A comparison of the performance of child restraint systems between a variant of the ECE R44 bench and a vehicle seat.

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

Abstract Contemporary research has pointed out the differences observed in the kinematics of pediatric dummies and rear-facing child restraint systems (CRS) between the regulatory bench used in FMVSS 213 and CMVSS 213 regulations and real vehicle seats. The objective of this study was to compare the performance of forward-facing CRS between a variant of the ECE R44 bench and a production seat vehicle. Two different Anthropomorphic Test Device (ATD) sizes (P3 and P6) using the same child restraint system, a non-Isofix high-back booster seat, were exposed to the ECE R44 regulatory deceleration pulse in a deceleration sled. Three repeats per ATD and mounting seat were done, resulting in a total of 12 tests. A matched-pair statistical analysis R44 bench to vehicle seat was performed. Statistically significant differences associated with the mounting seat were observed in the kinematic responses of the ATD and the CRS. A 3D motion tracking system allowed identifying differences in the sagittal, transverse and frontal trajectories of the center of gravity of the head between the ECE R44 and the vehicle seat. It was observed that the use of the high-back booster on the vehicle seat improved the resultant accelerations of the head and thorax and reduced the motion of the head CG.

Keywords Frontal impacts, ECE R44, vehicle seat, R44 bench, pediatric occupants.

I. INTRODUCTION

Head injuries are the most frequent and severe injuries among pediatric car occupants, regardless of age group, impact direction or type of restraint used [1]. Head injuries are considered responsible for approximately 33% of all child deaths [2-3], and are particularly relevant due to the difficulties associated with the treatment of head injuries during development. Pediatric head injuries have been shown to be of critical importance with regard to long-term disability, including behavior-altering outcomes with reduction of academic achievement, increased family strain and quality of life comparable to pediatric oncology patients. These consequences can be found to exist for years after the incident [4-9].

Head injuries are often associated with the direct contact of the head with any of the interior components of the car [10-11]. Strategies to prevent these injuries include the limitation of the excursion of the head, the reduction of the speed of the head in case of contact and attenuation of the loads to the head during the impact. Existing standards to assess the performance of child restraint systems (CRS) recognize the importance of reducing the likelihood of head impacts. Both in Europe and North America, regulations (ECE R44, FMVSS 213, CMVSS 213) limit the maximum head displacement of the ATD in an effort to minimize the risk of head injury. Despite the prevention efforts present in these regulations, the motion of the head of real pediatric occupants is different from the one described in the crash tests included in the standards, even when the children are using an appropriate CRS. There is a growing body of evidence showing the existing biomechanical differences between pediatric ATD and real pediatric occupants [12-15]. The lack of biofidelity of pediatric dummies constitutes another barrier to translate into the real world the expected benefits of the standards. In addition, several naturalistic studies have shown that children often incur out-of-position situations even when they are restrained in the proper child restraint system [16-18].

In an effort to understand better the problem of real world pediatric head injuries despite the prevention countermeasures included in regulations, a recent study found substantial differences between rear-facing CRS depending on whether the CRS was installed on the CMVSS 213 regulation bench or on an actual vehicle seat [19]. Authors advised that further research was needed before generalizable conclusions could be drawn. Thus,

O. J. Lorente is a BEng at TESSA-I3A, University of Zaragoza (Ph: +34 976 762 611; Fax: +34 976 762043; ojuste@unizar.es). Dr. Alba is Prof. of Automobile technologies in the Mechanical Engineering Department and Director of the crash laboratory TESSA-I3A of the University of Zaragoza. F. J. Lopez-Valdes, PhD, is a Marie Curie fellow at TESSA-I3A, University of Zaragoza.

the goal of this study is to quantify the kinematic differences - if any - between the performance of a high-back booster seat installed on the ECE R44 test bench and on a real vehicle seat. As the current study just looked at one specific vehicle seat and one CRS, it was decided to choose the configuration in which the CRS was more loosely attached to the vehicle seat, which was considered to be a worst-case scenario for properly restrained pediatric occupants. The research hypothesis is that the stiffness of the seat cushion, the different belt geometry and the initial pretension of the belt used in regulation ECE R44 cause differences in the displacement of the head.

II. METHODS

Test Matrix

The test matrix consisted of 12 sled tests using the basic structure of the ECE R44 bench and the rear seat of a typical small-size car (Seat Ibiza). Two different dummy sizes were used to represent a 3-year-old occupant (P3) and a 6-year-old occupant (P6). ATDs were restrained by the same high-back booster seat and by a three-point seatbelt. The used CRS was the recommended one for both dummy sizes. Three repeats were done per each condition. Table I summarizes the test conditions and the associated test numbers.

TABLE I
TEST MATRIX

Bench	ATD	Test numbers
R44 bench	P3	908 909 910
R44 bench	P6	905 906 907
Vehicle seat	P3	911 912 913
Vehicle seat	P6	914 915 916

Vehicle and High-Back Booster seat description

The rear seat of a Seat Ibiza, one of the best selling small-car vehicles existing in Spain, was used as the real-world vehicle seat. The CRS used was a universal child restraint system (not fitted with ISOFIX) certified under ECE R44 and valid for mass groups I (9 to 18 kg), II (15 to 25 kg) and III (22 to 36 kg). Due to the use of the 3D motion capture system and to maximize visual access to the occupant, it was decided to use a system with small side wings to facilitate viewing of the cameras. The DS07 system of the manufacturer BABYAUTO fulfilled these requirements and was selected to be the one used in the study. The high-back booster allowed adapting the three-point belt restraint to the anthropometry of the pediatric surrogates.

Test Set-up

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.

The ECE R44 test bench consists of a rigid seat and a deformable cushion. A conventional three-point seatbelt (no retractor, non force-limited, non pre-tensioned) was used to restrain the occupants in the high-back booster seats. The lower inner anchor of the lap belt was located 80 mm ahead of the position indicated in regulation ECE R44. The belt was replaced after each test.

The Seat Ibiza buck was constructed to preserve the seat characteristics and structural integrity of the rear bench seat. Front seats were removed to facilitate viewing of the cameras. The commercially available three-point rear seatbelt of the Seat Ibiza (non force-limited, non pre-tensioned) was used to restrain the occupants in the high-back booster seats. The seatbelt and the belt retractor were replaced after each test, while the seat cushion was replaced after every other test.

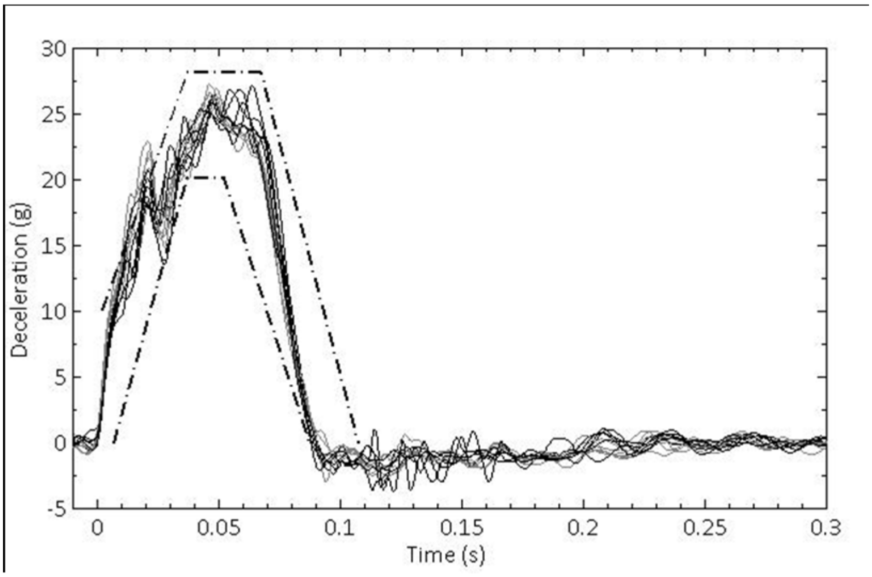


Fig. 1. Time-history plot of the deceleration of the test buck. All tests fell within the corridor required by regulation ECE R44/04. Solid black lines show the results obtained with R44 bench and solid grey lines the ones obtained with the vehicle seat.

