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Assessing Child Belt Fit, Volume I: Effects of Vehicle Seat and Belt Geometry on Belt Fit for Children with and without Belt Positioning Booster Seats

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16. Abstract

A laboratory study was conducted to quantify the effects of belt-positioning boosters on lap and shoulder belt fit. Postures and belt fit were measured for forty-four boys and girls ages 5 to 12 in four highback boosters, one backless booster, and on a vehicle seat without a booster. Belt anchorage locations were varied over a wide range. Seat cushion angle, seat back angle, and seat cushion length were varied in the no-booster conditions.

All boosters produced better mean lap belt fit than was observed in the no-booster condition, but the differences among boosters were relatively large. With one midrange belt configuration, the lap belt was not fully below the anterior-superior iliac spine (ASIS) landmark on the front of the pelvis for 89% of children in one booster, and 75% of children failed to achieve that level of belt fit in another. In contrast, the lap belt was fully below the ASIS for all but two children in the best-performing booster. Child body size had a statistically significant but relatively small effect on lap belt fit. The largest children sitting without a booster had approximately the same lap belt fit as the smallest children experienced in the worst-performing booster. Increasing lap belt angle relative to horizontal produced significantly better lap belt fit in the no-booster condition, but the boosters isolated the children from the effects of lap belt angles. Reducing seat cushion length in the no-booster condition improved lap belt fit but changing cushion angle did not.

Belt upper anchorage (D-ring) location had a strong effect on shoulder belt fit in conditions without shoulder belt routing from the booster. Unexpectedly, the worst average shoulder belt fit was observed in one highback booster with a poorly positioned shoulder belt routing clip. The shoulder belt was routed more outboard, on average, with a backless booster than without a booster, but raising the child also amplified the effect of D-ring location, such that children were more likely to experience poor shoulder belt fit due to outboard and forward D-ring locations when sitting on the booster. Taller children experienced more-outboard shoulder belt fit in conditions without shoulder belt routing by the booster and in the one booster with poor shoulder belt routing. Adjustable shoulder belt routing on three of the highback boosters effectively eliminated stature effects, providing approximately the same shoulder belt fit for all children. Seat back angle did not have a significant effect on shoulder belt fit.

The belt fit was measured in each test condition using the 6YO and 10YO Hybrid-III ATDs. ATD belt fit was strongly correlated with child belt fit across test conditions, but offsets between the ATD and child belt fit scores were observed due to anatomical and postural differences between the ATDs and children.

The results of this study have broad applicability toward the improvement of occupant restraints for children. The data show substantial effects of booster design on belt fit, particularly the effects of alternative lap and torso belt routing approaches. Regression analyses quantify the critical importance of belt anchorage location for child belt fit, providing an important foundation for efforts to optimize belt geometry for children. The strong correlation between ATD and child belt fit scores means that ATD-based measurements can reliably be used to assess booster and vehicle designs with respect to child belt fit.

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Metric Conversion Chart

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
In	inches	25.4	millimeters	mm
Ft	feet	0.305	meters	m
Yd	yards	0.914	meters	m
Mi	miles	1.61	kilometers	km
AREA				
in^2	squareinches	645.2	square millimeters	mm^2
ft^2	squarefeet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
Ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
ºF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	ºC
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N

lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
ºC	Celsius	1.8C+32	Fahrenheit	ºF
FORCE and PRESSURE or STRESS				
N	Newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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CONTENTS

ACKNOWLEDGMENTS 5

EXECUTIVE SUMMARY 9

1.0 INTRODUCTION 11

2.0 METHODS 13
- 2.1 Overview of Approach 13
- 2.2 Reconfigurable Vehicle Mockup and Belt Configurations 13
- 2.3 Boosters 19
- 2.4 Test Conditions 21
- 2.5 Participants and Standard Anthropometry 24
- 2.6 Three-Dimensional Anthropometry 25
- 2.7 Protocol 28
- 2.8 Belt Fit Measures 29
- 2.9 ATD Belt Fit Measures 32

3.0 RESULTS 33
- 3.1 Overview 33
- 3.2 Lap Belt Fit Across Booster Conditions 33
- 3.3 Effects of Lap Belt Angle on Lap Belt Score 37
- 3.4 Effects of Cushion Angle and Cushion Length on Lap Belt Score 38
- 3.5 Effects of Booster on Shoulder Belt Fit 40
- 3.6 Effects of Body Size on Shoulder Belt Fit 41
- 3.7 Effects of D-Ring Location on Shoulder Belt Fit 43
- 3.8 Effects of Seat Back Angle on Shoulder Belt Fit 45
- 3.9 ATD Belt Fit 46
- 3.10 Comparison Between Child and ATD Lap Belt Fit 47
- 3.11 Comparison Between Child and ATD Shoulder Belt Fit 49
- 3.12 Ideal Shoulder Belt Fit 52
- 3.13 Belt Tension 55

