Assessment of a head support system to prevent pediatric out-of-position: an observational study

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ABSTRACT – Head injuries are the most common severe injuries sustained by pediatric occupants in road traffic crashes. Preventing children from adopting positions that can result in an increased injury risk due to unfavorable interactions with the restraints is fundamental. The objective of this paper was to assess the effect of a head support system (SS) on the lateral position of the head, the vertical position of the sternum and the shoulder belt fit. Thirty pediatric rear-seat passengers were exposed to two 75-minute trials. Volunteers were restrained by a three-point belt and, if needed, used the appropriate child restraint system for their anthropometry (high-back booster, low-back booster, no booster). A case crossover study was designed in which the volunteers used the head support system (SS) during one of the trials, acting as their own controls (No SS) in the other. Compared to the control group, the head support reduced significantly the 90th percentile value of the absolute value of the relative lateral motion of the head, regardless of the restraint used. The system also reduced the maximum downward position of the sternal notch within the low-back booster group. As for the belt fit, the use of the head support improved significantly the position of the shoulder belt on the occupant in the low-back booster and in the no booster groups.

INTRODUCTION

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 (Arbogast et al., 2002). Head injuries are responsible for one third of all pediatric injury deaths (Adekoya et al., 2002; Thompson and Irby, 2003).

A review of 92 pediatric fatalities suggested that intrusion played a major role in crashes with a lateral component, in which the child's head contacted the intruding door and window sill (Sherwood et al., 2002). Brown et al. (1995) found that child restraint systems with large head side wings could prevent head contact in side impacts. A recent study of CIREN cases involving restrained forward facing pediatric occupants in frontal collisions (principal direction of force from 11 to 1 o'clock) showed that the head/face area was the one exhibiting the most severe injuries and that injuries to other body regions were uncommon in pediatric occupants (Arbogast et al, 2012). The authors pointed out that even when the children were appropriately restrained, there was a substantial amount of head excursion that resulted in contact against the back seat of the front row or against the B-pillar (whenever there was also a lateral component to the collision). A review of NASS CDS and CIREN cases, including children restrained in frontal crashes who sustained AIS2+ head injuries, showed that head injuries were associated to the contact of the head with the seatback or the side interior of the car in approximately 60% of the cases (Bohman et al., 2011). The remaining of the cases showed no evidence of head contact and were characterized by a higher crash severity and accompanied by severe thoracic and spinal injuries.

Both FMVSS 213 (Child restraint systems) and ECE-R44 (Uniform provisions concerning the approval of restraining devices for child occupants of power-driven vehicles) regulations limit the maximum forward head displacement in a 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 to an increased risk of pediatric head injuries. Children's posture also affects the injury risk, modifying the interaction between the occupant and the restraints, and its kinematics (van Rooij et al., 2005).

Observational studies have gained importance over the last years as they provide qualitative information about the behavior, restraint fit and children posture

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during real trips (Meissner et al, 1994; Charlton et al, 2010; Andersson et al, 2010).

In particular, Forman et al. (2011) exposed 30 children to an in-transit study during night-time driving in which sleeping children may exhibit risky postures due to seeking more comfortable positions. Children were rear-seated and adequately restrained according to their anthropometry. The position of the children and the belt fit was recorded with a low-light video camera to measure lateral head position and to assess shoulder belt fit. The study concluded 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. Although it was also observed a reduction of both magnitudes within the low-back booster seat, they were not statistically significant.

The thirty children included in Forman et al. (2011) were exposed to the same experimental conditions but with the addition of a head support to control the motion of the head of the volunteers. While Forman et al. (2011) only analyzed the position and belt fit when the pediatric occupants were restrained by the appropriate restraint system for their anthropometry, this study expands the analysis to evaluate if the addition of the head support system may help prevent out-of-position events during the travel. The head support system had been assessed with adults showing an improvement in their position in the vehicle (Lopez-Valdes et al, 2012), but it had never been tried with pediatric subjects before.

The specific objectives of the present study are:

- To assess if the use of a head support system influenced the observed differences in belt fit and occupant position between the different restraints in the pediatric occupants analyzed in Forman et al. (2011).
- To evaluate whether the use of a head support system in addition to a proper restraint improved the lateral position of the head, vertical position of the torso and belt fit of restrained children.

METHODS

An observational, in-transit position study was performed with 30 pediatric volunteers. Trials consisted of organized trips of 75-minute duration performed during the night, with a dedicated study vehicle and study driver. Two consecutive trials were performed with each volunteer: one trial with the head support system (SS trials) and one trial without the device (No SS trials). A resting period up to 15 minutes was observed between trials. The trials order was randomized. A high-back booster seat (HB), a low-back booster seat (LB), or no booster seat (N) was used based on the height and weight of the volunteers. The lateral head position, vertical sternum position, and shoulder belt position were observed using a low-light video camera mounted on the vehicle interior for an anterior view of the volunteers. The volunteers were accompanied by a parent or caregiver at all times. All study procedures were reviewed and approved by the parent/caregiver prior to the trials. All study procedures were also approved by the University of Navarra Institutional Review Board.

Volunteers

Thirty pediatric volunteers participated in the study. Inclusion criteria were that the children were of ages 7-14 years, with a maximum height of 165 cm. Table 1 summarizes each participant's characteristics.