Three-axial accelerometers and three-axial angular rate sensors were used to measure the linear acceleration and the rotational speed of the center of gravity of the head. Three-axial acceleration was also measured at the thorax of the Anthropomorphic Test Devices (ATD). Data were acquired at 10 kHz. The components of the accelerometers and angular rate sensors were obtained in a local coordinate system that moved synchronously with the ATD head and torso, oriented according to the SAE recommendations [20]. Thorax and head acceleration data were filtered using a low-pass CFC-180 filter and head rotational speed was filtered using a CFC-600 filter. An additional accelerometer measured the deceleration of the sled and a seat belt sensor measured the tension of the belt between the D-ring and the CRS (R44 bench) or the belt retractor and the CRS (vehicle seat). Both readings were filtered using a CFC-60.

High-speed video was captured at 1000 fps using a high-speed video camera (WEINBERGER SpeedCam Visario G2 camera systems). The view included a close up of the left side of the child restraint to capture forward excursion in the sagittal plane of the occupant.

Kinematic data were collected at 1000 Hz using an optoelectric stereophotogrammetric system consisting of 10 cameras (Vicon, TS series, Oxford, UK). The system captured the position of retro-reflective spherical markers within a calibrated 3D volume. A calibration procedure, performed prior to testing, estimated the optical characteristics of each camera and established its position and orientation in a reference coordinate system. The trajectory of each marker was recorded and smoothed through a rigidity constraint using the least squares pose (LSP) estimator [21-24]. A global coordinate system (GCS) was defined at a laboratory fixed location. A local coordinate system (LCS) moving with the test buck was defined at the mid point of the front edge of the buck. Local X axis pointed forward in the direction of the motion of the buck, the vertical Z axis pointed downwards (towards the ground) and the Y axis was defined to form a right-hand oriented coordinate system. Unless otherwise indicated, displacement data are expressed with respect to this LCS. A photogrammetric algorithm within the Vicon Nexus software package (Nexus 1.8.5, Vicon, Oxford, UK) reconstructed the 3D position of each target for each video sample increment from the multiple 2D camera images.

Reflective markers were attached to relevant ATD landmarks, belt webbing, booster seat, R44 bench and Ibiza seat. Table II summarizes the locations of these markers, shown in Fig. 2.

TABLE II
SEGMENTS CONSIDERED

Segment	Nº Markers
Head	3
Thorax	3
Arms and forearms	6
Thighs and legs	6
High back booster	6
R44 bench or Vehicle seat	6
Shoulder belt	3
D-ring seat belt	1
Trolley or Seat Ibiza Buck	4

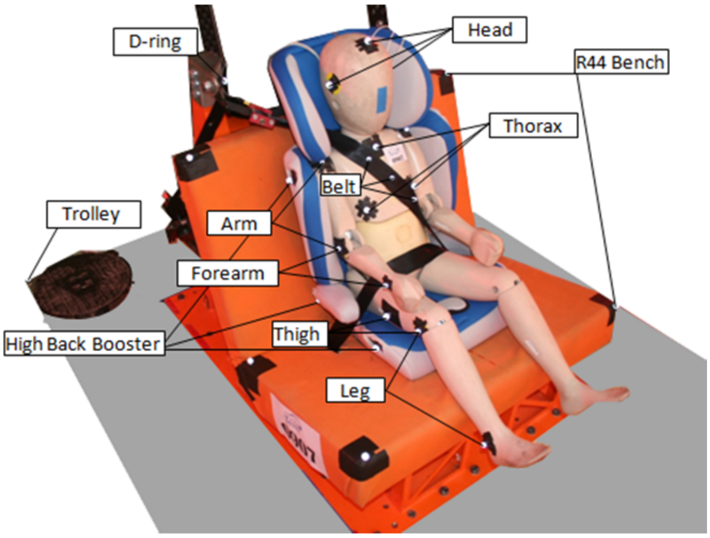


Fig. 2. Position of the VICON markers..

ATD Positioning and Belt Geometry

The high-back booster was positioned centered on the R44 bench and on the right side of the rear seat of the vehicle. ATDs were positioned centered in the high-back booster. The torso angle was adjusted so that the back of the dummy was initially in contact with the backrest of the booster. Table A.I in the Appendix shows the measurement of the torso and head angle in each of the tests. Head angle was also measured prior to the test and set to 0 degrees (nominally).

To ensure a repeatable position of 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 regulation sets the level of pretest belt tension to 50 N to ensure repeatability between tests. In the case of the vehicle seat, the belt was tensed on the torso and over the lap of the occupant to remove any possible slack.

Data Analysis

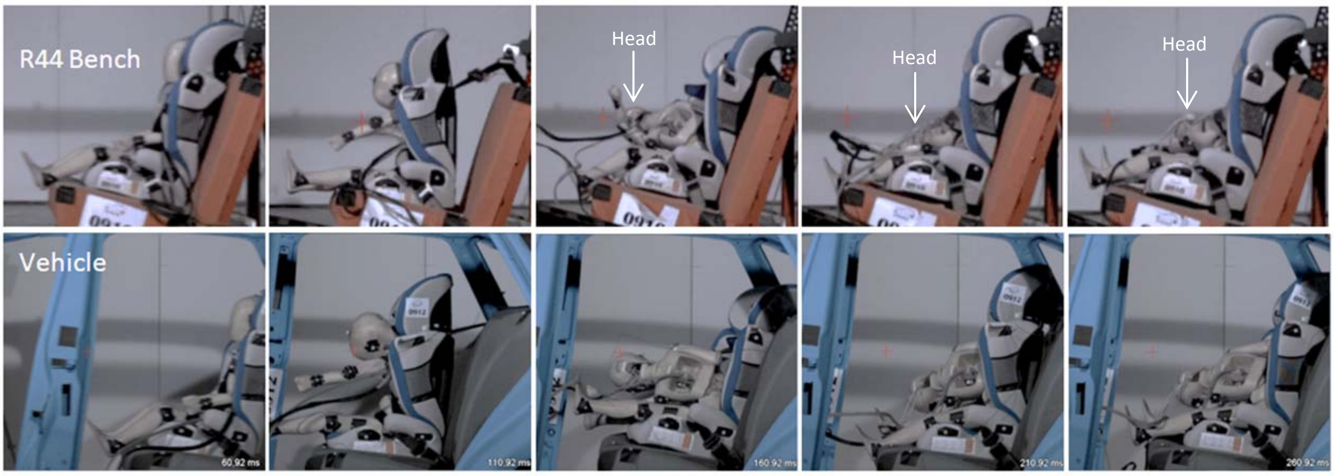
This study focused on the influence of the test bench of regulation ECE R44/04 and a vehicle seat on the response of a pediatric occupant in a frontal impact. Parameters included in the comparison were head and chest acceleration, head rotational speed in the sagittal plane, belt force, maximum head displacement in the sagittal and transverse planes of the occupant, and forward excursion and lateral inclination of the high-back booster. The statistical significance of the outcomes was assessed using matched-pair parametric statistical methods. The Anderson-Darling normality test, Ryan-Joiner normality test (similar to Shapiro-Wilk normality test) and Kolmogorov-Smirnov normality test confirmed that test results can be assumed to belong to a normal population with a significance level $\alpha = 0.05$. Thus, T-test parametric analyses were used in the comparison. Statistical analyses were performed using the statistical software package Minitab® 17.

