Child Posture and Shoulder Belt Fit During Extended Night-Time Traveling: An In-Transit Observational Study.

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ABSTRACT – Understanding pediatric occupant postures can help researchers indentify injury risk factors, and provide information for prospective injury prediction. This study sought to observe lateral head positions and shoulder belt fit among older child automobile occupants during a scenario likely to result in sleeping - extended travel during the night. An observational, volunteer, in-transit study was performed with 30 pediatric rear-seat passengers, ages 7 to 14. Each was restrained by a three-point seatbelt and was driven for seventy-five minutes at night. Ten subjects used a high-back booster seat, ten used a low-back booster seat, and ten used none (based on the subject height and weight). The subjects were recorded with a low-light video camera, and one frame was analyzed per each minute of video. The high-back booster group exhibited a statistically significant ($p<0.05$) decrease in the mean frequency of poor shoulder belt fit compared to the no-booster and low-back booster groups. The high-back booster group also exhibited statistically significant decreases in the 90th percentile of the absolute value of the relative lateral motion of the head. The low-back booster group did not result in statistically significant decreases in poor shoulder belt fit or lateral head motion compared to the no-booster group. These results are consistent with the presence of large lateral supports of the high-back booster which provided support to the head while sleeping, reducing voluntary lateral occupant motion and improving shoulder belt fit. Future work includes examining lap belt fit in-transit, and examining the effects of these observations on predicted injury risk.

INTRODUCTION

The postures of child automobile occupants are highly variable, affected by individual behaviors, anthropometries, external stimuli, and the restraints used (Andersson et al. 2010, Charlton et al. 2010). Posture has the potential to affect factors contributing to injury risk during a collision, including the interaction of the child with restraints, the kinematics of the child, and the potential for interaction with other structures in the interior of the vehicle (van Rooij et al. 2005).

Understanding realistic pediatric occupant postures can help researchers identify potential injury risk factors, facilitating the development of protective countermeasures. For example, in the last two decades research into post-toddler postures in adult seats highlighted concerns such as poor lap belt and shoulder belt fit (Arbogast et al. 2007, Bidez and Syson 2001, Jermakian et al. 2007, Nance et al. 2004, Reed et al. 2005a, Klinich et al. 1994, Nance et al. 2004, Reed et al. 2005a). Such observations prompted recommendations, and increases in use, of belt-positioning booster seats (Jermakian et al. 2007, Klinich et al. 1994, Sherwood et al. 2006, Winston et al. 2003, Winston et al. 2004).

In addition to the identification of risk factors, understanding the range of possible child postures can provide input for biomechanical studies seeking to predict injury risk in simulated collisions. Typical biomechanical evaluations (sled tests, full-scale crash tests, crash simulations) use surrogate occupants (dummies or computer models) seated in a position either defined by an industry standard, or by the average position observed in a laboratory posture study (e.g., Reed et al. 2005b, Reed et al. 2006). Limited studies, however, have sought to investigate the sensitivity of predicted child occupant responses (including injury risk) to changes in surrogate occupant posture (Arbogast et al. 2007, van Rooij et al. 2005). While in some cases out-of-position biomechanics studies should target artificially defined "worst case scenarios", some studies may seek to target typically-occurring positions. This requires quantified information on the range and distribution of postures observed in the field.

Previous investigations into child occupant posture and belt fit fall into three categories: laboratory studies, inspection studies, and observational studies. Laboratory studies observe and measure postures of children volunteers seated in a vehicle seat either mounted in a laboratory, or located in a stationary

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test vehicle (Huang and Reed 2006, Klinich et al. 1994, Reed et al. 2005, Reed et al. 2006, Reed et al. 2009). Those studies typically intend to quantify anthropometric characteristics in a single seating position, not necessarily investigating abnormal positions or time-varying postural changes or behaviors.

Inspection studies use on-site vehicle inspections and interviews to observe restraint use in the field (Decina and Knoebel 1997, Decina and Lococo 2005, Koppel and Charlton 2009, Morris et al. 2000, O'Neil et al. 2009, Paine and Vertsonis 2001, Staunton et al. 2005). These typically involve recording observations of motorists recruited at sites such as gas stations, parking lots, or police roadblocks. In those studies the recruitment and interview process interrupts normal transit, confounding the study of behavioral aspects of belt fit and posture. Instead, inspection studies typically seek to study basic restraint use and the quality of installation of child restraints.