Table 1: Subject information (SS: support system)

Subject	Age	Gender	Height (cm)	Weight (kg)	Booster	SS used in trial#
1	9	F	142	37	LB	1
2	8	F	139	31	HB	2
3	8	F	123	31	HB	1
4	8	M	132	25	HB	2
5	10	F	144	40	LB	2
6	8	F	131	28	HB	2
7	10	F	134	32	LB	1
8	8	M	126	24	HB	1
9	8	F	127	31	HB	2
10	8	M	132	32	LB	1
11	12	F	163	41	N	1
12	8	M	129	26	HB	1
13	9	M	136	34	LB	2
14	13	M	158	48	N	1
15	13	F	156	44	N	2
16	11	F	152	43	N	2
17	11	M	150	44	N	2
18	10	F	138	39	LB	2
19	9	F	140	42	LB	1
20	12	F	155	56	N	1
21	12	M	153	44	N	2
22	9	F	147	42	LB	1
23	13	F	163	48	N	2
24	7	F	131	30	HB	2
25	10	F	144	42	LB	2
26	12	M	153	37	N	2
27	9	F	139	37	LB	1
28	8	M	122	21	HB	1
29	14	F	164	49	N	1
30	10	F	127	27	HB	1

LB: Low Back booster; HB: High Back booster: N: No booster

Subjects were selected to result in three equal groups (10 subjects per group) based on the recommended restraint system for their anthropometry. A high back booster seat (2010 Rodi model, Maxi-Cosi) was used with all subjects under 32 kg in weight. A low-back booster (2010 Indy Team model, Jane) was used with subjects greater than or equal to 32 kg, but less than 147 cm in height. No booster seat was used for subjects greater than 147 cm.

Volunteers were seated in the right rear seat, and they were the only occupants of the rear seat.

Head support system

The head support system was a non-commercially available prototype. The system consisted of an elastic hammock suspended by a vertical elastic strip hanging from a plastic structure attached to the top of the headrest or the back of the booster seat. The system prevents excessive head flexion either in the sagittal or frontal plane (lateral flexion) while still providing freedom for small range motions. The system was originally designed to increase sleep efficiency, to reduce the number of awakenings and sleep latency, and to improve subjective sleep perception. The system can adapt to a variety of environments including passenger cars, wheelchairs, child restraint systems and passenger trains. A schematic of the system is shown in Figure 1.

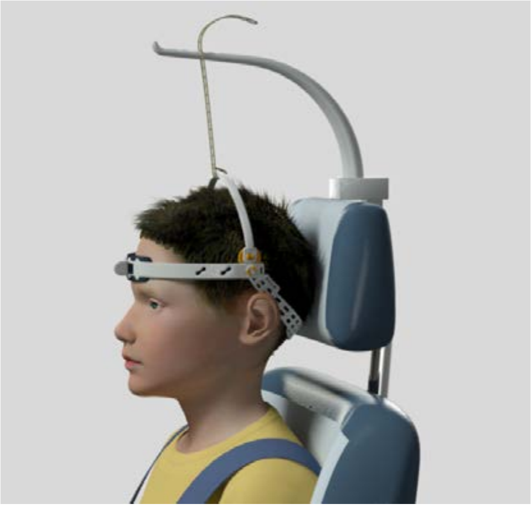

Figure 1. Schematic showing the head support system and its attachment to the vehicle headrest.

Instrumentation and video analysis

A low-light camera with infrared recording capability was mounted in front of the pediatric occupant and recorded the position of the volunteer during the whole duration of each trial. Prior to the initiation of the trip, the child was outfitted with a headband and taped-on shirt markers to facilitate observation of the position of various anatomical landmarks (Figure A.1 in Appendix). The marker headband was attached to the system elastic hammock, and the volunteers used the part of the system that was in contact with their head during both trials. The only difference was that the headband and hammock were connected to the plastic structure attached to the vehicle only in the SS trials. The child was asked to sit up-right with their head back to record an initial position. Displacements in the frontal plane were calculated relative to this initial position. Trips were interrupted if a marker on the test subject became mispositioned, in which case the driver would stop the vehicle, reposition the marker, and then continue the trip.

A sample of 75 video frames (the first frame per each minute of video) was analyzed for each trial.

Variables included in the study

This study assesses qualitatively the fit of the shoulder belt on the occupants and quantifies the lateral position of the head and the vertical displacement of the sternal notch in the frontal plane, across the three restraint groups.

Four categories were considered to classify a poor belt fit: “Off shoulder” if the entirety of the belt crossed the upper arm lateral to the acromion (Figure A2a); “Into neck” if the belt was visibly pressed into the lateral surface of the neck or if the belt was supporting the neck (Figure A2b); “Sternum” if any portion of the belt crossed the occupant midline superior to the sternal notch marker (Figure A2c); last, “Any” if the belt was off the shoulder or into the neck or above the sternum. The acromion position was identified as the apex of the curvature of the shoulder of the occupant. To compare the belt fit between the different groups, the percentage of video frames in which the above described situations were observed for each subject was calculated (variables $P_{Off\_shoulder}$, P_{Into_neck}, $P_{sternum}$ and P_{any}).

The lateral position of the head was quantified by means of the 90th percentile of the absolute value of each subject’s head lateral displacement ($Y90_{Head}$).The vertical position of the sternum was characterized by the minimum vertical position of the sternal notch of each volunteer ($Zmin_{sternum}$).

Analysis

Descriptive analysis. The frequency distribution of the head lateral position and the sternum vertical position were compared between the SS and the No

SS trials per subject and per restraint type. Also the mean percentage (and standard deviation) of video frames showing a poor belt position were compared between the two groups per restraint type.

Analytical analyses. The two objectives proposed for this study required using different statistical methods to assess the significance of the differences observed between restraint groups and use of the head support system.

- Assessment of the impact of using the head support in the differences between the restraint groups observed in Forman et al. (2011).

  There were three groups of 10 subjects using three restraints (N, LB and HB) and the head support. The non-parametric Kruskal-Wallis test was used to assess if there were differences between the median values across the three restraint groups. Should the Kruskal-Wallis test result in statistically significant differences, the Mann-Whitney test with the Bonferroni correction was used to identify the pairs exhibiting differences.