In addition to the aforementioned parameters, the time history of the displacement of the CG of the head was included to analyze the trajectory of the head throughout the duration of the deceleration phase.

III. RESULTS

High-Speed Video of R44 Bench to Vehicle Seat Comparison

Differences were observed between the motion of the ATD on the R44 bench and the vehicle seat. Figure 3 shows lateral frame images illustrating the kinematics of the P3 dummy at different times during the impact. The head of the ATD in the ECE R44 bench lagged behind the ATD`s head in the vehicle seat (t=110 ms). At t=160 ms, the torso of the ATD in the R44 bench rotated more around the global X axis than the torso of the ATD in the vehicle seat, resulting in a final position in which the dummy ended up completely bent, with the head resting on the upper thighs (t=260 ms).



t=60 ms t=110 ms t=160 ms t=210 ms t=260 ms

Fig. 3. Sequence of high-speed video frames showing influence of the seat on the overall motion of the P3.

Figure 4 presents lateral frame images that show the kinematics of the P6 dummy at different times during the impact to illustrate how the dummy moved in the R44 bench and in the vehicle seat. The comparison of the high-speed video captures showed kinematic differences between the two seats. Specifically, there was an upward motion of the legs as a consequence of an increased pelvic rotation in the case of the vehicle seat. These kinematics of the pelvis suggested submarining of the P6 dummy during the impact.

t=60 ms t=110 ms t=160 ms t=210 ms t=260 ms

Fig. 4. Sequence of high-speed video frames showing influence of the seat on the overall motion of the P6.

Data Statistical Analysis

Statistical results from the matched-pair analyses are presented in Table A.III. Two of the eight variables evaluated for the P3 ATD resulted in statistically significant differences between the R44 bench and the vehicle seat. These variables were the maximum 3 ms peak of the resultant head acceleration (54.5 ± 1.9 g in the R44 bench vs 44.2 ± 0.5 g in the vehicle seat; p value = 0.012) and the peak belt force that was higher on the R44 bench than on the vehicle seat (5488 ± 198 N vs 4160.6 ± 63.6 N; p-value = 0.008). The maximum 3 ms peak of resultant chest acceleration did not achieve statistical significance (52.6 ± 5.2 g on the R44 bench vs 44.2 ± 0.9 g on the vehicle seat).

The tests with the P6 ATD resulted in statistically significant differences in five out of the eight compared variables. Maximum 3 ms peak of resultant thorax acceleration was 51.2 ± 2.1 g on the R44 bench vs 43.6 ± 1.4 g on the vehicle seat (p-value = 0.013). Maximum 3 ms peak of vertical component thorax acceleration was 8.5 ± 1 g vs 15.6 ± 1.8 g, smaller on the R44 bench than on the vehicle seat (p-value = 0.009). Maximum 3 ms peak of resultant head acceleration was 56 ± 0.8 g vs 51.7 ± 1.2 g, higher on the R44 bench than on the vehicle seat (p-value = 0.015). The belt force was 7014.0 ± 271.0 N on the R44 bench vs 5719.3 ± 37.4 N on the vehicle seat (p-value = 0.015). In addition to the occupant parameters, the high-back booster lateral inclination (i.e. rotation around the global X axis) was 13.3 ± 1.3 deg on the R44 bench vs 9.0 ± 0.4 deg on the vehicle seat (p-value = 0.036).

Anthropomorphic Test Device time history responses

The comparison of the time history plots of the resultant thorax acceleration of the ATDs (Fig. 5.) did not show important differences associated with the use of the R44 bench and the vehicle seat.

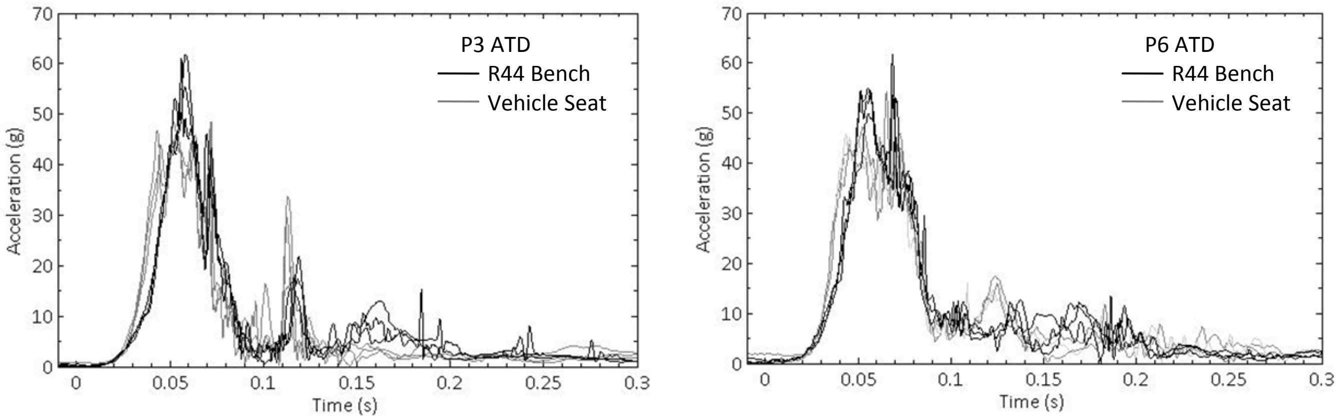


Fig. 5. Resultant thorax acceleration of P3 ATD (left) and P6 ATD (right). Black solid lines correspond to R44 bench tests and grey solid lines to vehicle seat.

Figure 6 presents the time history plots of the vertical thorax acceleration of the ATDs, another of the parameters included in the ECE R44 regulation. As in the previous case, there were not relevant differences in the case of the P3 ATD. In the P6 ATD tests, peak acceleration was significantly higher on the vehicle seat than on the ECE R44 bench, as mentioned above.