In contrast to laboratory or inspection studies, observational studies (also termed “naturalistic” studies) seek to observe real-world behaviors, restraint fit, and postures of occupants in-transit. This typically involves recording occupants traveling in a test vehicle outfitted with video cameras mounted to the vehicle interior. Meissner et al. (1994) summarized an observational study of child occupant postures recorded using hidden cameras during extended trips, providing a qualitative description of types of postures observed. Charlton et al. (2010) described an observational study using an instrumented vehicle lent to 12 volunteer families. That study qualitatively described the overall postures of children ranging from 1-8 years during trips ranging from 2 minutes to 3.6 hours (mean 19 minutes). Andersson et al. (2010) described an observational study investigating the effect of two different booster seat designs on posture. That study performed organized trials with six children ages 3-6, with trips of 40-50 minute length. That study found that the children tended to sit with their head forward from the head rest for a greater percentage of time when seated in a booster with large lateral head supports. They attributed this behavior to the children wanting to see around the head supports, out the window or across the interior of the vehicle, and postulated that this may remove any protective benefit of the lateral head supports in a side impact collision. Although it was not the aim of that study to investigate belt fit specifically, the authors did note observing some cases of gross misfit such as the routing of the belt under the arm. All of the trials of Andersson et al. (2010), and most (89%) of the trips recorded by Charlton et al. (2010) occurred during daylight.

While the previous studies have provided valuable information on children’s behaviors during daytime driving, none have yet targeted postures attained while sleeping. Sleeping children have the potential to exhibit postures not normally observed while awake, given the relaxation of the body and the necessity of resting the head against a supporting object. This may be exacerbated for older, larger children, who do not benefit from the whole-body support provided by child safety seats. This study sought to examine the lateral head position and shoulder belt fit among older children (with booster seat use based on the size of the subjects) in an observational study with conditions conducive to sleep – extended trips during the night. This paper asked the questions: In an in-transit scenario likely to produce sleeping of child automobile occupants, is there any effect of booster seat presence or type on A) the 90th percentile lateral motion of the head and B) the position of the shoulder belt on the shoulder?

METHODS

An in-transit, observational study was performed with child volunteers. Lateral head positions and shoulder belt fit were observed during organized trips (trials) of 75 minute length, performed at night. The children were seated in the rear seat, and were observed with a low-light video camera mounted to the rear of the passenger seat. The study and analysis methods are described in detail below.

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. Subjects were selected to result in three equal groups (10 subjects in each) based on the booster seat height and weight criteria described below. Exclusion criteria included children with an acute illness, previous evidence of motion sickness, difficulty sleeping inside of a vehicle, morbid obesity, or any musculoskeletal disorder described as a disease. The study subjects were accompanied at all times by a parent or caregiver.

These trials were performed as a part of a concurrent study to investigate a positioning device to improve child passenger comfort and sleeping in-transit. The trials reported here represent the baseline (the tests performed in a default configuration without the device tested in the larger study). Informed consent information forms covering all aspects of the study procedures were presented to, reviewed, and approved by a parent prior to the initiation of each trial. The subject/parent pairs were provided with 70€ as compensation for their time. All recruitment and study procedures were reviewed and approved by the University of Navarra Ethics Review Board.

Trip Method

Trials consisted of organized trips in a study vehicle. To promote sleeping, each trip began at either 21:30 or 23:00 hours (depending on the randomized order of trials within the concurrent study mentioned above). The parents were asked to avoid having their children nap during the day of the trial, to feed them dinner as normal prior to the trial, and to dress them in light comfortable clothing.

During the trips, the study subject was seated in the right rear seat (of a left-driving vehicle), and a parent or caregiver was seated in the right front passenger seat. 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 1). The headband also included an integrated eye-shade to further promote sleeping. The child was then seated and the seatbelt was installed, and the child was asked to sit up-right with their head back to record an initial position.

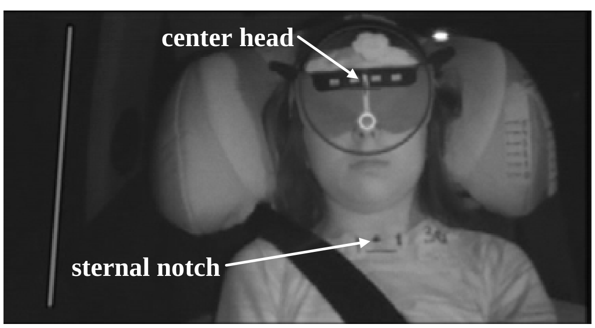

Figure 1: Typical video view with the center head and sternal-notch markings highlighted (also shown: video-view reference marks that were added during post-processing).

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.

The trips consisted of a combination of city and highway driving (approximately equal mix) on a pre-determined circuit in the vicinity of Pamplona, Spain. All trials were performed in a 2005 mid-sized, luxury, sports utility vehicle. The vehicle was piloted by a dedicated study driver.

Throughout the trip, the child's posture in the coronal plane was recorded with a camera (Sony Handycam model DCR-SR35) with low-light, infrared recording capability. The camera was mounted underneath the headrest of the front passenger seat. A second camera was used to record an orthogonal side-view of the subjects. This view was obscured, however, by the lateral head supports in the high-back booster cases. Because this represented a systematic, biased data loss, the side-view camera was not used in the analysis presented here.

The trips were recorded for a duration of 75 minutes. Temperature in the vehicle interior was controlled to between 22 and 23 C. The children were asked to relax comfortably, close their eyes, and to sleep if they wished. 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.

Video Analysis and Variables

A sample of 75 video frames (the first frame per each minute of video) was analyzed for each trial. Output variables were chosen to quantify the change in lateral position of the head in the coronal plane, and to qualitatively describe the fit of the shoulder belt on the shoulder.