  Linear regression was used to assess the magnitude of the differences between the three restraint groups. Regression models took the form shown in Equation 1, where C_{LB} was the model coefficient associated to a dummy variable indicating the use of low-back booster (LB), C_{HB} was the coefficient associated to a dummy variable indicating the use of a high-back booster (HB) and the intercept (C_{None}) is the baseline condition of the group with no booster seat.

  $$X = C_{None} + C_{LB} \cdot LB + C_{HB} \cdot HB \qquad [1]$$

  In Equation 1, the dependent variable X represented the magnitude of interest ($P_{Off\_shoulder}$, P_{Into_neck}, $P_{sternum}$, P_{any} or $Y90_{Head}$).

  The results from similar analyses for those trials without the head support were reported in Forman et al. (2011).

- Assessment of the impact of using the head support system in addition to a proper restraint on the lateral position of the head, the vertical position of the torso and belt fit of restrained children.

  The analysis compared the five output variables ($P_{Off\_shoulder}$, P_{Into_neck}, $P_{sternum}$, P_{any}, $Y90_{Head}$ and $Zmin_{sternum}$) depending on the use of the head support system and across restraint groups. This was a case crossover study since each subject was its own control. The non-parametric Wilcoxon rank test was chosen given that there were only 10 subjects within each restraint group. This paper presents the p-value of the two-sided test for the null hypothesis that the differences between the No SS and the SS groups for each output variable came from a distribution with zero median.

The significance level for the statistical tests was set at $p\text{-value} < 0.05$. Statistical analyses were done with MATLAB R2012b (MathWorks, Inc, USA).

RESULTS

Descriptive analysis comparing the distribution of the outcome variables depending on the use of the head support system

Head lateral position

Volunteers were grouped by restraint type used during the trial. Box plots of the lateral position of the head are included in Figure 2. The displacement was truncated to the maximum value observable within the frame in case the head marker moved laterally out of the frame. To compare the change of lateral head position with the use of the head support system, two box plots were produced per subject (denoted as SS when the subject was using the head support and NSS when the subject was not using it).

The plots show differences in the lateral displacement of the head when the volunteers were using the head support system. In general, the width of the box is smaller when the occupant used the system and the median is closer to the zero displacement position (which coincides with the reference position in which the child was asked to sit straight). The box plots indicate that when the volunteers were using the head support system, they remained more centered in the car seat and that their extreme values were smaller than the ones observed when they were not using the system. These differences are clearly seen within the No Booster and the Low-Back Booster groups, and they are less noticeable within the High-Back Booster group. In fact, there are two subjects within this last group (Sub3 and Sub12) in which the differences were not noticeable at all.

No video data was recorded for Sub4 when this volunteer was using the head support system. Thus, this subject was not included in further analyses focused on the lateral position of the head.

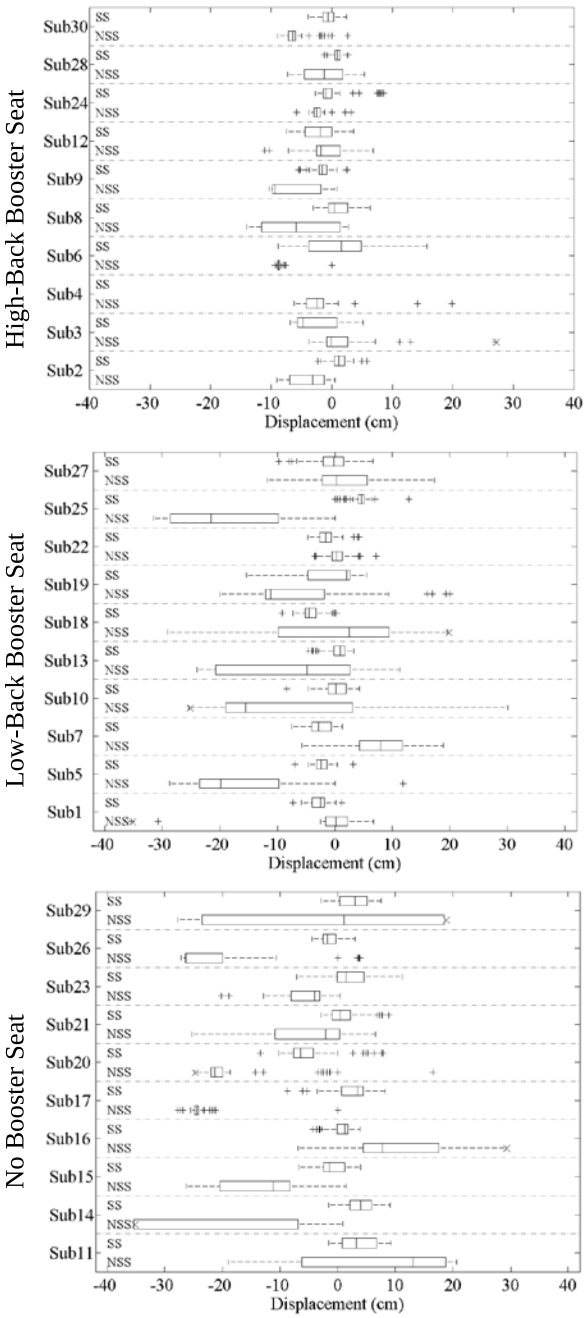

Figure 2. Box plots of the lateral displacement of the head (zero displacement is the reference position) showing median, 25th and 75th percentiles and outliers (+). Truncated values indicated with ×. Negative values indicate motion towards the window/door. (SS: support system; NSS: no support system)