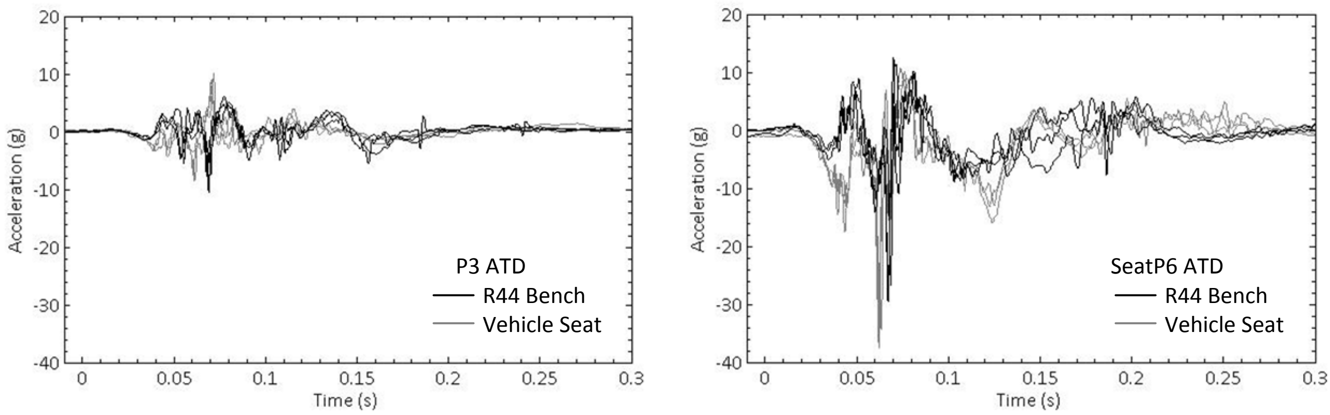


Fig. 6. Vertical thorax acceleration of P3 ATD (left) and P6 ATD (right). Black solid lines correspond to R44 bench tests and grey solid lines to vehicle seat.

The resultant head acceleration of the ATDs (Fig. 7.) did not show important differences related to the use of the R44 bench or the vehicle seat. For the two sizes of ATDs, the acceleration values of the vehicle seat tests were slightly lower.

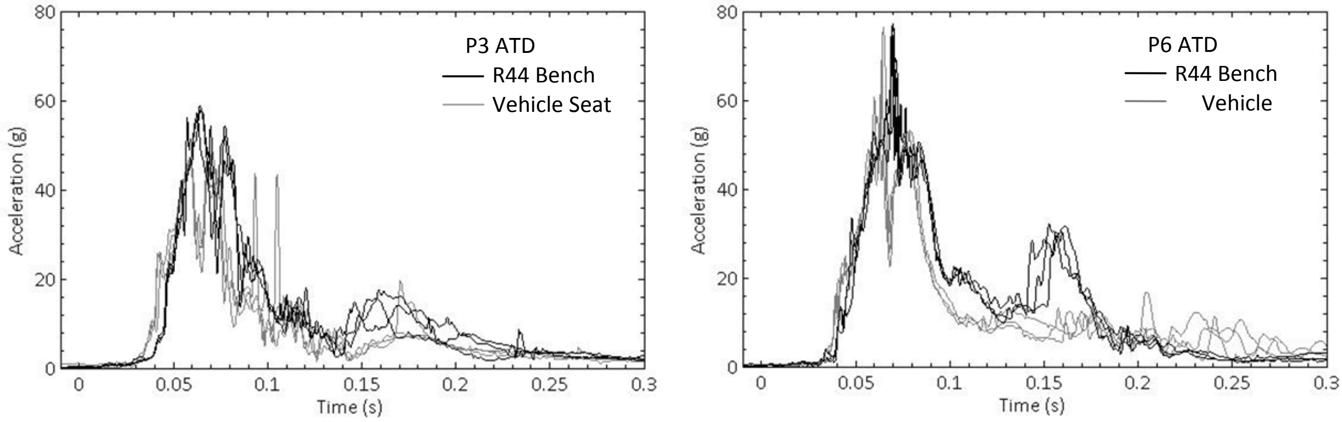


Fig. 7. Resultant head acceleration of P3 ATD (left) and P6 ATD (right). Black solid lines correspond to R44 bench tests and grey solid lines to vehicle seat.

Fig. 8 shows the rotational speed of the ATD's head in the sagittal (XZ plane). Peak rotation magnitude was slightly greater on the R44 bench, despite the maximum peaks of rotation speed of the ATD's head occurred first on the vehicle seat as it had been indicated in Fig. 3 and Fig. 4.

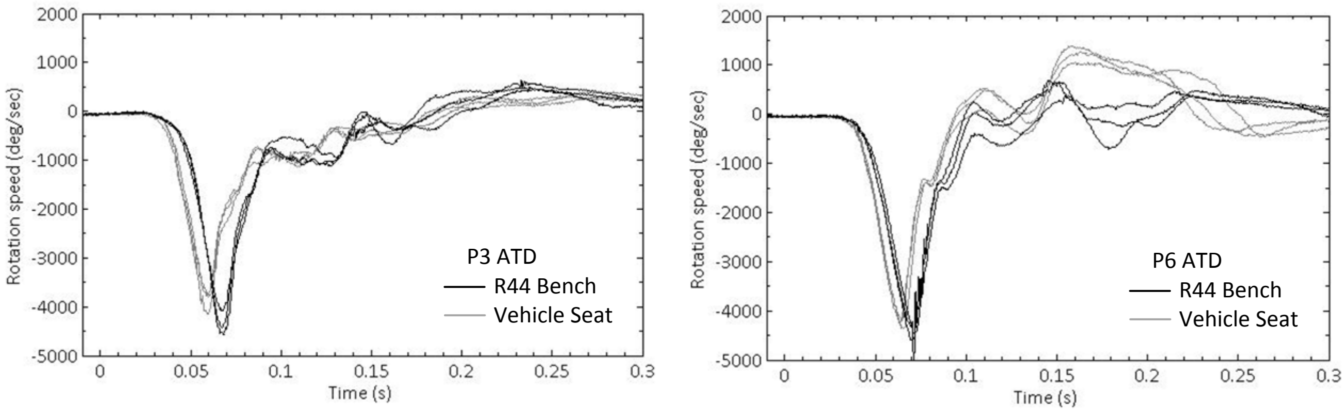


Fig. 8. Sagittal plane rotational speed of the head of P3 ATD (left) and P6 ATD (right). Black solid lines correspond to R44 bench tests and grey solid lines to vehicle seat.

The time history plots of the shoulder belt force (Fig. 9.) showed important differences between the use of the R44 bench and the vehicle seat. As stated in the previous section, belt forces were greater on the R44 bench regardless of the ATD size. Interestingly, the ATD began to load the belt earlier when the CRS was mounted on the vehicle seat.

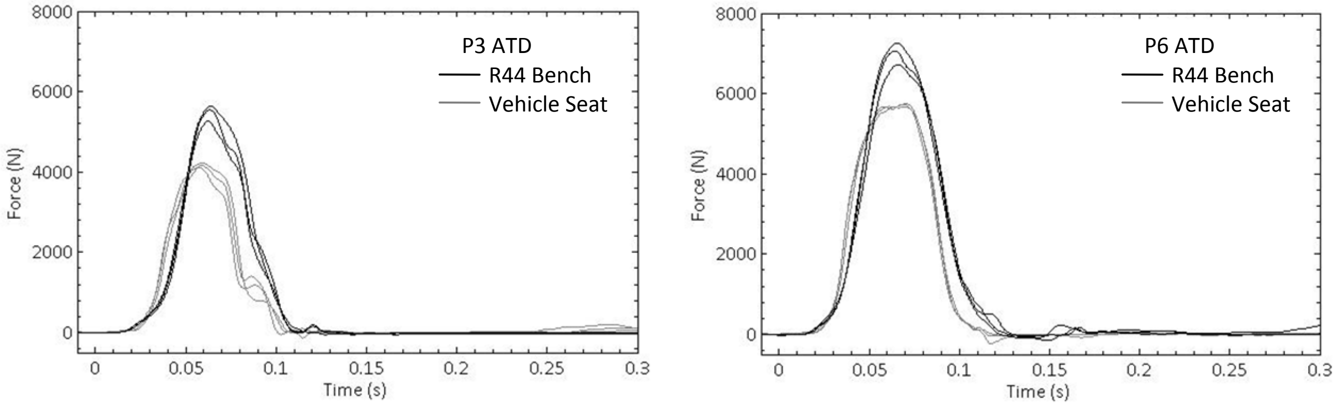


Fig. 9. Shoulder belt forces measured with the P3 ATD (left) and the P6 ATD (right). Black solid lines correspond to R44 bench tests and grey solid lines to vehicle seat.