The shoulder belt fit was examined for each selected frame. The fit was qualified as "off of the shoulder" if the entirety of the belt crossed the upper arm lateral to the acromion (Figure 2a). The fit was qualified as "into the neck" if the belt was visibly pressed into the lateral surface of the neck, or if the belt was supporting the neck (Figure 2b). The fit was qualified as "above the sternum" if any portion of the belt crossed the occupant midline superior to the sternal notch marker (Figure 2c). Each of these were considered "poor" belt positions.

The position of several points on the head and thorax were digitized for each video frame. These included the position of three markers on the forehead, the tip of the nose, the inferior-most points of the ears, and a marker on the sternal notch. These points were digitized in each frame using Phantom High Speed Camera Control software (Version 9.0.649.0, Vision Research Inc.). Because the purpose of the current study was to examine lateral head motion, only the position of the center forehead marker is presented here (Figure 1). Whenever the marker moved outside of the field of view, the frame number and direction

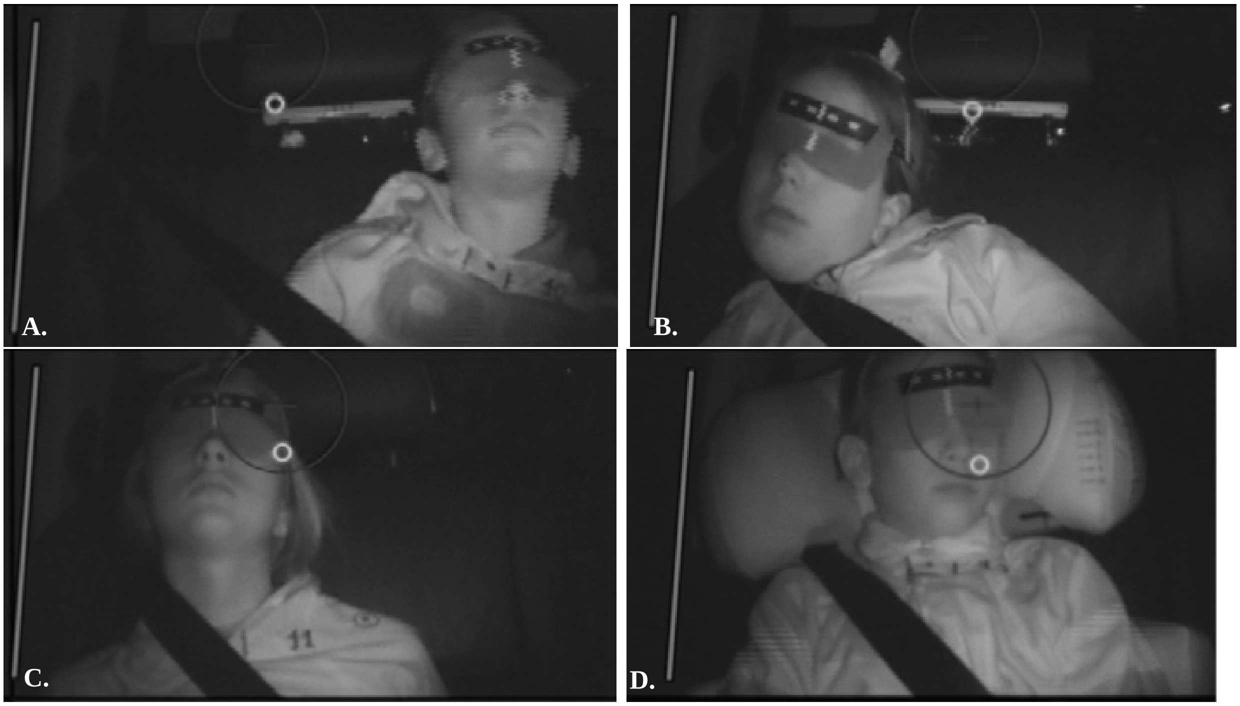

Figure 2: Illustrations of the various belt fit definitions. A) Off of the shoulder – the belt crosses the upper arm lateral to the acromion. B) Into the neck – the belt is visibly pressing into or supporting the neck. C) Above the sternum – any portion of the belt crosses the occupant midline superior to the sternal notch marking. D) No "poor" belt position notes.

of the excursion was noted. When the marker was obscured or mispositioned, the position entry for that frame was left blank.

Analysis

Belt position. The qualitative belt position notes were used to study the percentage of trip time in which the various types of "poor" belt positions were observed. The percentage of frames exhibiting each belt-position type was determined for each subject. The resulting values were continuous variables (between 0 and 1) representing sample-derived percentages of trip time spent with each belt position type, for each subject. These variables are termed P_{any} (percentage of frames with any poor belt position), P_{neck} (belt pressing into the neck), $P_{sternum}$ (belt above the sternal notch), and $P_{shoulder}$ (belt laterally off of the shoulder) for the remainder of this manuscript.