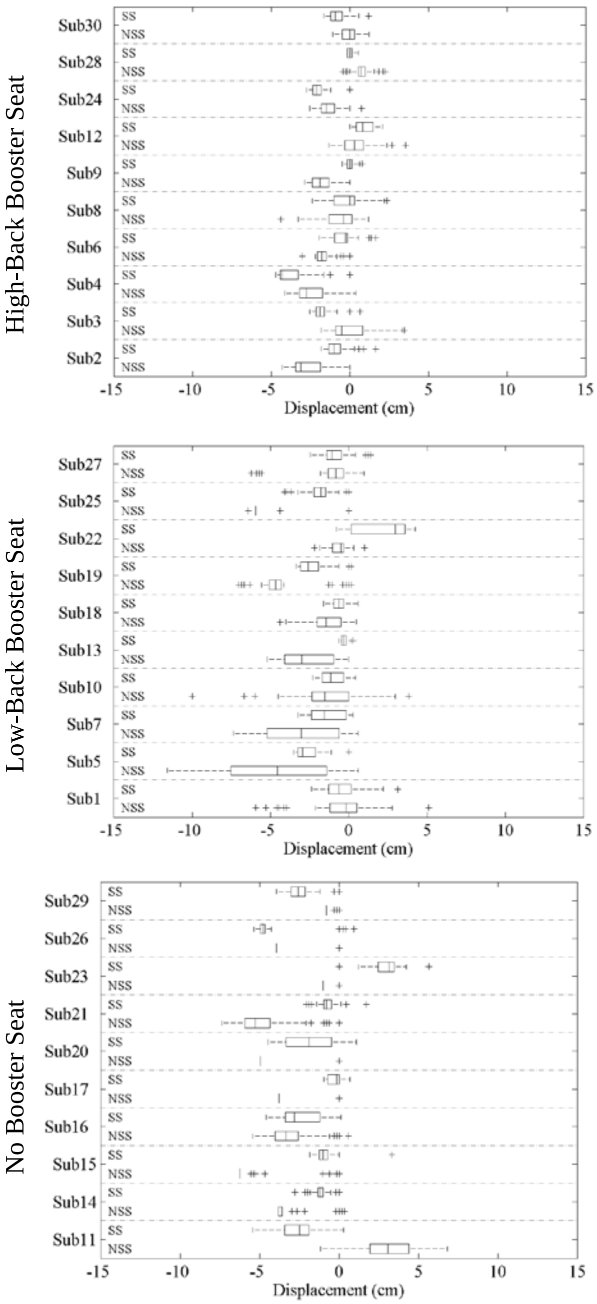

Figure 3. Box plots of the vertical displacement of the sternal notch (zero displacement is the reference position) showing median, 25th and 75th percentiles and outliers (+). Negative values indicate downward motion. (SS: support system; NSS: no support system)

Sternum vertical position

Figure 3 shows the box plots corresponding to the vertical position of the sternal notch of the volunteers per restraint group.

With the exception of Sub22 (Low-Back Booster) and Sub23 and Sub11 (No Booster), the median of the position adopted by all volunteers was always negative, indicating that the position of the sternal notch moved mostly downwards from the initial reference position.

The box plots of the distribution of the vertical position of the sternal notch of the volunteer group that did not use a booster consisted of just a single vertical line. These lines indicate that the sternal notch could be recorded only in that particular position in a certain number of frames and that the marker was obscured during the rest of the trial (either by the head of the volunteer or the seat belt, or both). There were also other cases in which it was possible to record the position of the sternal notch above a certain limit but the measurements had to be truncated due to the marker being obscured. Table 2 summarizes these cases.

Table 2. Cases in which the measurement of the vertical displacement of the sternal notch was truncated due to the marker being obscured (SS: support system)

Restraint type	Using SS	Not using SS
High Back Booster	None	None
Low-Back Booster	None	Sub1, Sub10, Sub25
No Booster	Sub29	Sub14, Sub15, Sub16, Sub17, Sub20, Sub21, Sub23, Sub26, Sub29

Regardless of the use of the support system, none of the volunteers in the High-Back Booster moved downwards farther than the visibility limit of the sternal notch marker. In the Low-Back Booster, only three subjects overpassed this limit when they were not using the head support system. Most of the cases in which the measurement was truncated occurred within the No Booster group and more specifically when the volunteers were not using the head support system.

Belt fit

Figure 4 shows the mean percentage (error bars indicate plus one standard deviation) of frames exhibiting poor belt positions depending on the use of the head support system and per restraint group.

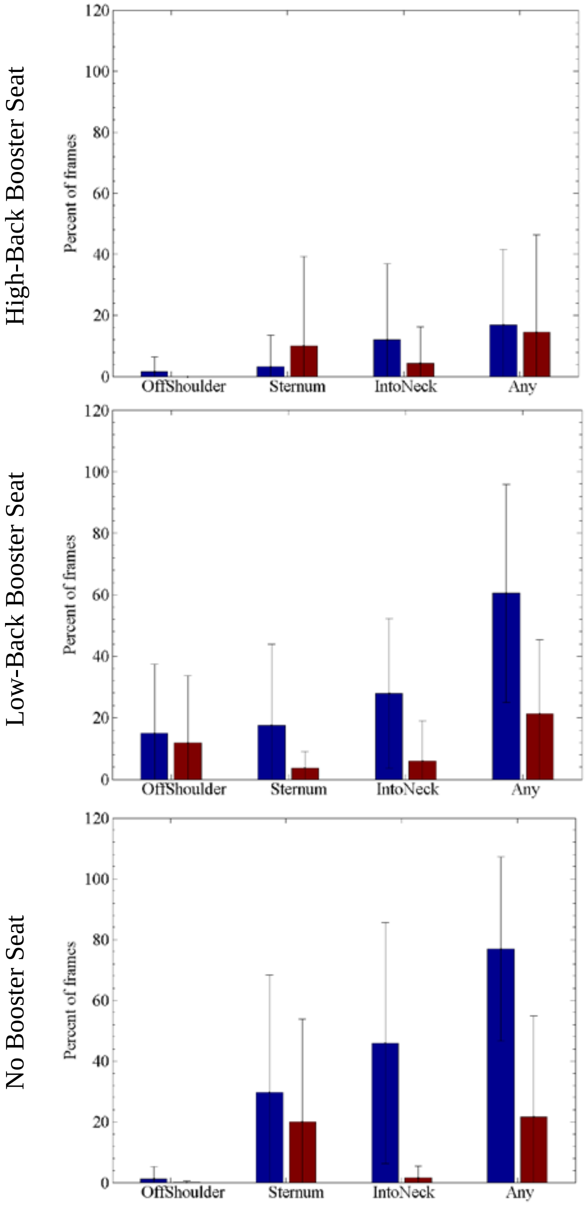

Figure 4. Mean percentage of frames with a poor belt fit (3 categories and the occurrence of either one combined). Error bars show +1 standard deviation. Blue bars indicate No SS cases and red bars indicate SS cases.

