apparent differences related to the use of the HSS. The overall motion of the ATD head and torso and of the CRS was not influenced by the HSS. Although the video frames included in Fig. 4 correspond only to the P6 dummy, similar observations were made for the other dummy size and CRS types. Maximum forward displacement of the head happened at around t=130 ms. As shown in the sequence of video captures, the flexible components of the HSS detached from the ATD head before the head reached its maximum forward position, while the support remained attached to the back of the CRS throughout the test.



t=60 ms t=90 ms t=110 ms t=130 ms t=150 ms

Fig. 4. Sequence of high-speed video frames showing no apparent influence of the use of the HSS on the overall motion of the ATD (P6)

Maximum head forward movement horizontal

As required by regulation ECE R44/04, the maximum forward displacement horizontal of any point on the ATD head, measured from a reference point Cr on the seat, must be smaller than 500 mm or 550 mm, depending on the type of CRS. The displacement was estimated using video analysis. The estimated maximum forward horizontal displacement and the associated time are shown in Table III. Also Table III includes the average value of the maximum displacement and of the time in which the maximum displacement was reached (and corresponding standard deviation values) within each restraint and ATD group and depending on the use of the HSS. The maximum forward ATD head excursion was always smaller than the performance criteria established by regulation ECE R44/04 shown in Table II.

The comparison between the average maximum horizontal head displacement within each restraint group showed that the HSS reduced the magnitude of the displacement in the tests in which the booster seat was used (regardless of the presence of ISOFIX). However, in the forward-facing seat group, the maximum head displacement horizontally was greater when the HSS was present. The examination of the values of the standard deviation suggests that there were not significant differences within the restraint groups, indicating that the use of the HSS did not influence significantly the maximum forward displacement of the ATD head horizontally regardless of the type of CRS used. A similar conclusion can be reached for the timing of the head displacement.

TABLE III
MAXIMUM FORWARD HEAD DISPLACEMENT HORIZONTAL

Restraint and ATD group	Test number	Maximum forward head displacement, horizontal (mm)	Time (ms)
Booster seat, P3, No HSS	496	318	134
	497	378	137
	498	364	130
	Mean (SD)	353.3 (31.4)	133.7 (3.5)
Booster seat, P3, HSS	495	384	139
	511	315	118
	512	322	129
	Mean (SD)	340.3 (38.0)	128.7 (10.5)
Booster seat (ISOFIX) , P3, No HSS	499	387	137
	500	380	127
	501	319	133
	Mean (SD)	362.0 (37.4)	132.3 (5.0)
Booster seat (ISOFIX) , P3, HSS	508	324	122
	509	352	129
	510	323	130
	Mean (SD)	333.0 (16.5)	127.0 (4.4)
Forward-facing seat, P3, No HSS	502	308	128
	503	285	126
	504	265	126
	Mean (SD)	286.0 (21.5)	126.7 (1.2)
Forward-facing seat, P3, HSS	505	280	120
	506	313	135
	507	281	117
	Mean (SD)	291.3 (18.8)	124.00 (9.6)
Booster seat (ISOFIX) , P6, No HSS	513	358	133
	514	372	127
	Mean (SD)	365.0 (9.9)	130.0 (4.2)
Booster seat (ISOFIX), P6, HSS	515	348	129
	516	339	135
	517	362	133
	Mean (SD)	355.0 (9.9)	131.0 (2.8)

Head CG displacement in the sagittal plane

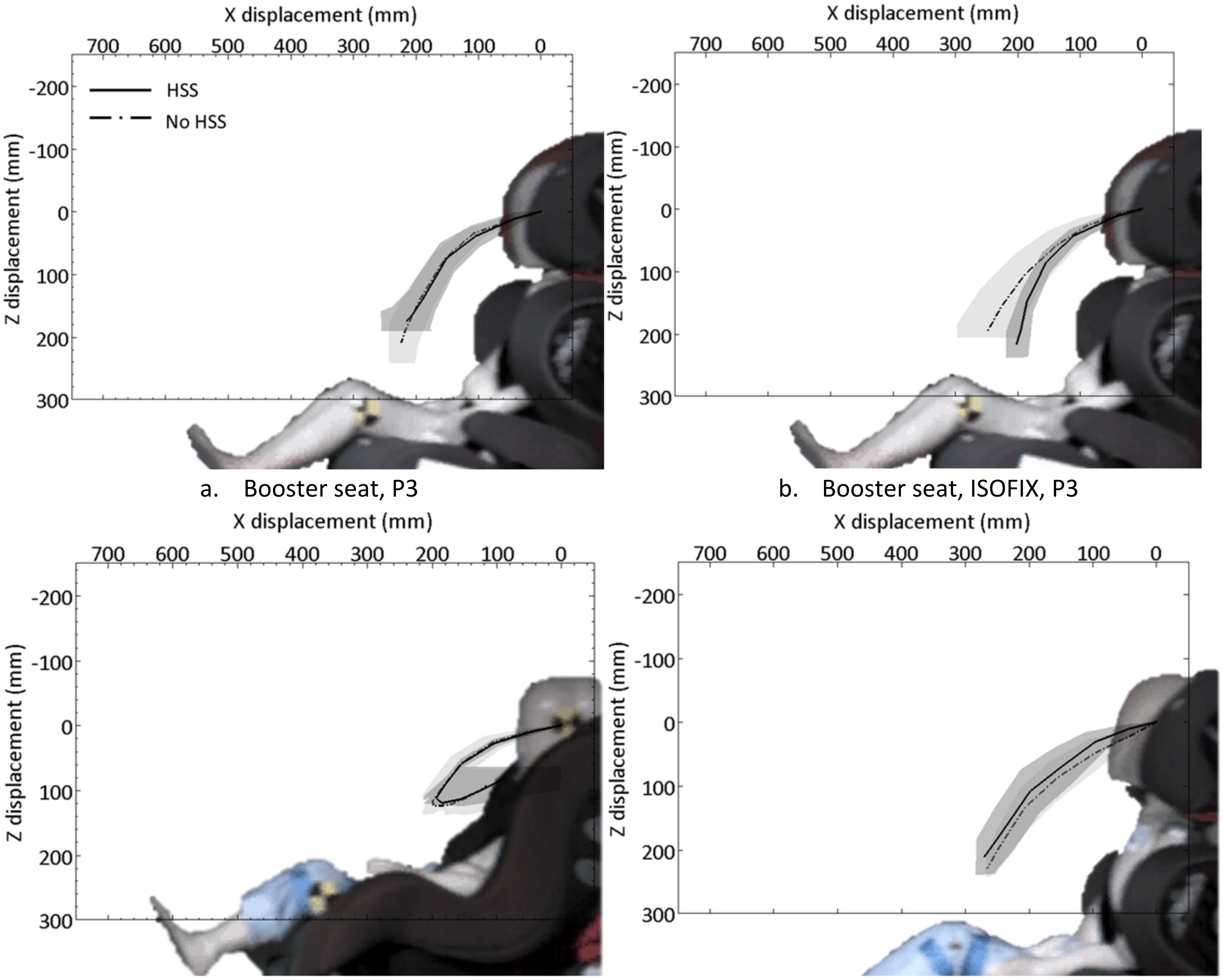
Figure 5 includes the comparison of the trajectory of the ATD head CG within each restraint group and depending on the use of the HSS to provide a qualitative assessment of the effect of the HSS on the sagittal trajectory of the head. It should be noted that unlike the data included in Table III, these trajectories were calculated always for the center of gravity of the ATD head and the reference was the initial position of the head CG.