Head position. The lateral motion of the center forehead marker was determined for each analyzed frame. The initial (time zero) position was subtracted from the position in each frame to determine the relative lateral displacement of the marker. Whenever the marker moved laterally out of the frame, the displacement value was truncated to the maximum value observable within the frame for that subject (note: because the relative displacement was reported, the truncation values varied between subjects due to differences in the initial position of the head).

Because truncated values were present in some observations, non-parametric descriptors were used to summarize the head displacement data. Maximum and minimum values, and 10th, 50th, and 90th percentile values were determined for each subject. The 90th percentile of the absolute value of the lateral displacement was also calculated for each subject. This variable is termed Y_{90} for the remainder of this manuscript.

Comparison Between Groups. The P_{any}, P_{neck}, $P_{sternum}$, $P_{shoulder}$, and Y_{90} values were compared between the three study groups in two different ways. First, an analysis of variance (ANOVA) was performed. A two-way ANOVA was performed with the independent variables defined as the presence of a low-back booster ("low-back" = 0 or 1) and the presence of a high-back booster ("high-back" = 0 or 1). In that analysis the no-booster group was used as a baseline for comparison. That analysis produced comparisons of the means of the low-back group and the high-back booster group relative to the no-booster group. An additional two-way ANOVA was performed with the presence of no booster ("no-booster" = 0 or 1) and the presence of a high-back booster as independent variables, with the low-back booster group as a baseline. That produced a comparison between the no-booster and low-back booster groups (redundant with the ANOVA above), and a comparison between the high-back and low-back booster groups. Differences were considered to be statistically significant if the p-values were less than 0.05.

Although ANOVA is useful in identifying statistically significant differences between groups of data, it does not provide insight into the magnitude of those differences. Linear regression models were developed to examine the magnitude of any potential differences between the means of the no-booster group (the baseline) and the low-back and high-back booster groups. The linear regression models took the form shown in Equation 1, where C_{LB} is the model coefficient associated with the use of a low-back booster, C_{HB} is the model coefficient associated with the use of a high-back booster, C_{None} is the coefficient (constant) associated with the baseline condition of the group with no booster seat. The variable LB is equal to one if a low-back booster is used; the variable HB is equal to one if a high-back booster is used. The output variable X represents the dependent variable of interest (P_{any}, P_{neck}, $P_{sternum}$, $P_{shoulder}$, or Y_{90}).

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

RESULTS

All thirty trials were performed successfully. The characteristics of the study subjects are shown in Table 1.

Table 1: Subject Information

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

* N = None; HB = High Back Booster; LB = Low Back Booster

Belt Position

The percentages of frames exhibiting poor belt positions are shown in Table 2 and Figure 3. The no-booster group exhibited poor belt positions during an average of 78% of the frames examined, with a range from 16% to 99%. The most commonly observed poor belt position in that group consisted of the belt impinging on or supporting the neck ("into the neck"). In the low-back booster group, 61% of the frames exhibited a poor belt position. In the high-back booster group, 17% of the frames exhibited a poor belt position.

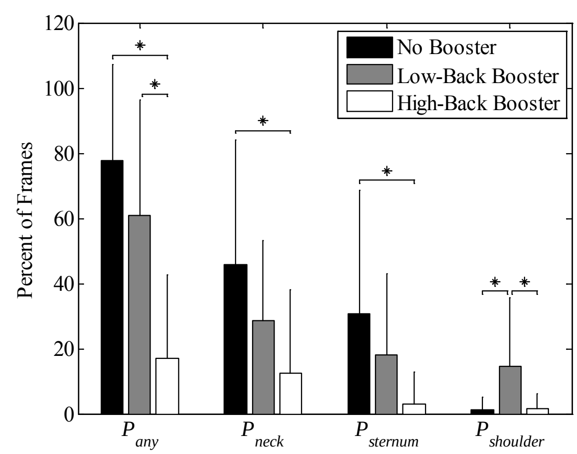

Figure 3: Mean values for the percent of frames exhibiting poor belt positions, by booster seat use and by belt position category. The error bars indicate + one standard deviation. The asterisks indicate statistically-significant ($p<0.05$) differences between group pairs (via two-way ANOVA).

Relative Lateral Head Position

Observations of the lateral head position (including truncated instances of the marker outside of the frame) were recorded for 81% of the frames (1825 frames out of a possible 2250). In the remainder, the head marker was within the video frame, but was

Table 2: Percent of frames (N=75 per subject) exhibiting the various "poor" belt position classifications, by subject number and booster seat type (standard deviations for means shown in parentheses).