The main differences in the shoulder belt fit related to the use of the head support system were observed in the Low-Back Booster and in the No Booster groups. In the Low-Back Booster group, the average percentage of frames exhibiting a poor belt fit due to the belt being above the sternum was 17.5% when the volunteers were not using the head support system and 3.7% when they were using it; the comparison was 27.9% (No SS) vs. 5.9% (SS) for the “Into neck” category. Considering all the poor belt fit categories as a whole, the average number of frames showing a poor belt fit was 60.4% (No SS) vs. 21.4% (SS). Within the No Booster group, the main differences were observed in the “Into neck” category, in which the volunteers were observed to have a poor fit in an average 45.9% of frames when they were not using the support system compared to an average 1.5% when they were using it. The comparison considering any poor belt fit category resulted in an average 76.9% of frames in the No SS situation vs. an average 21.7% of frames in the SS.

As shown in Figure 3, the mean percentage values of poor belt fit in the High-Back Booster group were similar regardless of the use of the head support system.

Assessment of the impact of the use of the head support system on the differences between the different restraints observed in the pediatric occupants analyzed in Forman et al. (2011).

The following paragraphs focus on analyzing the influence of the use of the head support system on belt fit and the vertical displacement of the head. These analyses were performed also in Forman et al. (2011) when the volunteers were not using the head support system.

Belt fit. Comparison between the three restraint types.

Figure 5 compares the percentages of frames exhibiting a poor shoulder belt fit when the volunteers were using the head support system.

The main differences between the groups were seen in $P_{Off\_shoulder}$ in which the group using the Low-Back Booster seat exhibited a poor fit during an average of 11.8% of the frames examined while the average number of frames was close to zero in the other two restraint groups. When any of the poor belt fit categories was considered, the average number of frames exhibiting a poor belt fit was similar across the different restraint types: 21.7% in the No Booster group, 21.4% in the Low-Back Booster group and 14.5 in the High-Back Booster group.

The Kruskal-Wallis test for the comparison of medians between more than two independent groups when the groups do not come from normal distributions was used to quantify the significance of the differences. Table 3 shows the p-values obtained in the comparison, indicating that the only statistically significant difference among the three restraint groups occurred for the “Off shoulder” category as suggested in the bar plot showed in Figure 5.

Table 3: Comparison between restraint groups as given by the Kruskal-Wallis test for the comparison of medians. Asterisks indicate statistically significant differences.

Belt position	p-value
Off shoulder	0.002*
Sternum	0.538
Into neck	0.340
Any	0.122

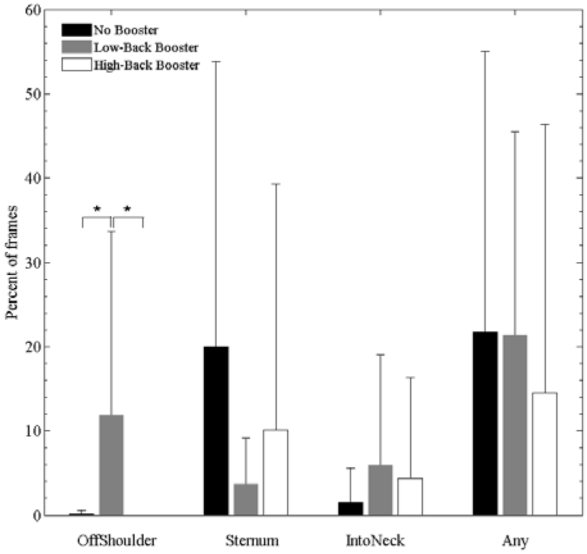

Figure 5. Mean values for the percent of frames exhibiting poor belt positions when the volunteers used the head support system, by restraint type. Error bars indicate + one standard deviation. Asterisks indicate statistically significant differences.

The Mann-Whitney test using the Bonferroni correction for multiple comparisons was used to identify the pairs that exhibited the differences within the “Off shoulder” category. Table 4 shows the p-values of the comparison, which confirmed that the only statistically significant differences were found in the comparison between the group using the Low-Back booster seat and the group using the High-Back booster seat. The comparison between the No booster seat and the Low-Back booster seat produced a corrected p-value very close to the level of significance (p=0.054) and, although it was over the proposed level of significance, it was termed as marginally significant.

Table 4: Comparison of poor belt fit in the "Off shoulder" category between pairs of restraint types as given by Mann-Whitney. Bonferroni correction applied for multiple comparisons. Asterisks indicate statistically significant differences.

Pair compared	p-value	p-value corrected	Comment
N vs. LB	0.018	0.054	Marginally significant differences found
N vs. HB	0.364	Not applicable	
LB vs. HB	0.012	0.036*	Significant differences found

LB: Low Back booster; HB: High Back booster; N: No booster

Regression models

The coefficients for the regression models of the outcome variables P_{any}, $P_{sternum}$, $P_{Off\_shoulder}$, P_{Into_neck} and $Y90_{Head}$ proposed in Equation 1 are shown in Table 5.