The plots included in Fig. 5 compare the sagittal trajectory of the head CG depending on HSS use. The solid black line corresponds to the average sagittal displacement of the head CG when the HSS was used, while the dashed black line corresponds to the cases in which the HSS was not used. The dark-grey shaded region shows the area encompassed by the average response of the head CG displacement with HSS, plus/minus one standard deviation in both the X and Z axes. The light-grey shaded corridor corresponds to the no HSS cases.

The displacement of the head was tracked until the position of the head CG was obscured by a combination of the swinging of the ATD arm and a lateral flexion of the dummy torso. In any case, the maximum forward position of the head was always reached before the CG marker was obscured. The description of the rebound motion of the head could be completely obtained only in the case of the forward-facing restraint (which loaded symmetrically the torso of the dummy)

As shown in Fig. 5 and with the exception of the ISOFIX booster seat group with the P3 dummy, the use of the HSS did not influence either the nature or the magnitude of the sagittal displacement of the head CG. The average responses as well as the associated corridors in the three groups were superimposed and showed no substantial differences. In the case of the ISOFIX booster seat with the P3, the average forward displacement was shorter when the HSS was used (203 mm vs. 249 mm) and the head described a more curvilinear trajectory than the one showed by the ATD when the HSS was not used. This group was the one that had exhibited also the greatest difference in Table III.

It was also observed that the use of the HSS contributed to reduce the variability of the position of the head CG in the sagittal plane, as displayed in the narrower displacement corridors exhibited by the HSS cases shown in Fig. 5.



a. Booster seat, P3

b. Booster seat, ISOFIX, P3

c. Forward-facing seat, P3

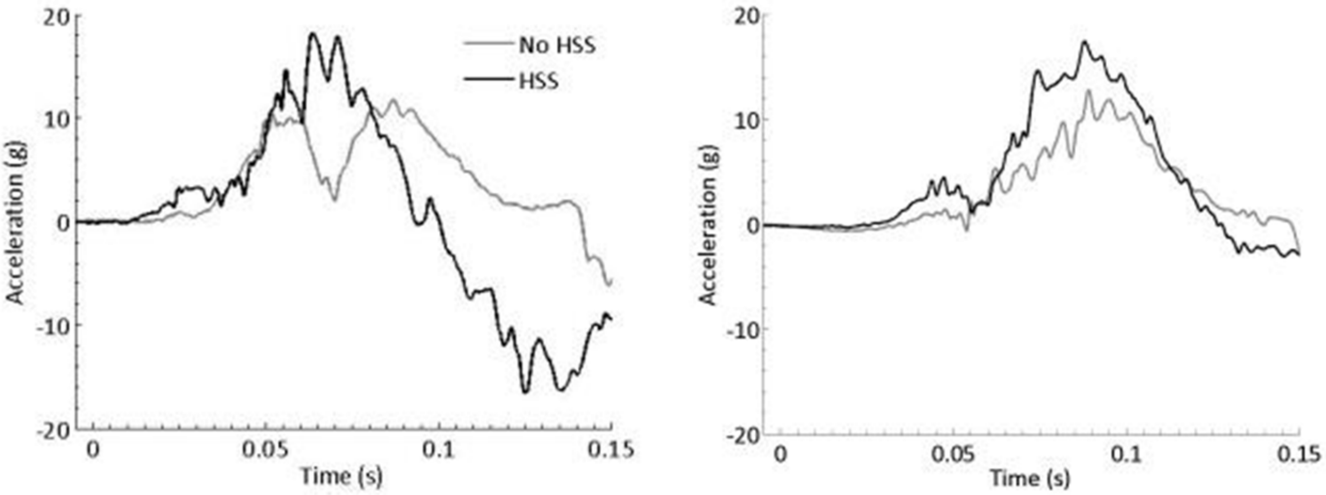
d. Booster seat, ISOFIX, P6

Fig. 5. Displacement relative to buck of the center of gravity of the head of the ATD in the sagittal plane. Average response with HSS (solid black line) and with no HSS (dashed black line). Associated displacement corridors are shown as dark grey shaded (HSS) and light grey shaded (No HSS) areas.