Head CG Displacement

Fig. 10 and Fig. 11 show the comparison of the trajectory of the ATD head CG between the R44 bench and the vehicle seat tests. The black solid lines correspond to the R44 bench tests and the grey solid lines to the vehicle tests. The upper left corner plots the sagittal displacement of the ATD head CG, the upper right corner plots the coronal displacement, and the lower left corner plots the transverse displacement. The lower right corner shows the coordinate systems for seated postures according to SAE J211 [20]. Displacements are reported with respect to the local coordinate system shown in Fig. 10 that was fixed to the test fixture.

The head CG of the P3 ATD did not show differences in the sagittal plane motion, but in the coronal and transverse planes the head CG displacement was lower in the Y axis when the ATD was on the vehicle seat.

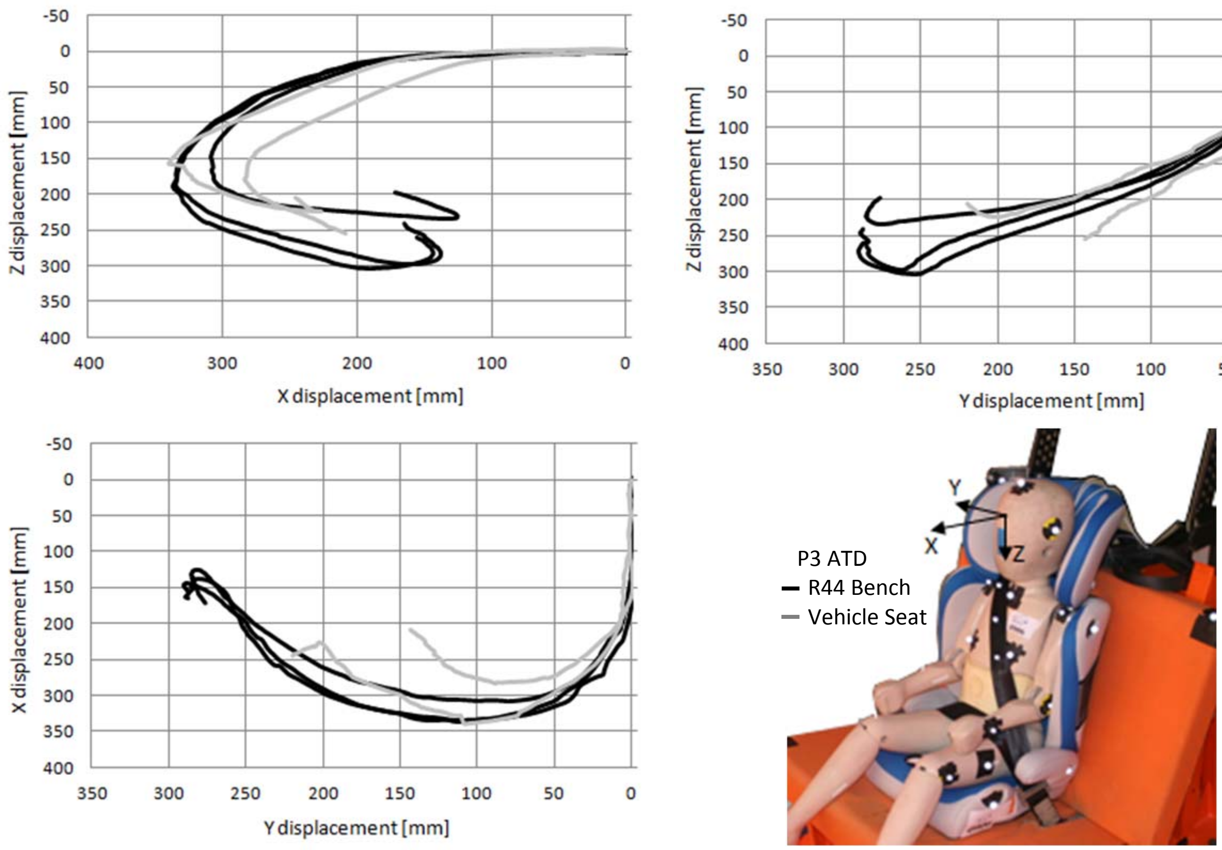
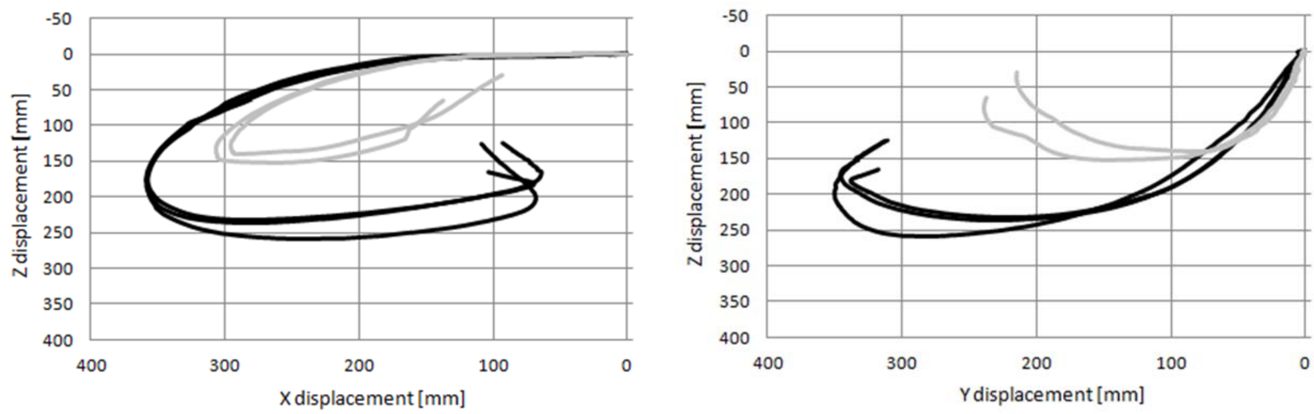
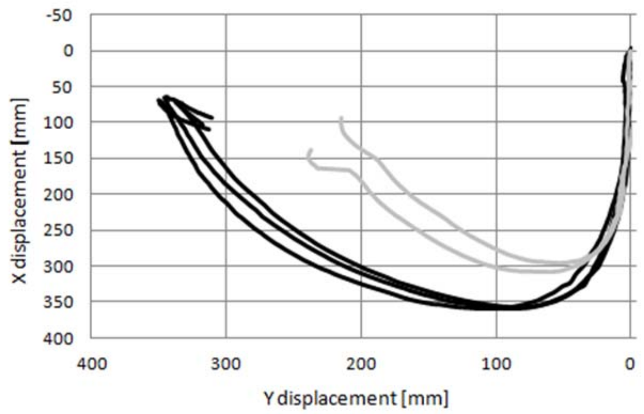


Fig. 10. Head CG displacement of the P3 ATD. Black on R44 bench and grey on vehicle seat.