The coefficients C_{None} were significantly greater than zero ($p<0.05$) for the P_{any}, $P_{sternum}$ and $Y90_{Head}$ output variables, indicating an over-exposition within the No Booster group to increased values of the outcome variables (e.g. the group using no booster was exposed to an increased risk of exhibiting a poor belt fit globally in all categories and in the "Sternum" category and to an increased risk of a greater $Y90_{Head}$ value). The only other coefficient that reached statistical significance was the C_{LB} parameter in the regression model of the outcome variable $P_{Off\_shoulder}$ that suggested an increased risk of a poor belt fit within this category when the occupants were using the head support system and a Low-Back Booster.

The absence of any other statistically significant coefficient indicates that when the occupants were using the head support system, the restraint used (with the exception of the cases aforementioned) did not influence the value of the outcome variable.

Table 5: Linear regression model coefficients for the belt position, and the 90th percentile, absolute value, relative lateral head position (N=30 subjects, up to 75 frames each). Asterisks indicate statistically significant coefficient values.

			Coefficient	95% CI	p-value
Belt position, percentage	Any P_{any}	No Booster, C_{None}*	21.69	2.218, 41.162	0.030
		Low-Back Booster, C_{LB}	-0.006	-0.567, 0.556	0.983
		High-Back Booster, C_{HB}	-0.147	-0.708, 0.415	0.597
	Into neck P_{Into_neck}	No Booster, C_{None}	1.549	-5.270, 8.368	0.645
		Low-Back Booster, C_{LB}	0.089	-0.107, 0.285	0.361
		High-Back Booster, C_{HB}	0.057	-0.139, 0.254	0.554
	Sternum $P_{sternum}$	No Booster, C_{None}*	20.000	3.127, 36.872	0.022
		Low-Back Booster, C_{LB}	-0.333	-0.820, 0.153	0.171
		High-Back Booster, C_{HB}	-0.201	-0.688, 0.285	0.404
	Off shoulder $P_{Off\_shoulder}$	No Booster, C_{None}	0.141	-8.050, 8.332	0.972
		Low-Back Booster, C_{LB}*	0.239	0.002, 0.475	0.048
		High-Back Booster, C_{HB}	-0.003	-0.239, 0.233	0.980
Lateral head position, $Y90_{Head}$ (cm)		No Booster, C_{None}*	5.884	4.595, 7.093	<0.001
		Low-Back Booster, C_{LB}	-0.015	-0.051, 0.020	0.386
		High-Back Booster, C_{HB}	-0.031	-0.068, 0.005	0.096

Assessment of the impact of the use of the head support system in addition to a proper restraint on the lateral position of the head, vertical position of the torso and belt fit of restrained children

The following paragraphs assess the statistical significance of the differences observed in the outcome variables depending on the use of the head support system that were illustrated in Figure 2, Figure 3 and Figure 4.

As indicated above, this was a case crossover study in which the Wilcoxon test was used to identify the differences between the two trials (No SS and SS).

Table 6: Head lateral motion (90th percentile of the absolute lateral head motion) and maximum sternum downwards vertical motion in trials without the head Support System (No SS) and with the head Support System (SS). p-values of the comparison of $Y90_{Head}$ and $Zmin_{sternum}$ per restraint group depending on the use of the head support. Asterisks indicate statistically significant differences.

	Subject #	$Y90_{Head}$		$Zmin_{sternum}$	
		No SS	SS	No SS	SS
Low-Back Booster	1	35.4	5.2	-5.9[2]	-2.4
	5	25.6	4.0	-11.6	-3.5
	7	16.0	4.4	-7.4	-3.2
	10	25.4	3.8	-10.0[2]	-2.3
	13	22.2	3.1	-5.2	-0.6
	18	26.9	6.0	-4.4	-1.6
	19	14.2	9.4	-7.0	-3.4
	22	3.0	3.9	-2.2	-0.8
	25	31.1	5.7	-6.4[2]	-4.1
	27	11.1	5.3	-6.2	-2.5
	Mean (Std. dev)	21.3 (9.8)	5.1 (1.8)	-6.6 (1.2)	-2.4 (2.7)
	p-value	0.004*		0.002*	
High-Back Booster	2	8.5	3.0	-4.3	-1.8
	3	6.3	5.9	-1.8	-2.5
	4	5.4	NA[1]	-4.1	-4.7
	6	9.1	5.5	-3.0	-1.9
	8	12.1	3.8	-4.4	-2.4
	9	10.0	2.7	-2.8	-0.5
	12	7.8	5.8	-1.3	0.0
	24	3.2	7.7	-2.5	-2.7
	28	7.0	2.0	-0.4	-0.1
	30	7.6	2.6	-1.1	-1.7
	Mean (Std. dev)	8.0(2.7)	4.3 (1.9)	-2.5 (1.4)	-1.8 (1.4)
	p-value	0.020*		0.160	
No Booster	11	19.3	8.7	-1.1	-5.4
	14	35.4	6.5	-3.8[2]	-2.7
	15	22.7	3.9	-6.3[2]	-1.8
	16	21.2	3.1	-5.4[2]	-4.5
	17	25.4	5.4	-3.8[2]	-0.9
	20	22.6	8.7	-4.9[2]	-4.4
	21	23.3	5.3	-7.4	-2.0
	23	12.0	7.4	-0.9[2]	0.0
	26	26.7	3.2	-3.9[2]	-5.3
	29	25.0	6.2	-0.8[2]	-3.9[2]
	Mean (Std. dev)	23.5 (5.9)	5.8 (2.0)	-3.8 (2.3)	-3.1 (1.9)
	p-value	0.020*		0.492	

[1] Value not available due to obscuring of the visual tracking marker throughout the trial. This subject was removed from the comparison for this output variable.

[2] Truncated values.