Head acceleration

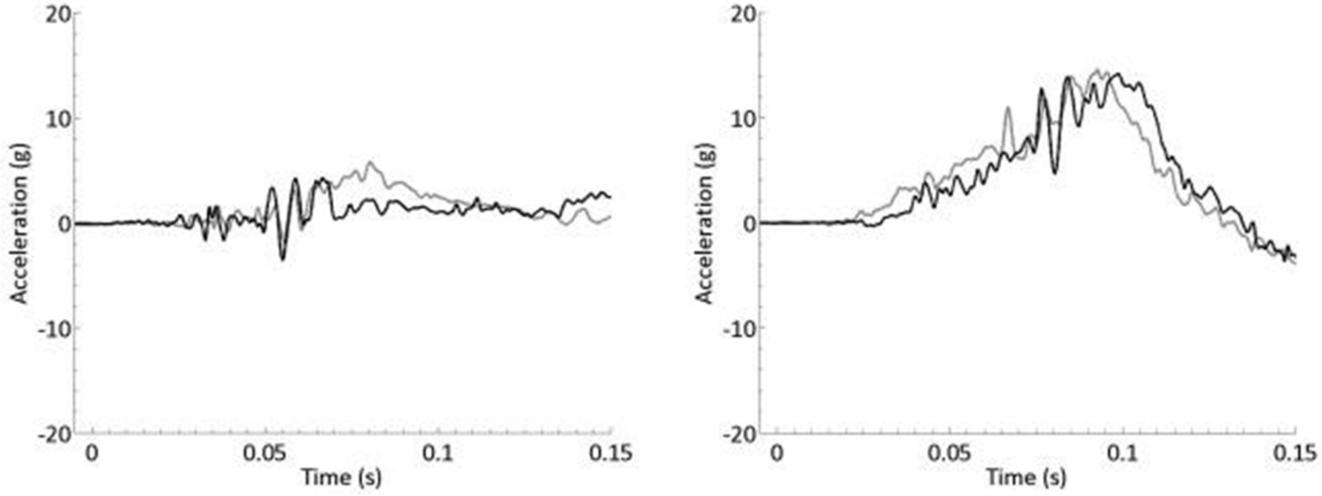
Although regulation ECE R44/04 does not limit the acceleration of the head of the ATD as one of the requirements of the CRS, it was thought that including a HSS could potentially affect the acceleration sustained by the ATD head during the impact. The plots included in Fig. 6 and Fig. 7 show the time-history traces for the average local head x and z components of the acceleration of the ATD head, per each restraint group.

The time history plots of the x component of the ATD head acceleration showed different effects of the use of the HSS on the kinematics of the head depending on the restraint used by the occupant. In the booster seat group with the P3 ATD, the peak average horizontal acceleration of the head was 18.2 g when the HSS was used and 11.7 g when there was no HSS. The use of the HSS also eliminated the bimodal time history characteristic of the acceleration measured without the HSS. A greater peak average value of the horizontal component of the head acceleration was also found in the booster seat with ISOFIX group in the case of the P3 ATD (17.4 g vs. 12.8 g). However in the remaining two groups, the peak average horizontal acceleration was greater or approximately the same when the HSS was not used (forward-facing seat: 4.1 g (HSS) vs. 5.7 g (no HSS); booster seat with ISOFIX, P6: 14.1 g (HSS) vs. 14.4 g (no HSS)). The data traces also showed that the forward-facing seat produced substantially lower head horizontal acceleration than any of the other two restraint systems (booster seat and booster seat with ISOFIX) for the same occupant size as shown in Fig. 6a, 6b and 6c.