The trajectories of the head CG of the P6 ATD showed differences in the three coordinate planes, resulting always in a shorter displacement when the CRS was installed on the vehicle seat.





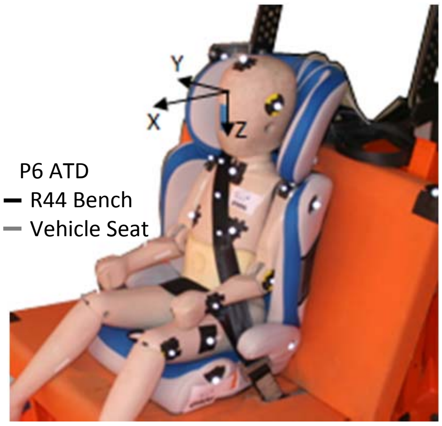


Fig. 11. Head CG displacement of the P6 ATD. Black on R44 bench and grey on vehicle seat.

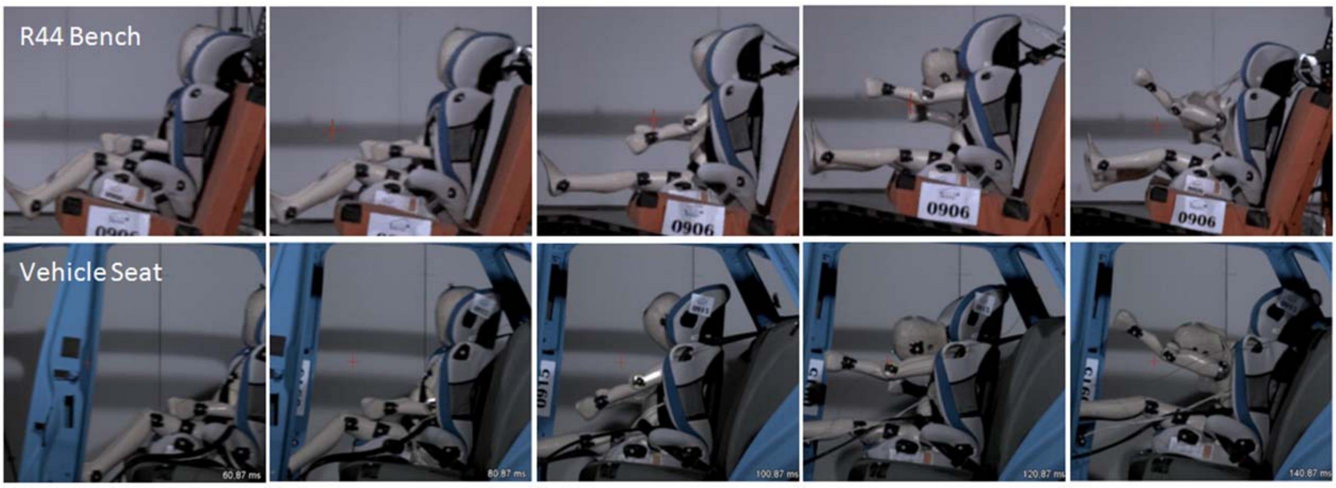
IV. DISCUSSION

This study compared the ATD responses and the motion of the child restraint system installed on a variant of the R44 bench and on the seat of a popular vehicle model in Spain. A test matrix including two ATD sizes (3 year old, 6 year old) and one child restraint system allowing the use of a 3D motion capture system was designed to quantify these differences. The assessment focused on frontal impacts.

A recently published study found substantial differences between rear-facing CRS depending on whether the CRS was installed on the CMVSS 213 regulation bench or on an actual vehicle seat [19]. Although further research was needed before generalizable conclusions could be drawn, rear-facing CRS showed improved performance when it was installed on the CMVSS 213 regulatory bench. This conclusion was not found in the current study.

In terms of the general kinematics, the selected high-speed video frames included in Fig. 4 had shown differences in the P6 ATD motion, although these differences occurred mainly during the rebound in which accelerations are lower than during the initial phases of the impact. Figure 12 shows a more detailed sequence of frames during the restraining phase of the P6 ATD. Other than the earlier head rotational motion observed in the vehicle seat, 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 R44 bench or vehicle seat.

As for the indications of submarining observed in these dummy tests when they were performed in the vehicle seat, it is interesting to highlight that the existence of potential submarining resulted also in a shorter head excursion in the three local coordinate planes. Similar findings for other types of occupants had been already reported in the literature [25-26]. We are not advocating here to induce submarining so that head excursion might be reduced, but we suggest that it is important to consider this trade-off to understand the kinematics of occupants.



t=60 ms t=80 ms t=100 ms t=120 ms t=140 ms

Fig. 12. Detailed sequence of high-speed video frames showing influence of the seat on the overall motion of the P6 ATD during the loading phase.

As for the dummy readings, the resultant head and thorax accelerations were lower in the vehicle seat tests due to the lower values of shoulder belt tension obtained with both ATD sizes. On the contrary, the vertical component of the thorax acceleration was 82.1% greater in the case of using a vehicle seat with P6 ATD, although it was still lower than the ECE R44 limit. The difference observed in the timing of the head rotation is related to the earlier interaction of the torso of the occupant with the belt. The P3 ATD started to load the seatbelt about 10 ms earlier on the vehicle seat and the P6 ATD loaded the belt 5 ms earlier on the same seat.

Although regulations do not limit the forward excursion or lateral inclination of the Child Restraint System under assessment, it is clear that the motion of the CRS determines substantially the kinematics of the occupant. Therefore, the probability of occupant interaction with the back of the occupant front seat or the structures of the vehicle body shell decreases with less CRS motion [10-11]. Statistically significant differences were not found for the forward excursion and lateral inclination of the CRS in the P3 case, but there was an estimated difference of 35.2 mm for the forward excursion of the CRS. As for the P6 case, the non-statistically significant difference was limited to 18.6 mm. Namely, the forward excursion of the high back booster was reduced 30.6% with the P6 ATD and 61.3% with the P3 ATD when the vehicle seat was used. On the contrary, the lateral CRS inclination was significantly smaller on the vehicle seat in the case of the P6 ATD. This might be related to the stiffness of the cushion of the R44 bench seat in comparison to that of a regular vehicle. As the geometry of the belt anchors likely influenced the kinematics of the CRS, it is relevant to mention that the position of the inboard belt anchor used in the tests with the ECE R44 did not match the one required by the regulation. This anchor was moved 80 mm forward from the required regulation position, still showing a good belt geometry on the lap of the dummy. As mentioned earlier, although the statistical comparison between the forward displacement of the booster with respect to the vehicle seat did not show significant differences, the lateral inclination of the CRS was significantly different between the two configurations in the case of the P6. The influence of the ECE R44 anchor position in the comparison should be further assessed in future studies. It is clear that an optimized geometry of the belt anchors will benefit the kinematics of the CRS and consequently the kinematics of the occupant. In relation to the improved performance of the CRS in a real vehicle geometry, it is relevant to point out the potential benefit of including advanced restraint systems in the rear seat. The benefits of these systems incorporating pre-tensioners and load limiters have been discussed in other studies [27-30]. Of course, it would be necessary to tailor these restraints to the particularities of pediatric occupants, optimizing the system performance to avoid increasing risk of head contact due to low load limiters. As this research was a pilot case to identify similarities and differences between the ECE R44 bench and real vehicles, all these questions will be addressed in future developments of the study.