4.0 DISCUSSION AND CONCLUSIONS 56
- 4.1 Primary Observations 56
- 4.2 Design Features that Produce Good Belt Fit 58
- 4.3 Study Limitations 60
- 4.4 Applications 61
- 4.5 Future Work 62

REFERENCES 65
APPENDIX A: Booster Use Instructions 67
APPENDIX B: Method for Measuring Belt Fit with ATDs 71
APPENDIX C: Computing Child Lap Belt Fit 81

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EXECUTIVE SUMMARY

A laboratory study was conducted to quantify the effects of belt-positioning boosters on lap and shoulder belt fit. Postures and belt fit were measured for forty-four boys and girls ages 5 to 12 in four highback boosters, one backless booster, and on a vehicle seat without a booster. Belt anchorage locations were varied over a wide range. Seat cushion angle, seat back angle, and seat cushion length were varied in the no-booster conditions.

All boosters produced better mean lap belt fit than was observed in the no-booster condition, but the differences among boosters were relatively large. With one midrange belt configuration, the lap belt was not fully below the anterior-superior iliac spine (ASIS) landmark on the front of the pelvis for 89% of children in one booster, and 75% of children failed to achieve that level of belt fit in another. In contrast, the lap belt was fully below the ASIS for all but two children in the best-performing booster. Child body size had a statistically significant but relatively small effect on lap belt fit. The largest children sitting without a booster had approximately the same lap belt fit as the smallest children experienced in the worst-performing booster. Increasing lap belt angle relative to horizontal produced significantly better lap belt fit in the no-booster condition, but the boosters isolated the children from the effects of lap belt angles. Reducing seat cushion length in the no-booster condition improved lap belt fit but changing cushion angle did not.

Belt upper anchorage (D-ring) location had a strong effect on shoulder belt fit in conditions without shoulder belt routing from the booster. Unexpectedly, the worst average shoulder belt fit was observed in one highback booster with a poorly positioned shoulder belt routing clip. The shoulder belt was routed more outboard, on average, with a backless booster than without a booster, but raising the child also amplified the effect of D-ring location, such that children were more likely to experience poor shoulder belt fit due to outboard and forward D-ring locations when sitting on the booster. Taller children experienced more-outboard shoulder belt fit in conditions without shoulder belt routing by the booster and in the one booster with poor shoulder belt routing. Adjustable shoulder belt routing on three of the highback boosters effectively eliminated stature effects, providing approximately the same shoulder belt fit for all children. Seat back angle did not have a significant effect on shoulder belt fit.

The belt fit was measured in each test condition using the 6YO and 10YO Hybrid-III ATDs. ATD belt fit was strongly correlated with child belt fit across test conditions, but offsets between the ATD and child belt fit scores were observed due to anatomical and postural differences between the ATDs and children.

The results of this study have broad applicability toward the improvement of occupant restraints for children The data show substantial effects of booster design on belt fit, particularly the effects of alternative lap and torso belt routing approaches. The data quantify the critical importance of belt anchorage location for child belt fit, providing an important foundation for efforts to optimize belt geometry for children. The strong correlation between ATD and child belt fit scores means that ATD-based measurements can reliably be used to assess booster and vehicle designs with respect to child belt fit.

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1.0 INTRODUCTION

Children who cannot achieve good belt fit with vehicle belts alone should be seated in an appropriately sized harness restraint or in a belt-positioning booster. Children heavier than 40 lb seated in booster with a three-point vehicle belt are considered to be appropriate restrained. NHTSA recommends that children continue to use boosters until they reach age 8 unless they are 57 inches (1450 mm) tall (NHTSA 2007a). Child restraints and belt-positioning boosters have been shown to be effective in reducing the risk of injury. Elliot et al. (2006) found that the use of child restraints reduces the risk of fatality by about 28% over seat belts alone for children from 2 to 6 years of age. Durbin et al. (2003), in an analysis of data from a field survey of crash-involved child passengers, found that children 4 to 7 years of age using a belt-positioning booster were 59% less likely to be injured than those using a vehicle belt alone, after adjusting for driver, vehicle, and crash characteristics. Jeremakian et al. (2007) analyzed an expanded set of data from the same survey and found that the risk of abdominal injury was significantly lower for children age 4-7 using boosters compared with those using vehicle belts alone, but identified three children who experienced abdominal injuries in frontal impact while using belt-positioning boosters.

Boosters are designed to improve belt fit by altering the seated position of the child and, in most cases, by changing the belt routing. Good belt fit is characterized by placement of the belt in anatomical regions where the restraint forces can be directed onto the skeleton rather than soft tissues. During a frontal crash, the lap portion of the belt should engage with the front of the pelvis and the shoulder portion of the belt should load the clavicle. To achieve this loading pattern, the pre-crash position of the lap portion of the belt needs to be below the anterior superior iliac spine (ASIS) landmark on the upper edge of the front of the pelvis bone. A lap belt that starts out too high can lead to a kinematic pattern known as submarining, in which the pelvis slides down and under the belt and the body is restrained through abdominal soft tissue, rather than through loads applied to the bony pelvis. Belt loading to the abdomen produces a constellation of injuries known as seat belt syndrome.