		Belt Position			
	Subject	Any Bad, P_{any}†	Into Neck, P_{neck}	Above Sternum, $P_{sternum}$	Off Shoulder, $P_{shoulder}$
No Booster Seat	11	40.0	26.7	13.3	0.0
	14	85.3	85.3	0.0	0.0
	15	94.7	0.0	94.7	0.0
	16	16.0	4.0	0.0	12.0
	17	98.7	98.7	0.0	0.0
	20	98.7	90.7	8.0	0.0
	21	90.7	37.3	53.3	0.0
	23	96.0	0.0	96.0	0.0
	26	98.7	66.7	32.0	0.0
	29	57.3	48.0	9.3	0.0
	Mean	77.6 (29.5)	45.7 (38.3)	30.7 (38.0)	1.2 (3.8)
Low Back Booster Seat	1	88.0	20.0	0.0	68.0
	5	74.7	74.7	0.0	0.0
	7	62.7	58.7	4.0	0.0
	10	90.7	13.3	54.7	22.7
	13	57.3	40.0	9.3	8.0
	18	46.7	14.7	14.7	17.3
	19	90.7	38.7	26.7	25.3
	22	1.3	0.0	0.0	1.3
	25	96.0	26.7	69.3	0.0
	27	1.3	0.0	0.0	1.3
	Mean	60.9 (35.3)	28.7 (24.5)	17.9 (25.0)	14.4 (21.3)
High Back Booster Seat	2	0.0	0.0	0.0	0.0
	3	62.7	62.7	0.0	0.0
	4	0.0	0.0	0.0	0.0
	6	60.0	60.0	0.0	0.0
	8	14.7	0.0	0.0	14.7
	9	0.0	0.0	0.0	0.0
	12	0.0	0.0	0.0	0.0
	24	1.3	1.3	0.0	0.0
	28	32.0	1.3	30.7	0.0
	30	0.0	0.0	0.0	0.0
	Mean	17. (25.5)	12.5 (25.7)	3.1 (9.7)	1.5 (4.6)

† Any poor belt position. Per-frame value equals one if either the "into neck", "above sternum", or "above sternum" variables equal one.

Table 3: 90th percentiles of the absolute value of the relative lateral head motion for each subject (Y_{90}), by booster seat type (standard deviations for means shown in parentheses)

No Booster		Low-Back Booster		High-Back Booster	
Subject	Y_{90} (cm)	Subject	Y_{90} (cm)	Subject	Y_{90} (cm)
11	19.3	1	35.4†	2	8.5
14	35.4	5	25.6	3	6.3
15	22.7	7	16.0	4	5.4
16	21.2	10	25.4†	6	9.1
17	25.4	13	22.2	8	12.1
20	22.6	18	26.9	9	10.0
21	23.3	19	14.2	12	7.8
23	12.0	22	3.0	24	3.2
26	26.7	25	31.1	28	7.0
29	25.0	27	11.1	30	7.6
Mean	23.4 (5.9)	Mean	21.1 (9.9)	Mean	7.7* (2.5)

† Truncated value.
* Significantly different than both the no-booster mean and the low-back booster mean ($p<0.05$, ANOVA).

obscured by an object, a body part, by video glitches, or by rotation of the head. Of the observations made, 4% (3% of the total frames) were notes of the marker positioned outside of the field of view.

The maximum, minimum, and percentile values for the relative lateral head displacement for each subject are shown in Figure 4. The 90th percentiles of the absolute values of the relative lateral head displacement (Y_{90}) are shown in Table 3. The minimum relative head displacement values ranged from -35 cm (a truncated value; negative indicates motion towards the subject's right, towards the window/door) to -4 cm. The maximum relative displacement ranged from 0 cm to 30 cm. The 50th percentile (median) relative displacements ranged from -35 cm (a truncated value) to 8 cm. The 90th percentile, absolute value lateral head displacements ranged from 3 cm to 35 cm (a truncated value).

Group Comparison

The results of the ANOVA comparisons are shown in Figure 3 and Table 3. For the high-back booster, the mean values of P_{any} (percentage of frames with any poor belt position), P_{neck} (belt pressing into the neck), $P_{sternum}$ (belt passing above the sternal notch), and Y_{90} (90th percentile, absolute value lateral head motion) were significantly different than the no-booster group ($p<0.05$). For the low-back booster group, only the mean value of $P_{shoulder}$ (belt passing lateral to the acromion) was significantly different than the no-booster group. The mean values of P_{any}, $P_{shoulder}$, and Y_{90} were significantly different between the high-back and low-back booster groups.

The coefficients for the linear regression models are shown in Table 4. The C_{None} coefficients for all of the models were significantly greater than zero ($p<0.001$). This indicates that the no-booster group resulted in mean values for each of the output variables (P_{any}, P_{neck}, $P_{sternum}$, $P_{shoulder}$, or Y_{90}) that were significantly greater than zero. The C_{LB} and C_{HB} coefficients indicate if, and by what magnitude, the presence of a low-back or high-back booster alters the mean values of the output variables relative to the baseline no-booster condition. For example, in the P_{any} model the C_{None} coefficient indicates that the subjects of the baseline no-booster group exhibited any poor belt position in an average of 78% of the video frames examined. The model coefficient associated with low-back booster use (C_{LB}) was not significantly different than zero ($p=0.231$), indicating that the mean P_{any} value for the low-back booster group was not significantly different from the no-booster group. In contrast, the coefficient associated with high-back booster use (C_{HB}) was significantly