a. Booster seat, P3

Booster seat, ISOFIX, P3

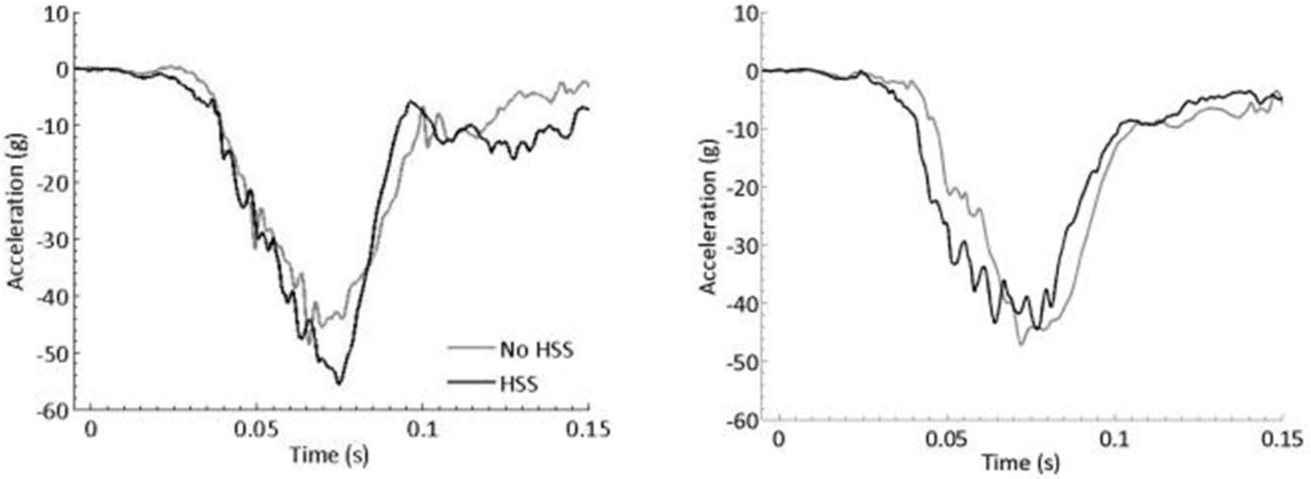


Forward-facing seat, P3

Booster seat, ISOFIX, P6

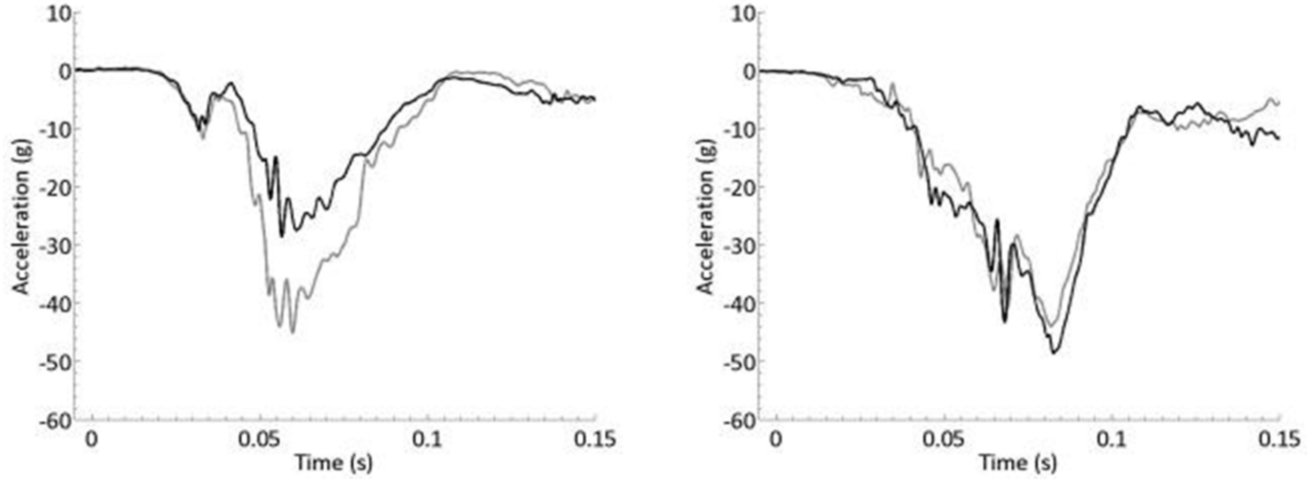
Fig. 6. Time history plots of the average horizontal component (x) of the acceleration of ATD's head center of gravity per restraint type. Gray lines indicate no use of HSS and black lines indicate use of HSS.

As for the local z component of the ATD head center of gravity acceleration, the differences between the average values associated with the use of the HSS depend also on the type of restraint use. Unlike the previous acceleration component, using the HSS did not modify the shape of the time history curves, but only introduced differences in the phasing and in the magnitude of the acceleration. The peak values of the average vertical component of the head acceleration remained practically unchanged in the booster seat with ISOFIX groups, regardless of the size of the occupant (Fig. 6b and 6d). In the booster group without ISOFIX, the peak value was higher when the HSS was used (-55.4 g (HSS) vs. -48.1 g (no HSS)) and it was substantially lower in the forward-facing seat (-28.4 g (HSS) vs. -45.1 g (no HSS)).



a. Booster seat, P3

b. Booster seat, ISOFIX, P3



c. Forward-facing seat, P3

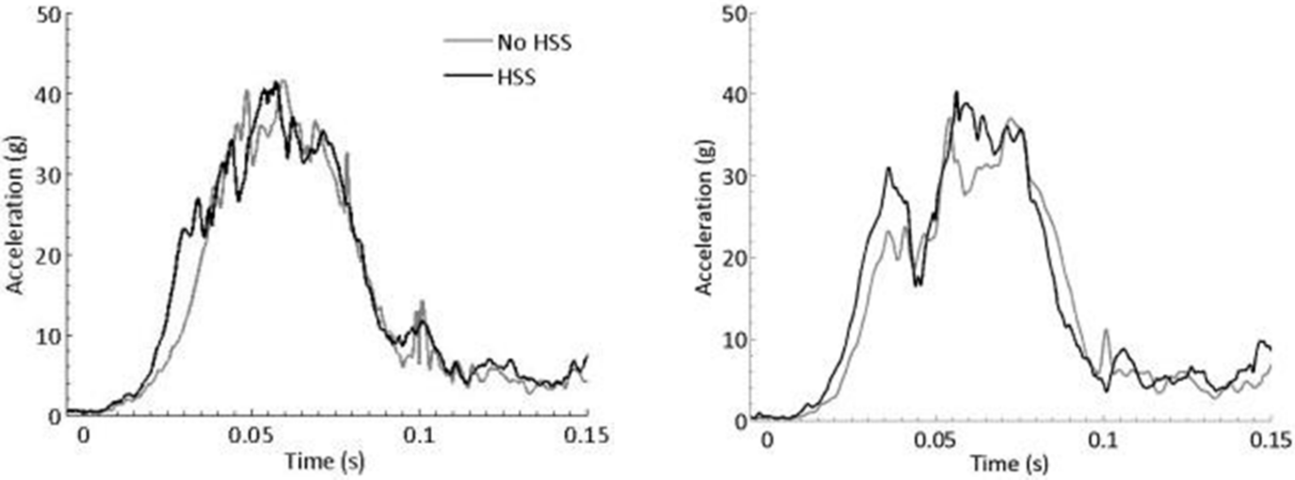
d. Booster seat, ISOFIX, P6

Fig. 7. Time history plots of the average vertical component (z) of the acceleration of ATD's head center of gravity per restraint type. Gray lines indicate no use of HSS and black lines indicate use of HSS.