The 3D motion capture of the trajectory of the head CG allowed analyzing the different kinematics of the ATD head during frontal impacts. The P3 ATD is the smaller ATD size allowed to travel using a CRS and restrained by a three-point belt without harness. The behavior of the occupant's head was not different in the sagittal plane between the two seats, but it was found that the lateral displacement (Y axis) of the head CG was lower on the vehicle seat. This behavior was likely related to the lateral inclination of the high-back booster that was lower on the vehicle seat. In the case of the P6 ATD tests, the motion of the head CG was smaller in all directions when the ATD was on the vehicle seat. Although the displacement of head CG in the sagittal plane did not achieve statistical significance probably due to the low sample size, the estimated difference was 15.8% greater on the R44 bench. Caution is advised before extrapolating these results to the generality of vehicles and CRS. Only one vehicle seat and one CRS have been analyzed in this study and therefore the same findings cannot be expected for all vehicles and all CRS.

V. CONCLUSIONS

Twelve crash tests with a nominal impact speed of 50 km/h were performed in a decelerator sled according to European regulation ECE R44, using two different sizes of ATD (P3, P6), one high-back booster without ISOFIX and two different types of seats, a variant of the R44 bench and a real vehicle seat. Variables analyzed were the resultant and vertical chest accelerations, the resultant acceleration and the rotational speed in the sagittal plane of the head center of gravity, and the force of the belt. Additionally the 3D motion of selected ATD landmarks, the CRS and the test buck were tracked. The relative displacements of the ATD head center of gravity as well as other kinematic outcomes were reduced when the CRS was mounted on the vehicle seat. The observed results suggested that the overall response of the occupant improved when the real vehicle seat was used, regardless of the size of the occupant. Further research is needed, as these results were obtained for a particular vehicle model and a specific CRS and therefore cannot be extrapolated to the generality of vehicle seats and CRS.

VI. Acknowledgement

This study was partially funded by the General Directorate for Traffic (DGT) of Spain (Contract No. 0100DGT23308), by the CRS manufacturer BABYAUTO and by the People Programme (Marie Curie Actions) of the European Union's Seventh Framework Programme (FP7/2007-2012) under REA grant agreement 299298. The authors would like to thank the collaboration of Ms. Ana Lorente and Mr. Javier Santos, who processed and reconstructed VICON markers trajectories, and Mr. Jose Merino for his assistance during the tests. The opinions expressed here are solely those of the authors and are not necessarily those of the funding institutions.

VII. References

[1] Arbogast KB, Cornejo RA, Kallan MJ, Winston FK, and Durbin DR. Injuries to children in forward facing child restraints. *Annual Proceedings of the Association for the Advancement of Automotive Medicine*, 46:213-230. 2002.

[2] Adekoya N, Thurman DJ, White DD, and Webb KW. Surveillance for traumatic brain injury deaths-united states, 1989-1998. *MMWR. Surveillance summaries: Morbidity and mortality weekly report. Surveillance summaries / CDC,* 51(10):1-14. Dec 6 2002.

[3] Thompson MD and Irby JW Jr. Recovery from mild head injury in pediatric populations. *Seminars in pediatric neurology,* 10(2):130-139. Jun 2003.

[4] Aitken ME, McCarthy ML, Slomine BS, el al. Family burden after traumatic brain injury in children. *Pediatrics,* 123:199-206. 2009.

[5] Anderson VA, Catroppa C, Morse S, Haritou F, Rosenfled JV. Identifying factors contributing to child and family outcome 30 months after traumatic brain injury in children. *J Neurol Neurosurg Psychiatry,* 76:401-408. 2005.

[6] Rivara JM, Jaffe KM, Polissar NL, Fay GC, Liao S, Martin KM. Predictors of family functioning and change 3 years after traumatic brain injury in children. *Arch Phys Med Rehabil,* 77:754-764. 1996.

[7] Taylor HG, Yeates KO, Wade SL, Drotar D, Stancin T, Minich N. A prospective study of short-and long.term outcomes after traumatic brain injury in children: behavior and achievement. *Neuropsychology,* 16:15-27. 2002.

[8] Wade SL, Taylor HG, Yeates KO, et al. Long-term parental and family adaptation following pediatric brain injury. *J Pediatr Psychol,* 31:1072-1083. 2006.

[9] Yeates KO, Taylor HG, Wade SL, Drotar D, Stancin T, Minich N. A prospective study of short- and long-term neuropsychological outcomes after traumatic brain injury in children. *Neuropsychology,* 16:514-523*.* 2002.

[10] Arbogast KB, Wozniak S, Locey CM, Maltese MR, and Zonfrillo MR. Head impact contact points for restrained child occupants. *Traffic Injury Prevention,* 13:172-81. 2012.

[11] Bohman K, Arbogast KB, and Bostrom O. Head injury causation scenarios for belted, rear-seated children in frontal impacts. *Traffic Injury Prevention,* 12:62-70*.* 2012.

[12] Ash J, Sherwood C et al. Comparison of anthropomorphic test dummies with a pediatric cadaver restrained by a three-point belt in frontal sled tests. *Proc 21st Enhanced Safety of Vehicles (ESV) Conference, Stuttgart, Germany.* 2009.

[13] Lopez-Valdes F, Forman J, Kent R, Bostrom O, Sergui-Gomez M. A comparison between a child size PHMS and the Hybrid III 6 YO in a sled frontal impact. *Annu Proc Assoc Adv Automot Med,* 53:237-46. 2009.

[14] Seacrist T, Arbogast KB et al. Kinetics of the cervical spine in pediatric and adult volunteers during low speed frotal impacts. *J Biomech,* Vol 45(1), 99-106. 2012.

[15] Seacrist T, Balasubramanian S et al. Kinematic Comparison of Pediatric Human Volunteets and the Hybrid III 6-Year-Old Anthropomorphic Test Device. *Ann Adv Automot Med,* 54:97-108. 2010.

[16] Lopez-Valdes FJ, Fernandez-Bolanos Martin M, Alvarez Ruiz-Larrinaga A, and Sergui-Gomez M. Reduction in the exposure to being out-of-position among car occupants who used a sleeping device. *Injury Prevention,* Vol 18:165-169. 2012.

[17] Lopez-Valdes FJ, Forman JL, Ash JH, Kent R, Alba JJ, and Sergui-Gomez M. Assessment of a head support system to prevent pediatric out-of-position. *Annu Proc Assoc Adv Automot Med.* 2013.

[18] Osvalder AL, Hansson I, Stockman I, Carlsson A, Bohman K, and Jakobson L. Older children's sitting postures, behaviour and comfort experience during ride - a comparison between an integrated booster cushion and a high-back booster. *International Research Council on Biomechanics of Injury (IRCOBI), Gothenburg, Sweden.* 2013.

[19] Tylko S, Locey CM, Garcia-Espana J F, Arbogast KB, and Maltese MR. Comparative performance of rear facing child restraint systems on the CMVSS 213 bench and vehicle seats. *Ann Adv Automotiv Med.* 57. 2013.