The shoulder portion of the belt must be centered on the shoulder, as inboard as possible without contacting the head or neck. If the belt is too far inboard, the associated discomfort may lead to misuse such as putting the belt behind the back or under the arm. If the belt is too far outboard, the belt may slide off the shoulder and fail to properly restraint the torso during a crash, leading to excessive head excursion and increased injury risk.

Most rear vehicle seats are too long for children and small adults (Huang and Reed 2006), which can lead to slouching and poor belt fit (Klinich et al. 1994). A booster effectively shortens the seat cushion, allowing the child to sit comfortably with less slouching. A booster also raises the child by about 100 mm (Reed et al. 2006) which tends to improve both shoulder and lap belt fit, reducing neck interference and increasing the lap belt angle in side view relative to horizontal. Boosters also have features designed to alter the belt routing. Nearly all boosters have belt guides in the lap area, and many have guides to control shoulder belt position.

Boosters sold in the U.S. are subject to the dynamic testing and other requirements of Federal Motor Vehicle Safety Standard (FMVSS) 213. Among other criteria, boosters must pass dynamic frontal impact sled testing with one or more crash dummies (depending on the manufacturer's specified weight range for children) on a standard seating buck. Boosters are not required to meet static belt fit criteria. However, the dynamic testing does not adequately assess the belt fit provided by the boosters. Chamouard et al. (1996) compared the geometry of anthropomorphic test devices (ATDs) representing three- and six-year-old children to x-ray data and concluded that the substantial differences between ATDs and children in the pelvis area made the ATDs insufficiently sensitive to submarining. Moreover, the FMVSS 213 test procedures use a single, midrange belt and seat geometry that does not evaluate the ability of the booster to produce good belt fit in the disadvantageous conditions often found in vehicle rear seats.

Few studies have examined belt fit in belt-positioning boosters. Using categorical scales, Klinich et al. (1994) coded belt fit using video data of children sitting on each of three boosters and on a vehicle seat without a booster. The boosters improved belt fit significantly, but the analysis did not quantify the location of the belt with respect to the child's skeleton. In another study with child volunteers, measurements of the belt fit in several boosters with markedly different construction indicated that some boosters may provide better belt fit than others (Reed et al. 2005).

The current study examines the belt fit provided by four boosters in a wide range of vehicle belt conditions for children ages 5 to 12. The test conditions were selected to span a large range of the vehicle seat and belt configurations found in a survey of second-row seating positions in late-model vehicles. The booster belt fit is contrasted with the belt fit obtained without a booster. Child belt fit was compared to belt fit measurements made with the 6YO and 10YO Hybrid-III ATDs.

2.0 METHODS

2.1 Overview of Approach

A laboratory mockup was constructed that could represent a wide range of seat and belt geometries. Four boosters were selected that represent a range of design approaches. Children were recruited by newspaper ads and word-of-mouth to span the full range of body sizes for which boosters are recommended. Participants sat in each of 40 test conditions and donned the belt themselves. Posture and belt fit were characterized by recording the three-dimensional locations of landmarks on the belt and on the child's body.

2.2 Reconfigurable Vehicle Mockup and Belt Configurations

Testing was conducted in an UMTRI laboratory using a reconfigurable mockup of a vehicle rear seating area shown in Figure 1. The seat was mounted to fixtures that allowed the back angles, cushion angles, and cushion lengths to be varied over wide ranges. Testing was conducted in the right-most outboard seating position. The side bolster on the seat back was removed so that the shoulder belt would have minimal interaction with seat. The seats were mounted high enough from the floor that none of the children were able to touch the floor while sitting all the way back on the seat, reproducing the typical situation for children in rear vehicle seats. The H-point location, seat back angles, and seat cushion angles were measured using the procedures in SAE J826 (SAE, 2004). Figures 2 and 3 show the mockup at the seat back angles, seat cushion angles, and seat cushion lengths used in testing.

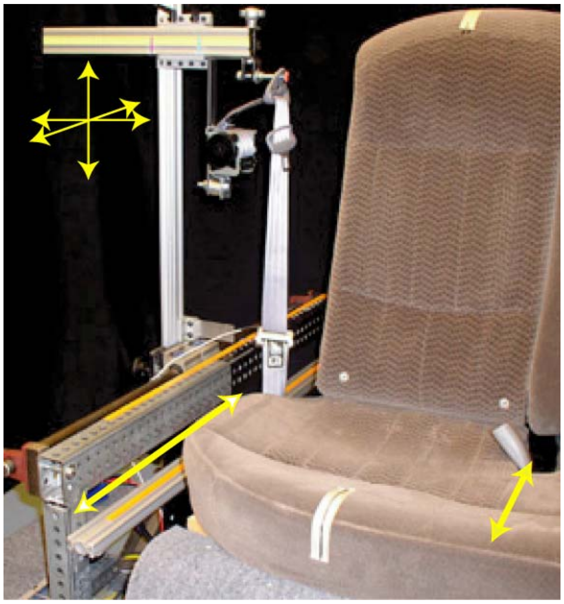


Figure 1. Reconfigurable rear seat mock-up. The upper anchorage (D-ring) location can be adjusted on three axes and the lower anchorages can be adjusted fore-aft.