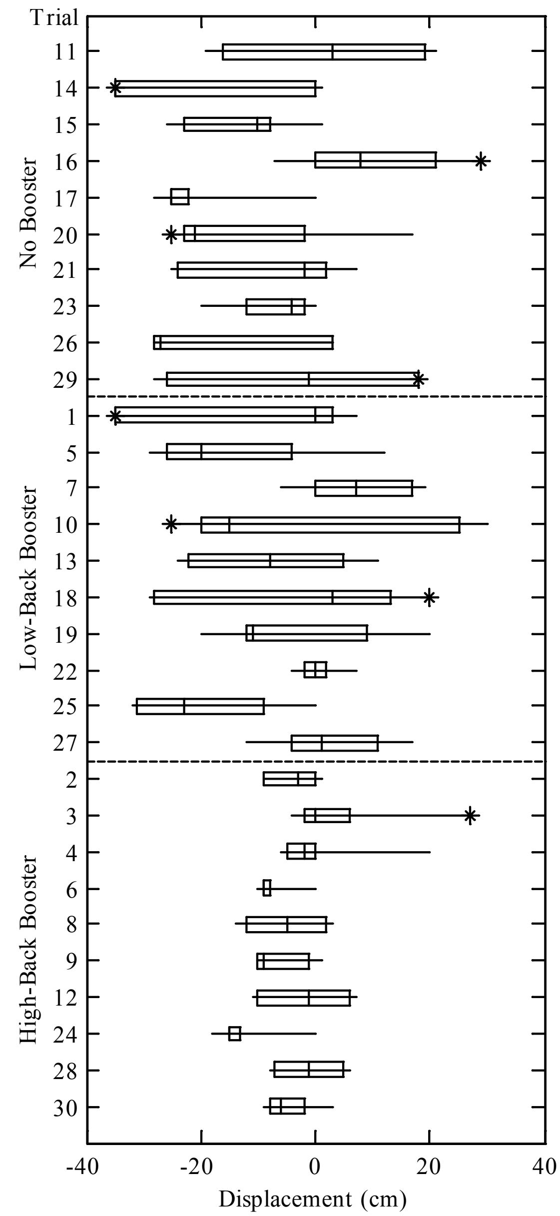

Figure 4: Box plots of the lateral head displacement (from the initial position) showing the 10th, 50th, and 90th percentile values, and the maximum and minimum values. Negative values indicate motion towards the subject's right, towards the window/door. The asterisks indicate values that were truncated due to the marker traveling outside of the video frame.

different from zero ($p<0.001$), indicating that the mean P_{any} was significantly different from the no-booster group. The point estimate for that coefficient (-0.607) indicates that the high-back booster group exhibited a decrease in the mean P_{any} value of 61 percentage points relative to the no booster group. The 95% confidence interval for that coefficient indicates that decrease may range from 89% to 33%.

Table 4: 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).

			Coefficient	p†	95% C.I.
Belt Position, Percentage*	Any Bad, P_{any}	No Booster, C_{None}**	0.777	<0.001	0.579, 0.975
		Low Back Booster, C_{LB}	-0.167	0.231	-0.447, 0.113
		High Back Booster, C_{HB}	-0.607	<0.001	-0.887, -0.327
	Into Neck, P_{neck}	No Booster, C_{None}**	0.458	<0.001	0.262, 0.654
		Low Back Booster, C_{LB}	-0.171	0.217	-0.449, 0.107
		High Back Booster, C_{HB}	-0.33	0.021	-0.611, -0.055
	Above Sternum, $P_{sternum}$	No Booster, C_{None}**	0.306	0.001	0.132, 0.480
		Low Back Booster, C_{LB}	-0.127	0.300	-0.374, 0.120
		High Back Booster, C_{HB}	-0.275	0.030	-0.522, -0.028
	Off Shoulder, $P_{shoulder}$	No Booster, C_{None}**	0.012	0.768	-0.071, 0.095
		Low Back Booster, C_{LB}	0.131	0.030	0.014, 0.248
		High Back Booster, C_{HB}	0.002	0.972	-0.115, 0.119
Lat. Head Position, Abs. Value, 90th %, Y_{90} (cm)		No Booster, C_{None}**	23.6	<0.001	19.2, 28.1
		Low Back Booster, C_{LB}	-2.26	0.466	-8.51, 4.00
		High Back Booster, C_{HB}	-14.4	<0.001	-20.7, -8.18

* Expressed as decimal values ranging between 0 and 1.
** Constant values serving as the baseline for comparison.
† P-value. Probability that the coefficient is equal to zero.

Consistent with the ANOVA results, the high-back booster group exhibited statistically-significant ($p<0.05$) negative (decreasing) model coefficients for the mean P_{any}, P_{neck}, $P_{sternum}$, and Y_{90} values, relative to the no-booster condition. In addition to the P_{any} results described above, the model coefficients indicate a decrease of 33 percentage points for the mean P_{neck} value, 28% for $P_{sternum}$, and 14 cm for Y_{90}. The low-back booster group did not result in any statistically-significant model coefficients, except for a small (13%), but statistically significant ($p=0.03$) positive (increasing) coefficient for the $P_{shoulder}$ variable.