[20] SAE. *Instrumentation for impact test -part 1- electronic instrumentation.*

[21] Cappozzo A, Croce UD, Leardini A, Chiari L. Human movement analysis using stereophotogrammetry . *Part 1: Theoretical background. Gait and Posture* 21:186-196. 2005.

[22] Chiari L, Croce UD, Leardini A, Cappozzo A. Human movement analysis using stereophotogrammetry. *Part 2: Instrumentals errors. Gait and Posture,* 21:197-211. 2005.

[23] Croce UD, Leardini A, Chiari L, Cappozzo A. Human movement analysis using stereophotogrammetry . *Part 4: assessment of anatomical landmark misplacement and its effects in joint kinematics. Gain and Posture,* 21:226-237. 2005.

[24] Leardini A, Chiari L, Croce UD, Cappozzo A. Human movement analysis using stereophotogrammetry. *Part 3: Soft tissue artifact assessment and compensation. Gait and Posture* 21:212-225. 2005.

[25] Adomeit D, Heger A. Motion sequence criteria and design proposals for restraint devices in order to avoid unfavorable biomechanic conditions and submarining. *Proc. 19th Stapp Car Crash Conference, pp. 139-165, SAE, Warrendale, PA.* 1975.

[26] Kent R, Lopez-Valdes FJ, Dennis NJ, Lessley D, Forman JL, Higuchi K, Tanji H, Ato T, Kameyoshi H, Arbogast KB. Assessment of a three-point restraint system with a Pre-tensioned Lap Belt and an Inflatable, Force-Limited Shoulder Belt. *Stapp Car Crash Journal,* Vol. 55. Pp. 141-159. Noviembre 2011.

[27] Forman J, Michaelson J, Kent R, Kuppa S, Bostrom O. Occupant restraint in the rear seat: ATD responses to standard and pre-tensioning, force-limiting belt restraints. *Ann Adv Automot Med.* 52. 2008.

[28] Forman J, Lopez-Valdes FJ, Lessley D, Kindig M, Kent R, Ridella S, Bostrom O. Rear seat occupant safety: an investigation of a progresive force-limiting, pretensioning 3-point belt system using adult PMHS in frontal sled tests . *Stapp Car Crash Journal.* Vol 53, pp 49-74. November 2009.

[29] Forman J, Lopez-Valdes FJ, Dennis N, Kent R, Tanji H, Higuchi K. An inflatable belt system in the rear seat occupant environment: investigating feasibility and benefit in frontal impact sled tests with a 50th percentile male ATD. *Ann Adv Automot Med* 54:111-26. 2010.

[30] Kent R, Forman JL, Parent D, Kuppa S. Rear seat occupant protection in frontal crashes and its feasibility. *20th Proceedings International Technical Conference on the Enhanced Safety of Vehicles (ESV), Lyon, France.* 2007.

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

Bench and ATD group	Test number	Torso angle (deg)	Head angle (deg)
R44 Bench, P3 ATD	908	61.0	1.0
	909	59.6	2.0
	910	60.0	2.4
R44 Bench, P6 ATD	905	58.3	0.0
	906	57.9	1.2
	907	59.5	0.5
Vehicle seat, P3 ATD	911	58.9	0.9
	912	60.0	0.5
	913	61.6	2.0

Vehicle seat, P6 ATD	914	59.0	2.0
	915	57.7	1.0
	916	57.0	2.0

Harness and shoulder belt position on the dummy

Table A.II shows the initial position of the 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.

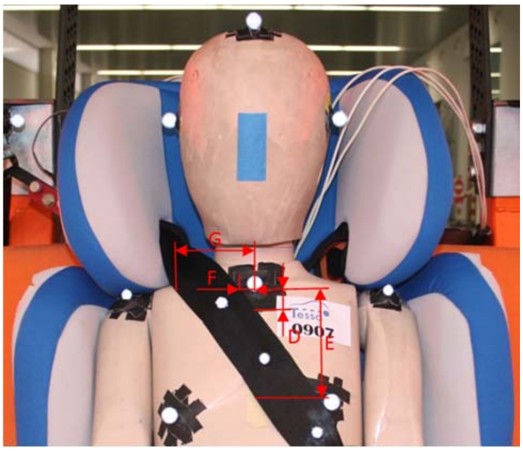


Fig. A.I. Schematic showing the positioning parameters used to place the harness/shoulder belt on the torso of the ATD.

TABLE A.II
ATD SHOULDER BELT POSITION BEFORE TEST

Restraint and ATD group	Test number	D (mm)	E (mm)	F (mm)	G (mm)
R44 Bench, P3 ATD	908	0	78	0	58
	909	0	85	0	56
	910	0	75	0	57
R44 Bench, P6 ATD	905	25	105	14	68
	906	20	100	10	75
	907	16	106	10	75
Vehicle seat, P3 ATD	911	0	90	0	51
	912	0	98	0	52
	913	0	89	0	55
Vehicle seat, P6 ATD	914	10	98	5	58
	915	12	102	8	60
	916	12	98	6	64

Statistical Analysis

Table A.III shows averages, standard deviation (SD), standard error (SE) and the t-test results to the selected variables.

TABLE A.III

STATISTICAL RESULTS FOR THE MATCHED PAIR ANALYSIS

			Head Displ. [mm]	Thorax Acc. R. (3 ms) [g]	Thorax Acc. V. (3 ms) [g]	Head Acc. R. (3 ms) [g]	Head Rot. Speed (Sagittal plane) [deg/sec]	Belt Force [N]	High Back Booster Forward Excursion [mm]	High Back Booster Lateral Inclination [deg]
ATD P3	**R44 Bench**	**Average**	333.5	52.6	3.2	54.5	4356.0	5488.0	57.3	9.9
		SD	3.9	5.2	0.6	1.9	255.0	198.0	3.4	0.2
		SE	2.3	3.0	0.4	1.1	147.0	114.0	2.0	0.1
	Vehicle Seat	**Average**	312.1	44.2	3.3	44.2	3913.0	4160.6	22.1	5.3
		SD	39.4	0.9	0.5	0.5	213.0	63.6	14.1	2.6
		SE	28	0.5	0.3	0.3	123.0	37.0	10.0	1.9
	T-Test p-value		0.584	0.109	0.815	0.012	0.104	0.008	0.179	0.244
ATD P6	**R44 Bench**	**Average**	358.3	51.2	8.5	56.0	4831.0	7014.0	60.5	13.3
		SD	0.9	2.1	1.0	0.8	528.0	271.0	7.9	1.3
		SE	0.5	1.2	0.6	0.5	305.0	157.0	4.6	0.8
	Vehicle Seat	**Average**	301.6	43.6	15.6	51.7	4287.1	5719.3	41.9	9.0
		SD	7.9	1.4	1.8	1.2	77.6	37.4	5.5	0.4
		SE	5.6	0.8	1.0	0.7	45.0	22.0	3.9	0.3
	T-Test p-value		0.063	0.013	0.009	0.015	0.220	0.015	0.091	0.036

Note: The head CG displacement of the ATD, forward excursion and lateral inclination of the high back booster in vehicle seat tests were calculated with n=2, due to missing VICON data in tests 911 and 914, rest of all parameters were calculated with n=3.