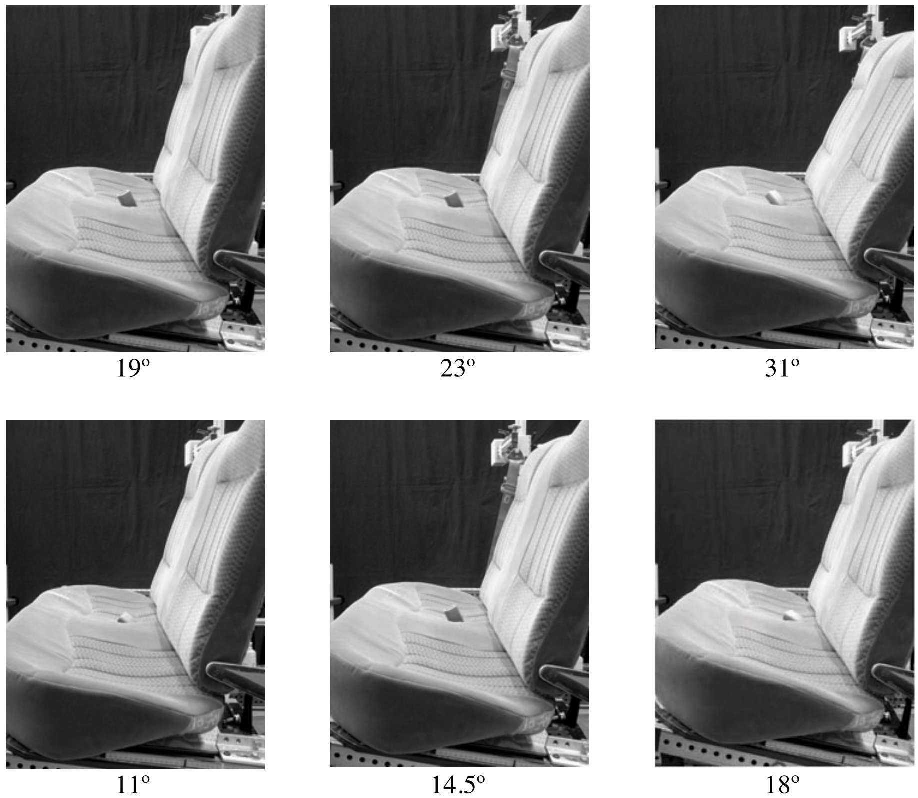


Figure 2. Back angle (top) and cushion angle (bottom) settings on the vehicle seat, back angle set at 23 degrees

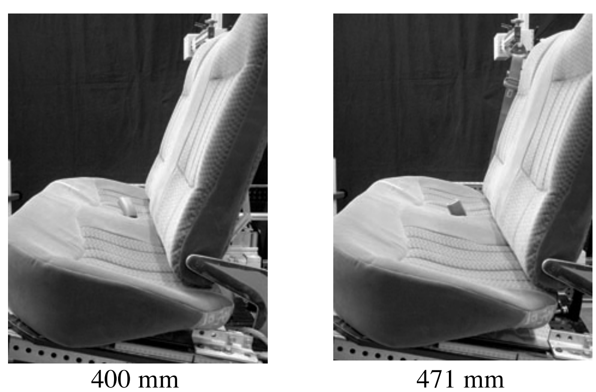


Figure 3. Cushion length settings on the vehicle seat, back angle at 23 degrees and cushion angle at 14.5 degrees

The vehicle mockup was equipped with a three-point belt system with a sliding latchplate and emergency (inertial) locking retractor obtained from a late-model sedan. The retractor and D-ring were mounted to an adjustable fixture that provided a large range of fore-aft, vertical, and lateral adjustability. A webbing-mounted buckle was mounted on an adjustable anchorage on the inboard side of the seating position. Both the inboard and outboard belt anchorage locations could be moved fore-aft over a wide range to change the lap belt angle.

Belt configurations were based on an analysis of second-row belt anchorage locations in 28 model year 2001 to 2006 vehicles, including passenger cars, minivans, and SUVs. In each of these vehicles, the seat H-point was recorded along with the D-ring, inboard (buckle), and lower outboard anchorage locations using a FARO Arm coordinate digitizer. Figures 4a and 4b show the vehicle data along with the anchorage locations used in this study. Anchorage locations were chosen to span over 90% of the range of the in-vehicle data in terms of three-dimensional location and angle with respect to H-point.

Table 1 lists the D-ring (bolt) locations at Low, Mid, and High levels on the three axes with X positive rearward, Y positive to the right (outboard), and Z positive vertical. All dimensions are measured from the H-point on occupant centerline. The D-ring locations used in testing were drawn from this grid, as shown in Table 2. Table 2 also lists the front- and side-plane angles (defined in Figure 4), associated with each D-ring location.