DISCUSSION

Shoulder Belt Fit

Forty-six percent of the frames examined exhibited a poor belt position of a medial nature, with the belt impinging on the neck or located superior to the sternal notch. Placing the belt in this manner has the potential to load the cervical spine, carotid arteries, trachea, and other vulnerable structures of the neck during a collision. Although belt-related spine and neck injuries to children are rare (Garcia-España and Durbin 2008), they can have devastating consequences in the circumstances in which they occur (Deutsch and Badawy 2008, Jeffery and Cook 1991, Lynch et al. 1996, Skold and Voigt 1977). The high-frequency of medial-related poor belt positions should also be considered when designing deployable devices integrated into the shoulder belts of rear seat restraints, such as pretensioners (Forman et al. 2008) or belt-integrated airbags (Forman et al. 2010).

In six percent of the frames the belt was located laterally off of the shoulder. Shoulder belts are designed to load the relatively strong structures of the clavicle, shoulder, and upper chest. Placing the shoulder belt laterally to the acromion limits the benefit gained from the strength of those structures. Instead, such a position would likely result in loading of the arm and mid-to-lower chest during a collision. This reduction in restraint of the upper torso may also allow greater motion of the chest and head in a collision (Sherwood et al. 2005), resulting greater risk of striking interior surfaces or other occupants.

Lateral Head Position

A considerable range of lateral head positions was observed (Figure 4), especially within the no-booster and low-back booster groups. Most of this motion occurred to the occupants' right, with 73% of the median values occurring in the negative (outboard) direction. This is consistent with a propensity to rest the head towards (or against) the window when attempting to sleep in-transit. This is also consistent with the relatively high frequency of medial-related "poor" shoulder belt positions, with the belt impinging on or supporting the neck, or with the belt passing superior to the sternal notch.

The lateral head position was truncated by moving outside of the visible range for 3% of the video frames. It is unlikely that this limited truncation affected the results of this study. Statistically significant differences were observed between the high-back booster group and the low-back and the no-booster groups. Since the data truncation only affected the 90th percentile, absolute value lateral head positions of select low-back booster cases (Table 3), removing this truncation would tend to increase the observed differences between that group and the high-back booster group. Removing the truncation would not affect the observed differences between the 90th percentile values of the high-back and no-booster groups. Thus, even if the limited truncation present was avoided, the conclusions of this study would remain unchanged.

Effect of Booster

The subjects with a high-back booster seat exhibited statistically significant decreases in the percentage of frames with poor belt fit, and in the 90th percentile of the absolute value of the relative lateral motion of the head, compared to the group with no booster seat. This is consistent with previous laboratory studies that have observed improved shoulder belt fit in static conditions with high-back boosters (Reed et al. 2009). This is the first study (to the authors' knowledge) to confirm those laboratory observations via an in-transit observational study targeting sleeping children positioned at their own will.

The low-back booster group tended to exhibit decreases in most of the poor belt position variables compared to the no booster seat group, however most of those decreasing trends were not statistically significant. The most notable exception is the incidence of the "off-shoulder" poor belt position. Although the low-back booster tended to exhibit a lesser incidence of any poor belt position relative to the no-booster group, the low-back booster group exhibited a statistically-significant greater incidence of the "off-shoulder" poor belt position relative to the no-booster group. This suggests that among the subjects and frames that exhibited poor belt positions, a greater proportion of the low-back booster cases tended to lean inboard, causing the belt to slip laterally off of the shoulder. In contrast, a greater proportion of the no-booster, poor belt position cases tended to lean outboard, causing the belt to press into the neck or pass above the sternal notch. As discussed below, the injury risk implications of these two types of poor belt fit are currently unknown. Future work should include studying the implications of these positions to identify priorities for improvement.

The high-back booster group exhibited statistically significant decreases in the percentage of frames with poor belt fit, and in the 90th percentile lateral head motion, relative to the low-back booster group. This is somewhat in contrast to the daytime observational study of Andersson et al. (2010). That study observed that the presence of large lateral head supports on a high-back booster resulted in children moving their heads outside of the volume of the booster seat to gain a better view out the window or across the interior of the vehicle. In the current study, the large lateral head supports provided support for the head while sleeping, resulting in less lateral motion of the head and improved shoulder belt fit. Such contrasting results are not simply academic, but could potentially have real implications in booster seat design. In the absence of other information, the results of the Andersson et al. study could potentially be interpreted to criticize high-back boosters with large lateral head supports. The current study, however, demonstrates a benefit of booster seats with large lateral head supports under conditions not considered by previous studies. It is unknown, however, if a low-profile high-back booster (like the alternative studied by Andersson et al.) would provide similar lateral head support to a sleeping child.