Thorax acceleration

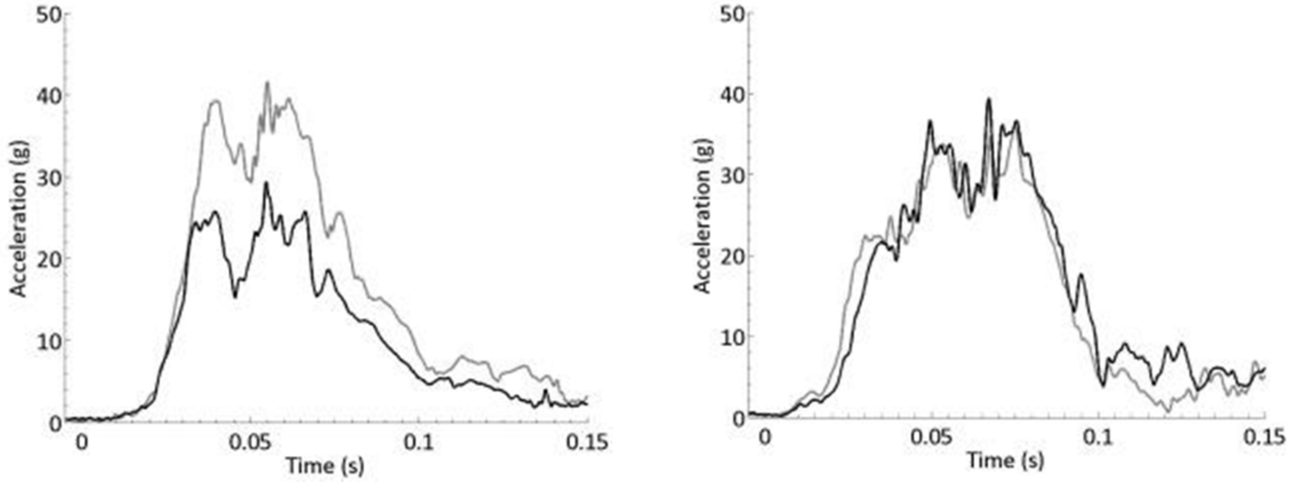
Regulation ECE R44/04 requires that the peak of the resultant thoracic acceleration measured by the ATD is smaller than 55g. As shown in Fig. 8, the average resultant thoracic acceleration within each restraint group remained always under the required maximum limit. The use of the HSS did not cause substantial changes in the magnitudes of the resultant acceleration in any of the three booster seat groups, but reduced importantly the magnitude of the thoracic acceleration in the forward-facing seat group (29.4 g (HSS) vs. 41.6 g (no HSS)). The reduction was observed not only in the peak value, but during the whole duration of the test, as shown in Fig. 8c.

As for the vertical component of the thoracic acceleration, the effect of using the HSS was also predominantly observed in the forward-facing seat. The use of the HSS in this restraint group caused a reduction of the absolute value of the most significant local minima and maxima of the average vertical component of the torso acceleration, as it can be observed in Fig. 9c.



a. Booster seat, P3

b. Booster seat, ISOFIX, P3



c. Forward-facing seat, P3

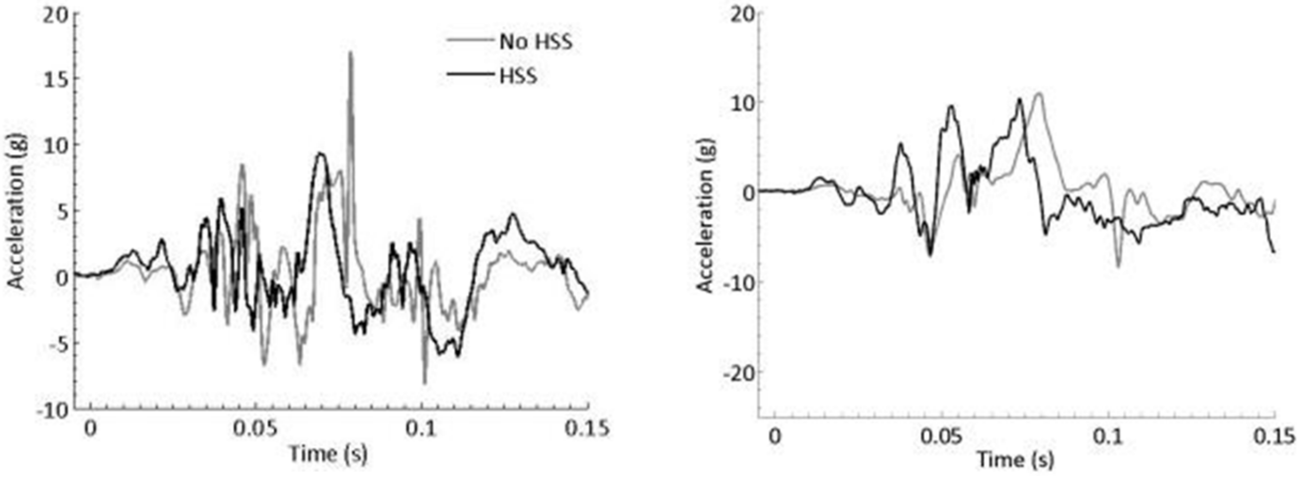
d. Booster seat, ISOFIX, P6

Fig. 8. Time history plots of the average resultant thoracic acceleration of the ATD per restraint type. Gray lines indicate no use of HSS and black lines indicate use of HSS.