Table 3 lists the lower anchorage locations (outboard and buckle) used in testing. The anchorage locations were selected to produce a range of lap belt angles with respect to H-point in side view. The buckle assembly was adjusted to maintain the buckle at a constant height relative to the seat surface as the lap belt angle was changed. Figure 5 shows the belt conditions as angles relative to H-point in side view (lap and shoulder) and front view (shoulder). Note that these angles do not correspond directly to any measurable belt angle. Rather, these angles are an alternative representation of the three-dimensional location of the D-ring relative to the seat that captures the fact that many three-dimensional D-ring locations will produce approximately the same belt angles for an occupant.

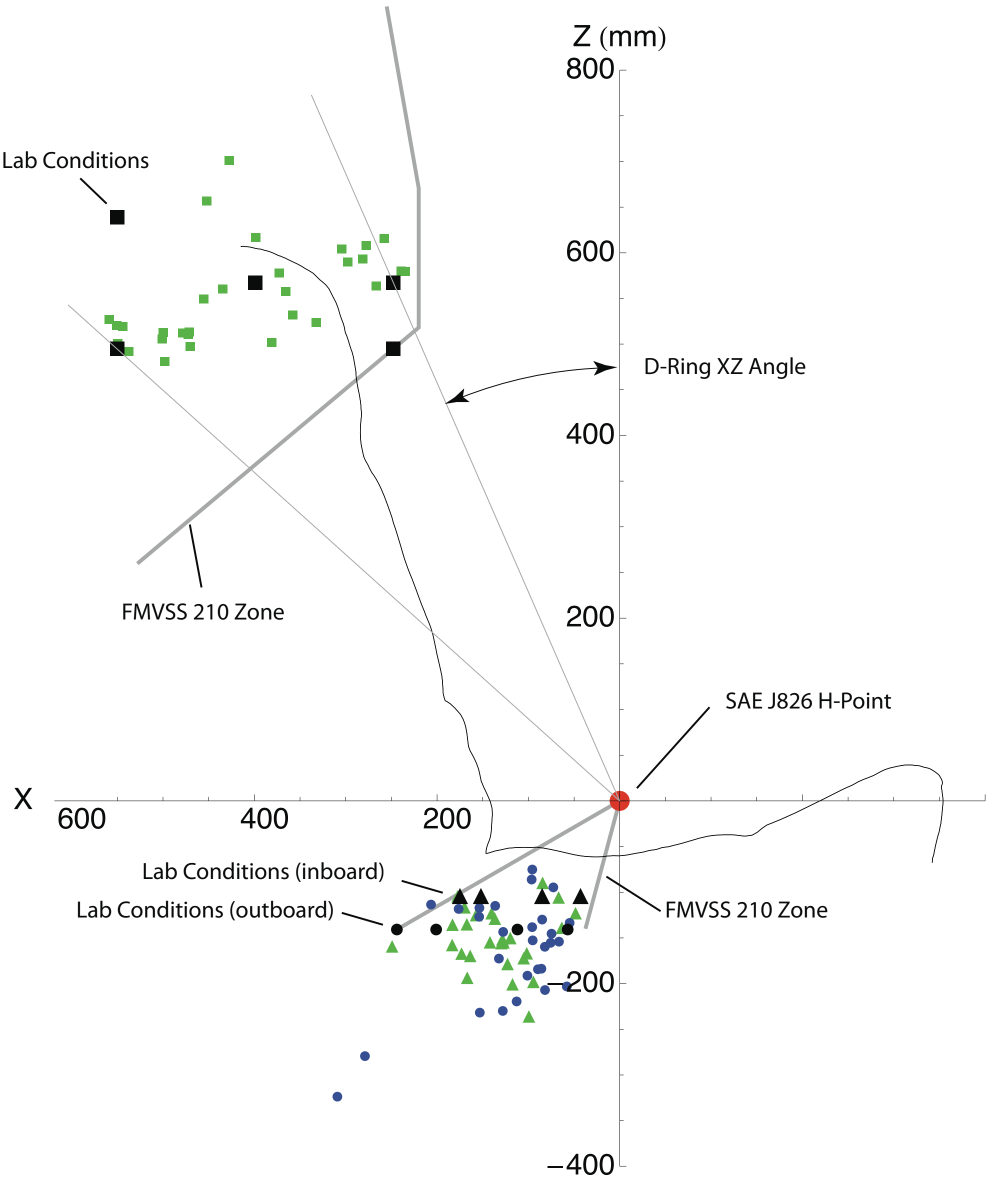


Figure 4a. Side view of belt anchorage locations from 28 second-row vehicle seating positions along with anchorage locations used in the laboratory relative to FMVSS 210 zones.