The observations of the current study are consistent with the field injury trends observed by Arbogast et al. (2005). That study found that high-back booster seats reduced the risk of AIS 2+ injuries (Abbreviated Injury Scale 1990 Revision) to pediatric rear seat occupants in side collisions compared to children without a booster seat, mostly through a reduction of head injuries. Low-back booster seats did not result in a statistically significant reduction of injury risk. The current study suggests several mechanisms that may result in the reduction of risk with a high-back booster, including improved shoulder belt fit, maintaining a greater initial distance between the head and the door, and the presence of the lateral head support wings which may potentially cushion a laterally-directed blow.

It is important to note that the subjects in this study were not randomized by size - booster seats were assigned based on the height and weight of the subjects. Those criteria were designed specifically to improve belt fit for smaller children whose height would result in a poor belt fit and posture with an adult restraint and seat. The results suggest that both the high-back and low-back booster were successful in this regard, in that the shoulder belt appeared to fit well with both groups when the children were seated upright with their backs against the seats. Likewise, the children in the no-booster group were tall enough (by design) so that the belt fit well when they were sat upright. Therefore, the variation in belt fit among the test groups was not necessarily a function of the subject anthropometry (in relation to the geometry of the seats and restraints), but instead was a function of the voluntary motion of the children during travel. Because of the lateral support provided, the children moved less with the high-back booster, resulting in a more consistently appropriate fit of the shoulder belt.

Head Rotation

This study used a marker located at the center of the forehead to quantify head motion. The location of this marker may be affected by the rotation of the head, potentially causing artifactual motion observations of a magnitude up to the radius of the head (approximately 6 cm). This potential error is small, however, compared to the difference in 90th percentile lateral head motions observed between the groups (approximately 16 cm difference between the means of the high-back and the no-booster groups). As a check against the worst-case scenario – even if the maximum possible error of 6 cm were subtracted from absolute value head motions of the no-booster group, the mean 90th percentile values of that group would still be significantly greater than the original values of the high-back booster group ($p<0.01$, ANOVA). That represents an extreme example, attributing a 100% study group bias to any artifacts resulting from head rotation. In reality, head rotation artifacts were relatively unbiased (i.e., similar across the study population). The magnitude of head rotation can be qualitatively assessed by examining the number of frames in which the lateral-most markers on the forehead were obscured by rotation of the head to the left or right. The percentage of frames with a rotation-induced obscuring of those markers was not significantly different between any of the groups ($p>0.1$ for all study group comparison combinations, based on ANOVA). As a result, it is unlikely that adjusting for head rotation artifacts would affect the conclusions of this study regarding the effect of booster seats on lateral head motion.

Video View

This manuscript only presents the motion of the occupants in the coronal plane, recorded by an anterior video view. A lateral-view video camera was present during this study, but it provided limited information due to visual obstruction by the lateral head supports of the high-back booster. Previous observational studies recorded rear seat occupant behaviors using oblique video views (Andersson et al. 2010, Charlton et al. 2010). While that type of video view renders it difficult to determine quantitative measures of motion in any of the principal planes, it does facilitate the qualitative observation of motion in several different axes. Future observational studies may consider using a combination of video cameras located orthogonal to the principal planes for quantitative motion analyses, in addition to obliquely-mounted cameras to obtain qualitative overall descriptions.

Future Work

The goals of this study were to examine shoulder belt fit and lateral head motion in older children sleeping in-transit. The shoulder belt represents just one point of concern for belt fit among pediatric occupants – the other being the fit of the lap belt. Improper lap belt fit may lead to an increased risk of loading of the abdomen or lumbar spine during a collision (Arbogast et al. 2007). Like with the shoulder belt, it is possible that the lap belt may migrate into a sub-optimal location as the child moves during transit. Future work could include examining real-world lap belt fit with sleeping children in-transiit.

Finally, this study intentionally used conservative definitions of “poor” belt fit, relating to belt position categories that were distinctly definable. The nature and magnitude of the effects of these belt positions on injury risk remain to be investigated. It is also likely that there exist belt and body positions other than those classified here as “poor” that may negatively impact injury risk (van Rooij et al. 2005). Future efforts should include exploring the effects of body and belt position on predicted injury risk. This may be best accomplished through computer simulations, with the positions observed here serving as a realistic range to target for study.

CONCLUSION

This study observed the lateral head position and upper shoulder belt fit of thirty pediatric volunteers, while riding in the rear seat of a vehicle for an extended period during the night. The study group using a high-back booster exhibited a statistically significant ($p<0.05$) decrease in the mean frequency of poor shoulder belt fit, compared to the no-booster group and the low-back booster group. The high-back booster group also exhibited statistically significant decreases in the 90th percentile of the absolute value of the relative lateral motion of the head. The low-back booster group tended to exhibit decreases in the frequency of poor shoulder belt fit (compared to the no-booster group), but those decreases were not statistically significant ($p=0.231$ for any bad belt position). The low-back booster group did not result in decreases in the 90th percentile, absolute value, relative lateral motion of the head relative to the no-booster group. These results are consistent with the presence of large lateral head supports with the high-back booster, which reduced voluntary occupant motion by providing support to the head while sleeping. Future work could include expanding this study to examine lap belt fit in-transit, and examining the effects of these observations on predicted injury risk (potentially through computer modeling).

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