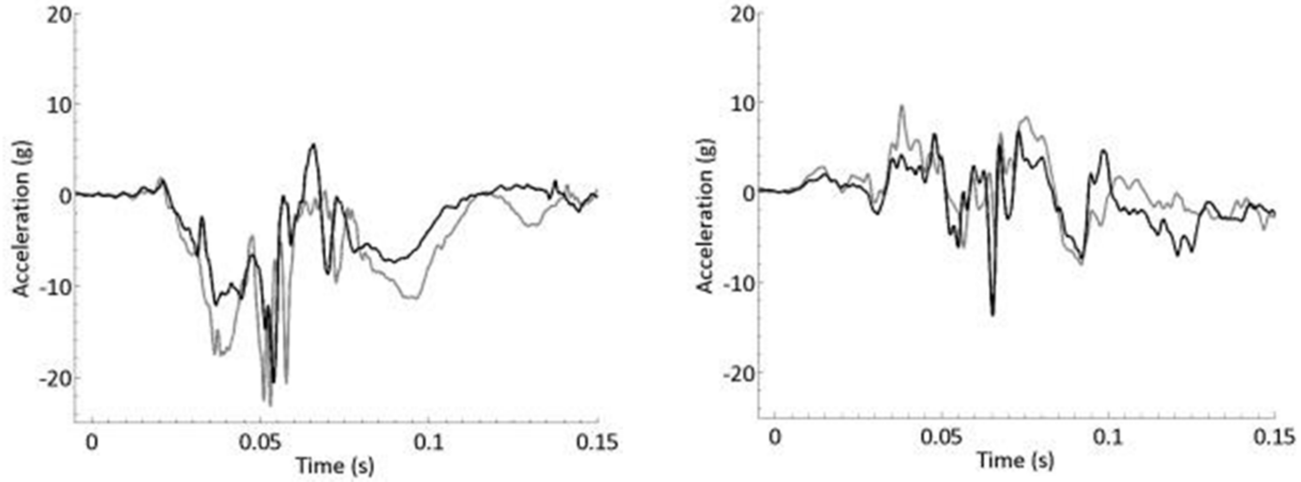
IV. DISCUSSION

This study assessed the effect of using a head support system in the sled test criteria required by regulation ECE R44/04 for CRS. A test matrix including three different restraint systems (booster seat, booster seat with ISOFIX and forward-facing seat with ISOFIX and top tether) and two ATD sizes (3-year-old, 6-year-old) was designed to assess the performance of the HSS in a variety of situations. The assessment focused on frontal impacts.

The head support system had been shown to reduce the frequency of head and torso positions that could potentially increase the risk of sustaining injuries [16,17]. An observational study including 41 adult occupants showed that the use of a previous model of the HSS contributed to reduce significantly the incidence of moderate and severe OOP events during night driving [16]. Similarly, a different observational study involving 30 pediatric volunteers using a case cross-over design had demonstrated that the use of the HSS improved significantly the lateral head position, the vertical position of the sternum and the position of the belt on the torso of the occupants [17]. This study was performed at night, and the children were susceptible to fall asleep and to adopt positions considered of high risk (such as excessive slouchy posture or reclining on the window). This circumstance also contributed to the acceptance of the use of the system, as the volunteers were asleep for most of the trials. Although both studies suggested that the use of such a system could be potentially beneficial to prevent OOP situations, the actual assessment of the system during an impact was lacking.



a. Booster seat, P3 b. Booster seat, ISOFIX, P3



c. Forward-facing seat, P3 d. Booster seat, ISOFIX, P6

Fig. 9. Time history plots of the average vertical (z) component of the ATD torso acceleration per restraint type. Gray lines indicate no use of HSS and black lines indicate use of HSS.

The results included in this paper have shown that the HSS did not influence significantly the performance of the CRS in frontal sled tests performed according to ECE R44/04, at least in the magnitudes of the criteria required by the regulation. The maximum forward head displacement horizontal measured from the reference point Cr remained well within the limit established by ECE R44/04 for each of the CRS regardless of the use of the HSS. With the exception of a slight increase in the mean value of the displacement (approximately 4 mm) in the forward-facing seat, the use of the HSS reduced the magnitude of the forward head excursion of the ATD. However, looking at the standard deviation of the parameter, it can be concluded that there were not significant differences associated to the use of the HSS. This was also true for the timing of the displacement.

The acceleration measured at the head CG and torso of the ATD showed that the use of the HSS affected differently to these magnitudes depending on the type of CRS used. Although the magnitude of some of the measured parameters increased when the HSS was used, this increment was far from resulting in a violation of the ECE R44/04 criteria.

Interestingly, the use of the HSS produced substantial reductions in the head vertical, thoracic resultant and thoracic vertical accelerations of the P3 ATD in the forward-facing seat. In this case, the CRS is attached to the test seat by the ISOFIX and the top-tether systems. This rigid attachment reduced considerably the motion of the CRS with respect to the test seat. The reduction of the vertical head and thoracic accelerations in this case suggests that the HSS contributed to hold the head and the trunk of the ATD initially during the test reducing the magnitudes of the vertical accelerations. This effect was not observed in the other CRS as they rotated with respect to the seat, dictating the motion of the head of the dummy regardless of the use of the HSS (Fig. 10).

Last, the HSS did not introduce any additional risk in the performed tests: the light-weight elastic parts (front and occiput bands and elastic vertical strip) detached from the support and the head of the occupant (Fig. 4), and the L-shaped support remained attached to the backrest of the CRS.

There were several limitations in the data analyses discussed here. As aforementioned, the geometry of the CRS and the arm swinging of the ATD during the impact made difficult to track the position of the ATD head at all times to produce the displacement plots shown in Fig. 5. In these cases, the position of the head CG was calculated using trigonometry if a reference in the dummy head could be identified or it was directly interpolated if a previous and a posterior position were known. Also, the large lateral wings of the CRS made difficult to estimate the rotation of the head of the ATD and how much it was influenced by the HSS. A qualitative analysis of the video frames in which the head was visible showed that there were not important differences in head rotation that could be attributed to the use of the system. Future assessments of the HSS should incorporate angular rate sensors in the ATD head.

The small size of the ATD (particularly the P3) and the use of high-back booster seats with large lateral head wings and of a forward-facing seat incorporating also lateral head wings prevented the use of belt tension gages without modifying substantially the geometry of the restraint. Therefore, it was decided not to measure the belt or harness tension during the tests. However, the initial tension of the restraints was set to the value indicated in the regulation to assure the same restraint conditions in all the trials.

Also, the HSS was placed always on the same position on the ATD head to isolate the effect of the use of the system. Thus, the results obtained in this study do not allow quantifying the effect on the ATD kinematics of different positioning of the system on the dummy head.