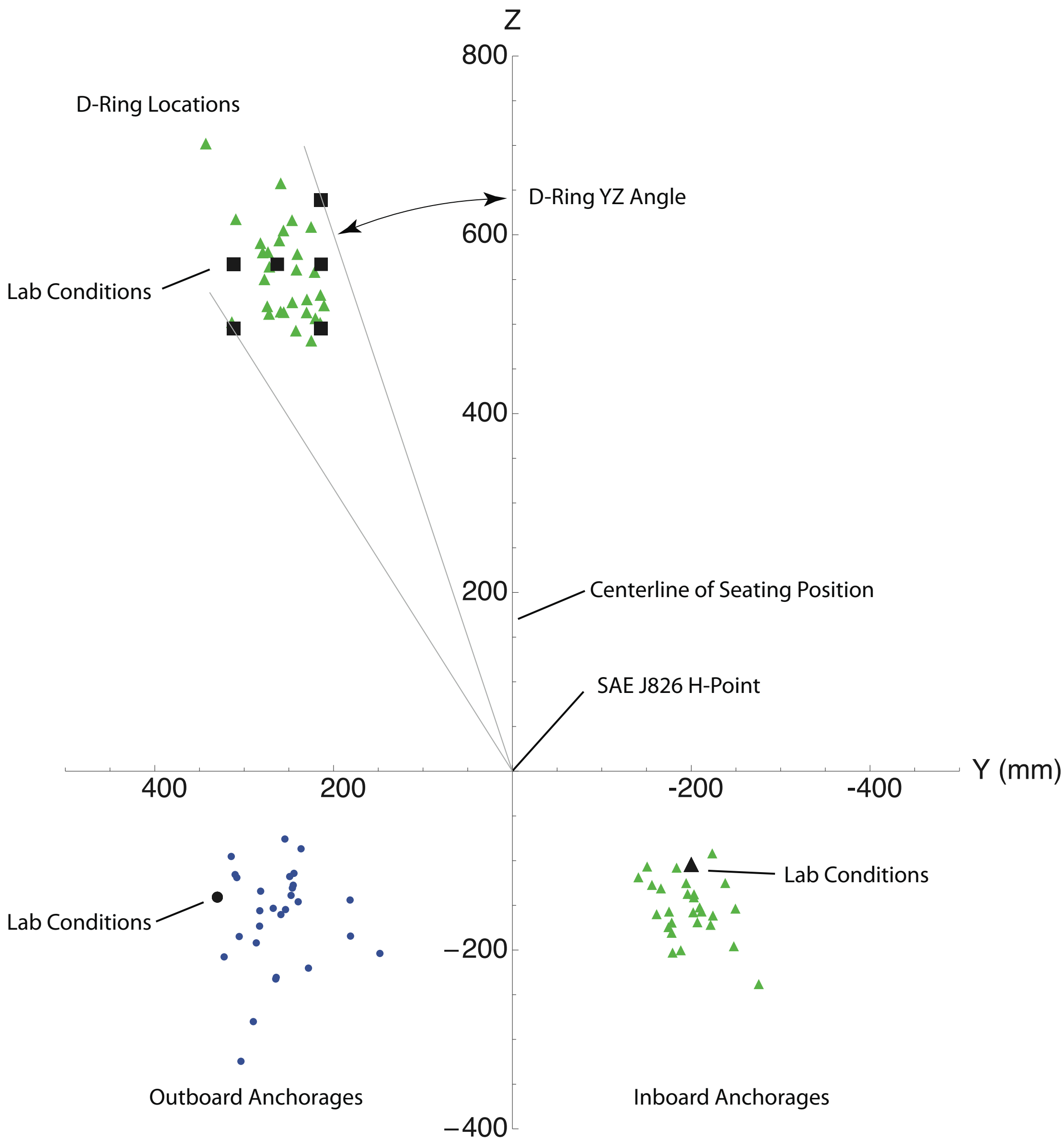


Figure 4b. Front view of belt anchorage locations from 28 second-row vehicle seating positions along with anchorage locations used in the laboratory.

Table 1
D-Ring Location Levels

Level/Axis	X	Y	Z
Low	248	214	494
Mid	399	263	566
High	550	312	638

Table 2
D-Ring Locations and Associated Angles

Side-View (XZ) Angle (deg)†	Front-View (YZ) Angle (deg)†	Nominal X	Nominal Y	Nominal Z	X (mm)*	Y (mm)	Z (mm)
35	25	Mid	Mid	Mid	399	263	566
24	21	Low	Low	Mid	248	214	566
24	29	Low	High	Mid	248	312	566
27	32	Low	High	Low	248	312	494
41	19	High	Low	High	550	214	638
48	23	High	Low	Low	550	214	494
48	32	High	High	Low	550	312	494

* With respect to H-point and seat centerline, rounded to the nearest degree.
† See Figures 4 and 5.

Table 3
Lower Anchorage Locations

Lap Belt Angle*	Lower Anchor Relative to H-point (mm)					
	Inboard			Outboard		
	X	Y	Z	X	Y	Z
51.5	85	200	-104	112	330	-141
30	175	200	-104	244	330	-141
35	152	200	-104	201	330	-141
68	43	200	-104	57	330	-141

* Re horizontal forward.