Table 7: Percent of frames exhibiting the various “poor” belt position classification in trials without the head Support System (No SS) and with the head Support System (SS), by subject and restraint type. p-value of the comparison of belt fit per restraint group depending on the use of the head support. Asterisks indicate statistically significant differences

	Subject #	Into Neck		Sternum		Off Shoulder		Poor Shoulder Belt Position	
		P_{Into_neck}		$P_{sternum}$		$P_{Off\_shoulder}$		P_{any}	
		No SS	SS	No SS	SS	No SS	SS	No SS	SS
Low-Back Booster	1	15.5	0.0	0.0	0.0	71.8	46.5	87.3	46.5
	5	73.2	2.8	0.0	0.0	0.0	0.0	73.2	2.8
	7	56.3	42.3	4.2	0.0	0.0	0.0	60.6	42.3
	10	12.7	0.0	56.3	8.5	22.5	2.8	91.5	11.3
	13	42.3	0.0	4.2	0.0	8.5	4.2	54.9	4.2
	18	15.5	2.8	15.5	14.1	18.3	0.0	49.3	16.9
	19	40.8	1.4	22.5	11.3	26.8	59.2	90.1	71.8
	22	0.0	0.0	0.0	0.0	1.4	2.8	1.4	2.8
	25	22.5	0.0	73.2	0.0	0.0	0.0	95.8	0.0
	27	0.0	9.9	0.0	2.8	0.0	2.8	0.0	15.5
	Mean(Std. dev.)	27.9(24.4)	5.9(13.1)	17.5(26.3)	3.7(5.5)	14.9(22.5)	11.8(21.9)	60.4(35.4)	21.4(24.1)
	p-value	0.008*		0.047*		0.578		0.008*	
High-Back Booster	2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3	60.6	38.0	0.0	0.0	0.0	0.0	60.6	38.0
	4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	6	57.7	0.0	0.0	0.0	15.5	0.0	57.7	0.0
	8	0.0	0.0	0.0	0.0	0.0	0.0	15.5	0.0
	9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	12	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	24	1.4	0.0	0.0	8.5	0.0	0.0	1.5	8.5
	28	1.4	5.6	32.4	93.0	0.0	0.0	33.8	98.6
	30	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	Mean(Std. dev.)	12.1(24.8)	4.4(12.0)	3.2(10.2)	10.1(29.2)	1.5(4.9)	0.0(0.0)	16.9(24.8)	14.5(31.9)
	p-value	0.375		0.500		1.000		0.813	
No Booster	11	22.5	0.0	14.1	0.0	0.0	0.0	36.6	0.0
	14	84.5	0.0	0.0	0.0	0.0	1.4	84.5	1.4
	15	0.0	0.0	94.4	9.9	0.0	0.0	94.4	9.9
	16	2.8	0.0	0.0	0.0	12.7	0.0	15.5	0.0
	17	98.6	0.0	0.0	100.0	0.0	0.0	98.6	100.0
	20	95.8	2.8	4.2	36.6	0.0	0.0	100.0	39.4
	21	33.8	12.7	56.3	0.0	0.0	0.0	90.1	12.7
	23	0.0	0.0	95.8	0.0	0.0	0.0	95.8	0.0
	26	70.4	0.0	28.2	53.5	0.0	0.0	98.6	53.5
	29	50.7	0.0	4.2	0.0	0.0	0.0	54.9	0.0
	Mean(Std. dev.)	45.9(39.6)	1.5(4.0)	29.7(38.7)	20(33.8)	1.3(4.0)	0.1(0.4)	76.9(30.3)	21.7(33.3)
	p-value	0.008*		0.742		1.000		0.004*	

Position variables

Table 6 shows the value of the outcome variables $Y90_{Head}$ and $Zmin_{sternum}$ for each of the subjects participating in the study when they were not using the head support system (No SS column) and when they were using it (SS column), per restraint type.

Values for the mean and standard deviation within each category are also provided.

The results obtained in the comparison between using and not using the head support system are also included in Table 6 (p-value row).

Statistically significant differences were found for the lateral head position ($Y90_{Head}$) regardless of the restraint used by the occupant. In the case of the comparison of the vertical minimum position of the sternal notch, there were statistical significant differences only within the Low-Back booster group.

Belt fit in trials with and without the head support system

Table 7 shows the percentage of fames exhibiting poor belt positions depending on the use of the head support system and per restraint group.

The results of the Wilcoxon test comparing between using and not using the head support system are also included in Table 7 (p-value row). In terms of belt fit, the main effect of using the head support system was observed within the Low-Back booster seat, followed by the No booster group. No significant effects were found within the High-Back booster group.

DISCUSSION

Comparison to Forman et al. (2011)

Restrained volunteers without using the head support system exhibited a poor belt position with respect to the sternum and shoulder in almost 50% of the video frames examined. Forman et al. (2011) also pointed out the importance of the lateral motion of the head, especially within the Low-Back Booster and the No Booster groups, and its impact on a negative belt fit. This study also found that using a high-back booster seat produced a significant decrease in the number of poor belt fit frames and in the 90^{th} percentile of the absolute value of the relative lateral head motion. These observations were consistent with the reduction of head and face injuries that can be related to the use of high back booster seats and the consequent belt fit improvement as suggested by other field studies such as Arbogast et al. (2005).

The use of the head support system reduced considerably the differences between the restraint groups found in Forman's study. The only belt fit significant differences were observed in the "Off shoulder" category, in which children in a low-back booster seat were overexposed compared to the other two restraint conditions. As shown in Table 7, although using the head support system reduced the average frame percentage with a poor shoulder belt fit, the system did not cause a substantial change from the observations without the head support.

As for the lateral motion of the head, only the group not using the booster showed a significant relationship with increasing values of $Y90_{Head}$. Contrary to the findings in Forman et al. (2011), the use of a high-back booster seat was not associated to a reduction in the lateral displacement of the head when the head support was present.