Despite these limitations, the study was able to compare how the use of the HSS influenced the assessment criteria required in the frontal impact sled test of regulation ECE R44/04. In June 2013, the newly adopted i-Size regulation will coexist with ECE R44/04 until 2018. Then, i-Size will be the mandatory regulation assessing the performance of CRS. The new regulation adds a side impact sled test to the existing frontal and rear impacts in ECE R44/04. Additional benefits included in i-Size are the use of the Q-series ATD family and the subsequent possibility of monitoring upper neck reaction forces and moments [18]. Contrary to the Q-series [19], the contemporary construction of the upper neck joint of the P-series ATD family does not provide any insight into the neck reactions that the occupants might experience during the crash. Nevertheless, high-speed video allowed comparing the overall kinematics of the ATD with focus on the potential influence of the HSS use in the motion of the head with respect to the torso. Figure 10 shows the video frames corresponding to the maximum forward position of the head for one representative test within each group. A qualitative comparison of these frames shows no substantial differences in the motion of the ATD that could be attributed to the use of the HSS. In particular, the position of the head with respect to the torso of the ATD does not seem to be affected by the use of the HSS. This is consistent with what was observed in the high-speed videos: the elastic components of the HSS detached from the head of the dummy in the early stages of the impact without causing the head to lag the displacement of the torso.

Although the current study focused only on the evaluation of the system in a frontal impact, it is recommended to assess the HSS in the case of a lateral impact in which the effect of the HSS could be more significant. Using the Q-series family also adds the benefit of obtaining measurements of the upper neck forces and moments.

To the knowledge of the authors there is no other study assessing the performance of a similar device. As aforementioned, the HSS evaluated here was not intended to work as a restraint system but to work in conjunction with the vehicle and child restraint systems preventing the occurrence of OOP events.

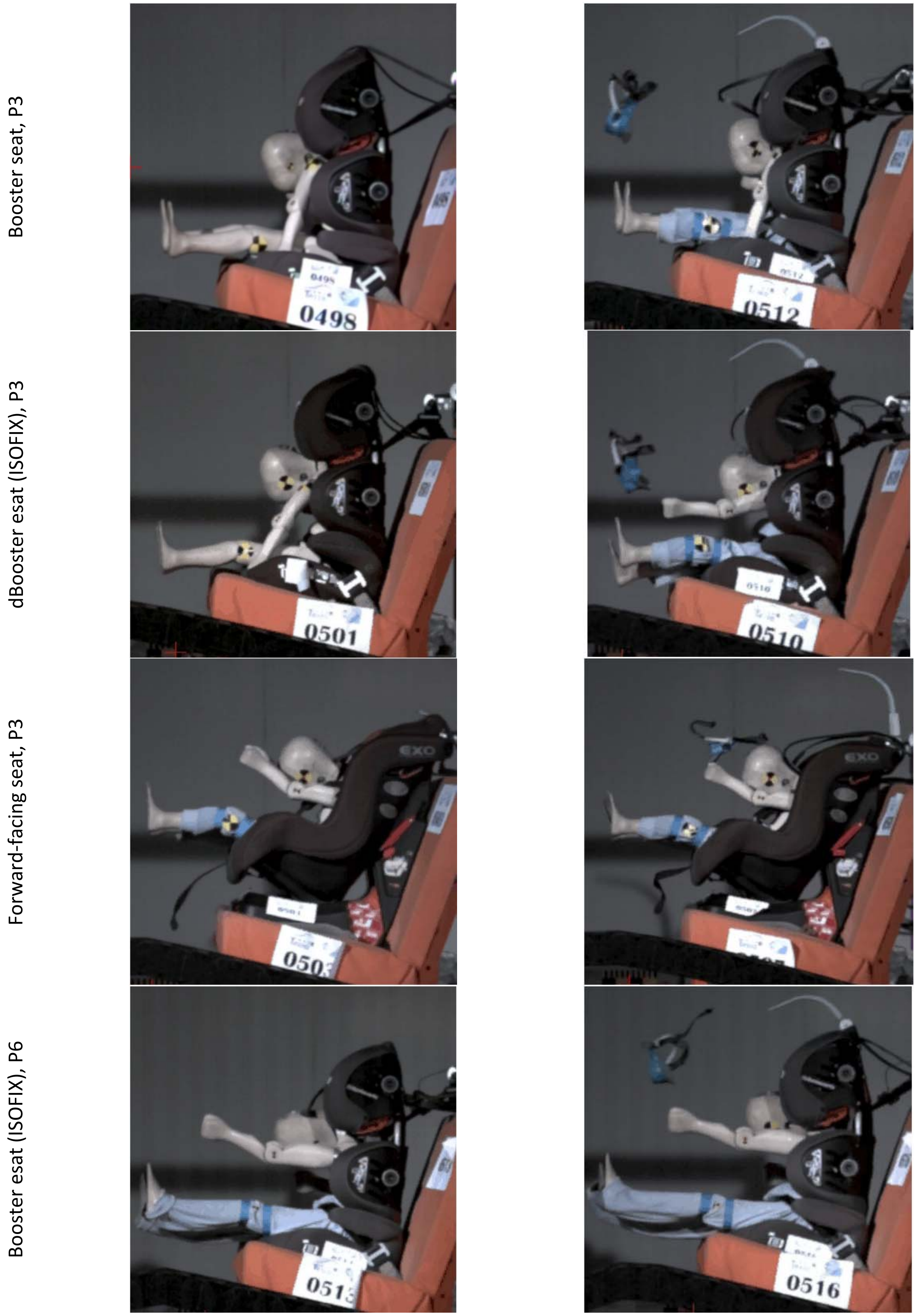


Fig. 10. Video frames comparing the overall motion of the ATD head and torso at the point of maximum forward head excursion for one representative test of each condition (right: no HSS; left: HSS).

V. CONCLUSIONS

Twenty-three crash tests with a nominal impact speed of 50 km/h were performed in a decelerator sled according to European regulation ECE R44/04, using two different sizes of dummies (P3, P6) and three different CRS: a forward-facing seat with ISOFIX and top tether, a high-back booster seat with ISOFIX and a high-booster seat. Variables analyzed were the horizontal and vertical forward head accelerations, the resultant and vertical thoracic accelerations and the displacement of the ATD head in the sagittal plane. It was found that the use of the device did not influence significantly the kinematics of the dummies. Even if the system modified slightly the trajectory of the head, it did not cause substantial changes in the magnitude of the head and chest accelerations. While further evaluation of the system in other impact directions is needed, the use of the HSS did not modify the performance of the CRS in frontal impacts when evaluated according to the ECE R44/04 regulation. Since the HSS had been shown to prevent OOP events, the use of such system can potentially contribute to decrease the incidence of restraint malfunctioning due to OOP.