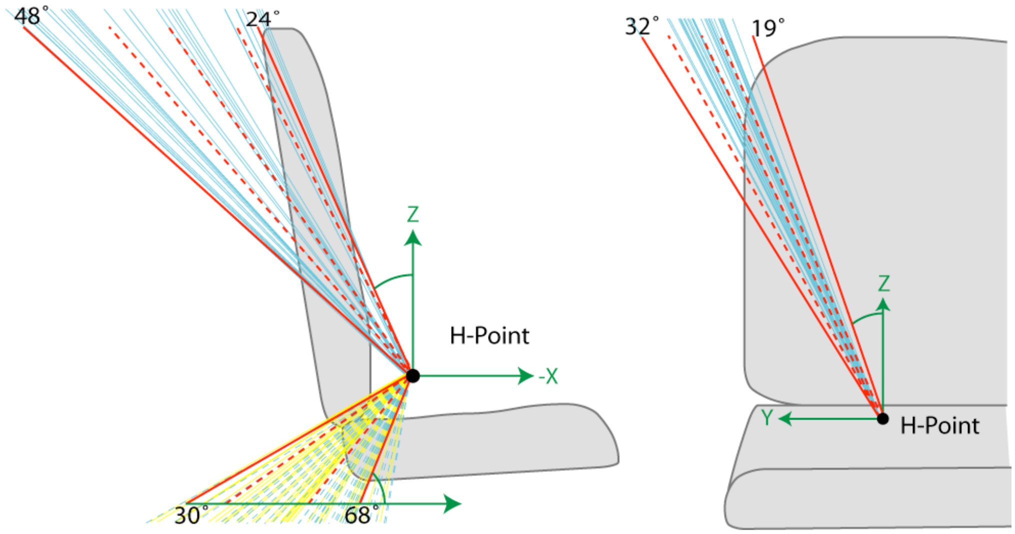


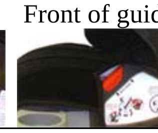
Figure 5. Range of shoulder and lap belt anchor locations relative to H-point. Red lines = test conditions, Blue lines= outboard vehicle, yellow lines = inboard vehicle.

2.3 Boosters

Table 4 lists the five booster configurations used in testing: Alpha Omega, Intera, Parkway, and Graco TurboBooster (highback and backless). Two of the CRS (Cosco Alpha Omega and Safety 1st Intera) are combination restraints that can also be used as forward-facing harness restraints, but they tested as belt-positioning boosters.

The installation and use of the boosters followed the respective manufacturers' instructions. Appendix A lists the instructions for each booster taken from the owner's manuals along with the instructions given to the participants for each condition. In all cases, the investigator's interaction with the participant with respect to booster usage was intended to model a conscientious caregiver, that is, a parent who read the owner's manual and instructed the child appropriately. The investigator adjusted each booster to fit the child according to the manufacturers instructions and used the scripts in Appendix A to ensure that each child was given consistent direction.

Table 4
Boosters Used in Testing

Description	Boosters				
Model	Turbo Booster		Alpha Omega	Intera	Parkway
Manufacturer	Graco		Cosco	Safety 1st	Britax
Front view at lowest settings					
Side view with components at highest settings					
Type	Highback Booster	Backless Booster	Highback Combo	Highback Combo	Highback Booster
Lap belt routing	Under armrest 		Over guide 	Over guide 	Front of guide 
Shoulder belt routing	Closed guides, set at angle to seat back, moves with head restraint 	Clip with tether supplied, not used in study	Two, downward open hooks, perpendicular to seat back, fixed to sides of seat back 	Guides open downward, set at angle to seat back, moved with head restraint 	Closed guides, perpendicular to seat back, moved with head restraint 
Shoulder belt guide location indicated in booster's instruction manual	Bottom of headrest even with top of shoulders.	If shoulder belt lies outside red zone, the shoulder belt positioning clip MUST be used.	Secure the belt through guide so belt crosses base of neck and across chest.	Secure shoulder belt behind headrest.	Adjust headrest so belt guides are even with or just above shoulders.
Armrest placement during study	High	High	Rotated down; not used in belt routing	No armrest	No armrest
Seat Back Positions	2	NA	1	1	2
Width of footprint/ width at guide	Wide/Wide	Wide/Wide	Narrow/Wide	Narrow/Wide	Wide/Wide
Back of Booster					

Turbo Booster Highback | Turbo Booster Backless | Alpha Omega | Intera | Parkway

Figure 6. Boosters installed on vehicle seat set with back and cushion angle set to 23 and 14.5 degrees respectively.

2.4 Test Conditions

Table 5 lists the independent variables and their levels. Due to the large number of independent variables, each at multiple levels, it was not feasible to test all combinations of variables. Instead, conditions were selected to maximize the efficiency of the testing. Many potential interactions of independent variables were not studied because pilot testing indicated that the interactions had minimal effects. For example, D-ring (upper belt anchorage) locations and lap belt angles were not manipulated independently because pilot testing showed only minor effects of lap belt angle on shoulder belt fit, and vice versa. D-ring positions were selected to span the range of front- and side-view H-point-to-D-ring angles measured in vehicles (see Figure 4).