Head support system

This manuscript found that the use of the head support system reduced the frequency of the exposure of the pediatric occupants to extreme lateral head position (given by $Y90_{Head}$) regardless of the restraint used and to downward motions of the sternal notch ($Zmin_{sternum}$) in the Low-Back Booster group. The use of the system also improved significantly the occupant's shoulder belt fit within the No Booster and Low-Back Booster groups. The effect of the system in the High-Back Booster group was inappreciable.

In a case cross-over study involving 41 adult volunteers, Lopez-Valdes et al. (2012) had shown that the use of the head support system reduced significantly the incidence of severe and moderate out-of-position events during night driving. The current investigation involving pediatric occupants used the same study design and the findings support the conclusions of the adult study.

Error analysis

Forman et al. (2011) discussed the influence of estimating the lateral position of the head using a single marker located at the center of the forehead. The location of the marker is potentially affected by the rotation of the head, causing artifactual motion observations of a magnitude up to the length of the head (approximately 6 cm). To check that the differences identified in the study were relevant even in the worst-case scenario (that there was a maximum error of 6 cm in the lateral measurement of the position of the head), the values in the no booster group were found to be still significantly greater than the original ones in the booster group ($p<0.01$). Forman et al. (2011) also assessed the percentage of frames showing rotation of the head, finding that they were equally distributed across the restraint groups. This study concluded that adjusting for head rotation artifacts would not have affected the conclusions of the study.

As for the analysis of the video frames, only one individual scored the information from the videos, to avoid subject-variability in the assessment. However, a quality check was done using a second individual and no differences were observed between the two.

As for the number of samples analyzed per trial, the current sample size was able to detect statistically significant differences between the groups. Thus, it was considered that it was a sufficient approximation to the population of frames per subject.

Limitations of the analysis

This study included the vertical motion of the sternal notch as one of the outcome variables of the evaluation. As indicated in Figure 2 and Table 3, the sternal marker was obscured during some of the trials, especially within the No Booster group. It was not possible to establish whether the recorded position for the marker was an upper limit or not. However, the Wilcoxon test did not find significant differences using the truncated values, so nothing was concluded regarding the position of the sternum within the No-Booster group. The only significant differences in the position of the sternal notch were found in the Low-Back Booster group in which some of the measured values were also truncated. The Wilcoxon test was repeated without including these subjects and the comparison still found statistically significant differences (p=0.015) associated to the use of the head support system.

In the assessment of the impact of the head support system on the belt, the Kruskal-Wallis method was chosen to compare between the three groups and the Mann-Whitney test using the Bonferroni correction was used to identify the pair exhibiting statistically significant differences. Both methods have less statistical power than their parametric counterparts, but the reduced sample size within each group recommended its use. Despite of it, it was possible to identify differences within the “Off shoulder” category.

The experimental setup was designed to facilitate the children to fall asleep during the trials. Unfortunately it was not possible to assess whether the volunteers fell asleep without disturbing them and influencing the observations. This is a limitation of the analysis since the status of the volunteer likely influenced the observed results. The underlying methodological assumption is that the bias introduced in the analysis by being asleep or awake was equally distributed between the trials using the head support and those in which the support was not used.

Future work

As pointed out in Forman et al. (2011), the use of a lateral camera that could allow the assessment of the head support system in the sagittal plane would be beneficial to understand how the system influences the flexion of the head and spine.

Also, while the system has been shown to improve the position of the occupants in the frontal plane with an associated benefit of improving the shoulder belt fit during normal driving, the question of how this system would act in case of a collision still remains unknown. Since the system constrains the motion of the head, such impact studies should address the potential generation of cervical forces and moments that could modify the injury outcome of the crash.

CONCLUSION

A case crossover observational study was performed on 30 pediatric volunteers to assess the effect of using a head support system on the lateral position of the head, vertical position of the sternum and shoulder belt fit. Occupants were appropriately restrained during the trials and, for the purpose of the assessment, they were split in three groups depending on the restraint used (High-back Booster, Low-Back Booster, No Booster). Compared to the control group, the head support reduced significantly the 90th percentile value of the absolute value of the relative lateral motion of the head, regardless of the restraint. The system also reduced the maximum downward position of the sternal notch within the Low-Back Booster group. Last, the use of the head support improved significantly the percentage of video frames with a correct shoulder belt fit in the Low-Back Booster and the No Booster groups.

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APPENDIX

Figure A.1 shows the markers used on the volunteers to identify and measure the position of the center of the head and the sternal notch in the video frames

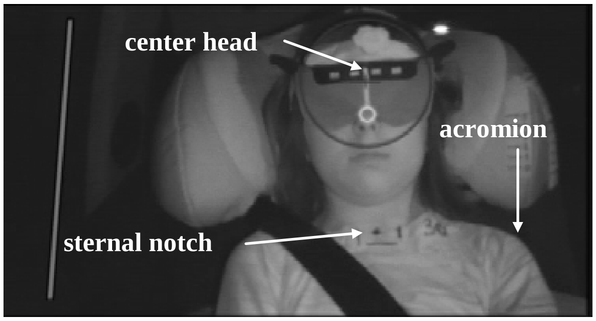

Figure A1: Typical video view with the center head and sternal-notch markings highlighted

Figure A2 illustrates the definition of the three poor fit categories for the shoulder belt and compares it to an acceptable belt position. These are the definitions also used in this study to assess the shoulder belt fit on the volunteers.

Figure A2: Illustrations of the various belt fit definitions. a) Off of the shoulder – the belt crosses the upper arm lateral to the acromion. b) Into neck – the belt is visibly pressing into or supporting the neck. c) Sternum – any portion of the belt crosses the occupant midline superior to the sternal notch marking. d) No "poor" belt position notes.