VI. ACKNOWLEDGEMENT

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VIII. APPENDIX

ATD torso and head angle

Table A.I shows the magnitude of the initial torso and head angles.

TABLE A.I
ATD INITIAL POSITION: TORSO AND HEAD ANGLE

Restraint and ATD group	Test number	Torso angle (deg)	Head angle (deg)
Booster seat, P3, No HSS	496	62.5	0.6
	497	66.0	0.8
	498	67.3	0.5
Booster seat, P3, HSS	495	64.1	0.0
	511	63.2	0.6
	512	67.4	0.3
Booster seat (ISOFIX) , P3, No HSS	499	60.5	0.2
	500	65.3	0.3
	501	69.6	0.7
Booster seat (ISOFIX) , P3, HSS	508	68.3	0.5
	509	67.3	0.3
	510	61.0	0.2
Forward-facing seat, P3, No HSS	502	50.0	0.4
	503	49.6	0.3
	504	48.3	0.3
Forward-facing seat, P3, HSS	505	48.1	0.3
	506	47.5	0.3
	507	48.3	0.7
Booster seat (ISOFIX) , P6, No HSS	513	63.7	0.1
	514	50.8	0.0
Booster seat (ISOFIX), P6, HSS	515	48.3	0.3
	516	47.2	0.3
	517	51.2	0.2

Harness and shoulder belt position on the dummy

Table A.II shows the initial position of the harness and shoulder belt on the torso of the ATD prior to test, according to the legend shown in Fig. A.I. Measurements were taken laterally and inferiorly (on the ATD's medial line) from the ATD landmark corresponding approximately to the sternal notch.

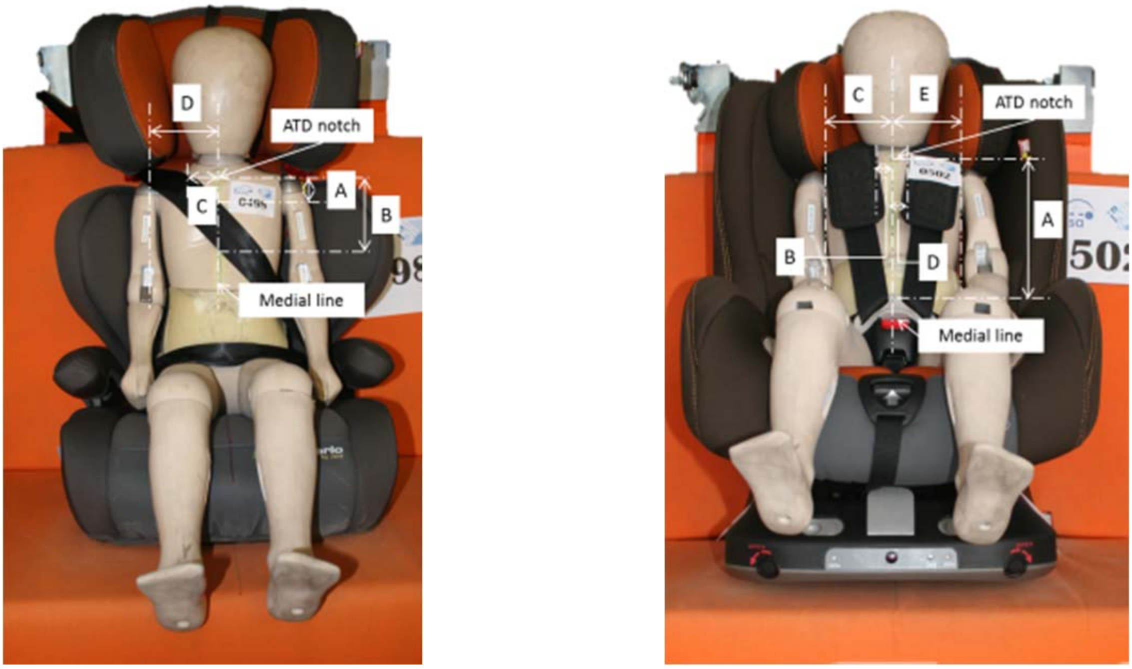

Fig. A.I. Schematic showing the positioning parameters used to place the harness/shoulder belt on the torso of the ATD.

TABLE A.II
ATD HARNESS AND SHOULDER BELT POSITION BEFORE TEST

Restraint and ATD group	Test number	A (mm)	B (mm)	C (mm)	D (mm)	E (mm)
Booster seat, P3, No HSS	496	35	103	30	88	–
	497	24	91	20	87	–
	498	31	98	26	100	–
Booster seat, P3, HSS	495	45	112	40	105	–
	511	27	88	30	110	–
	512	15	88	14	96	–
Booster seat (ISOFIX) , P3, No HSS	499	50	110	50	115	–
	500	55	120	65	130	–
	501	32	100	30	105	–
Booster seat (ISOFIX) , P3, HSS	508	25	90	25	96	–
	509	25	95	25	97	–
	510	25	95	23	97	–
Forward-facing seat, P3, No HSS	502	220	21	90	20	89
	503	234	17	86	17	82
	504	230	17	80	17	80
Forward-facing seat, P3, HSS	505	230	22	80	23	90
	506	230	25	86	30	90
	507	232	22	78	20	78
Booster seat (ISOFIX) , P6, No HSS	513	40	105	35	96	–
	514	37	108	32	105	–
Booster seat (ISOFIX), P6, HSS	515	24	100	20	85	–
	516	30	95	30	98	–
	517	30	93	30	97	–