Table 6 lists the test conditions. Note that belt/seat conditions 5, 7, 9, and 11 were used in another study but not in the current study and hence are excluded from the table. All participants were tested in all conditions. The largest range of belt and seat conditions was presented in the no-booster condition. The backless booster was tested in the full range of D-ring (upper belt anchorage) locations with the midrange or nominal values of the other variables. The Alpha Omega was tested at nominal seat settings, since its rigid shell eliminates most seat effects, and was tested over the range of lap and shoulder angles. The Intera and Parkway, which have both upper and lower belt routing, where tested only at the nominal condition. The TurboBooster in highback mode was tested at all lap belt angles at a single D-ring location, since the upper belt routing effectively eliminates the effect of D-ring location on shoulder belt fit. The Intera and Parkway were each tested twice in the same configuration, and the long cushion length condition with no booster was repeated. All other conditions were presented once.

Table 5
Independent Variables and Levels

Variable	Levels
Booster	None Graco TurboBooster Graco TurboBooster Backless Safety 1st Intera Britax Parkway Cosco Alpha Omega
Seat Back Angle (SAE A40)	19, *23*, 31 deg
Seat Cushion Angle (SAE A27)	11, *14.5*, 18 deg
Seat Cushion Length (mm)	400, *471 mm*
Lap Belt Angle wrt Horizontal†	30, 35, *51.5*, 68 deg
D-Ring XZ Angle wrt Vertical†	24, 27, *35*, 41, 48 deg
D-Ring YZ Angle wrt Vertical†	19, 21, *25*, 29, 32 deg

* Nominal or midrange values are shown in italics.
† See Figures 4 and 5.

Table 6
Test Matrix

Booster	Back Angle*	Cushion Angle	Cushion Length (mm)	Lap Belt Angle	Shoulder Belt XZ Angle	Shoulder Belt YZ Angle	Reps.	Condition (columns 2-7)	Unique Condition Number
1	2	3	4	5	6	7	8	9	10
Turbo Booster Highback	23	14.5	471	51.5	35	25	1	2	1
				30			1	23	2
				35			1	4	3
				68			1	6	4
Intera	23	14.5	471	51.5	35	25	2	2	5
Parkway	23	14.5	471	51.5	35	25	2	2	6
Alpha Omega	23	14.5	471	51.5	35	25	1	2	7
					27	32	1	1	8
					41	19	1	3	9
				30	35	25	1	23	10
				35			1	4	11
				68			1	6	12
Turbo Booster Backless	23	14.5	471	51.5	35	25	1	2	13
					24	21	1	13	14
					24	29	1	12	15
					27	32	1	1	16
					41	19	1	3	17
					48	23	1	15	18
					48	32	1	14	19
No Booster Seat	23	14.5	471	51.5	35	25	1	2	20
					24	21	1	13	21
					24	29	1	12	22
					27	32	1	1	23
					41	19	1	3	24
					48	23	1	15	25
					48	32	1	14	26
				30	35	25	1	23	27
				35			1	4	28
				68			1	6	29
	19	14.5	471	51.5	35	25	1	16	30
					27	32	1	8	31
	31	14.5	471	51.5	35	25	1	17	32
					41	19	1	10	33
	23	**11**	471	30	35	25	1	24	34
				35			1	18	35
				68			1	19	36
	23	18	471	30	35	25	1	25	37
				35			1	20	38
				68			1	21	39
	23	14.5	400	51.5	35	25	2	22	40

*Angles in degrees

2.5 Participants and Standard Anthropometry

Forty-four children (17 girls and 27 boys) ages 5 to 12 recruited for testing by word-of-mouth, fliers, and newspaper advertisements participated in the study. The goal was to recruit children who spanned the range of potential users of belt-positioning boosters with respect to stature and weight, including the range between the reference statures of the 6YO and 10YO Hybrid-III crash dummies (1168 mm and 1374 mm, respectively). Table 7 summarizes some characteristics of the sample. Figure 7 shows stature and body weight by gender in relation to the reference anthropometry for the Hybrid-III 6YO and 10YO ATDs (Mertz et al. 2001). Anthropometric dimensions were recorded using standard techniques.

Table 7
Participant Characteristics

Measure	Percentile						
	Min	5	25	50	75	95	Max
Age (yr)	5.2	5.7	6.7	8.6	10.3	12.0	12.6
Stature (mm)	1107.0	1135.2	1189.3	1265.0	1389.5	1470.0	1556.0
Weight (kg)	18.2	18.8	21.8	28.8	35.0	47.1	52.7
Erect Sitting Height (mm)	607.0	611.6	639.8	690.5	719.0	777.5	806.0
Body Mass Index (kg/m^2)	13.6	14.0	15.6	16.7	18.2	24.5	28.4

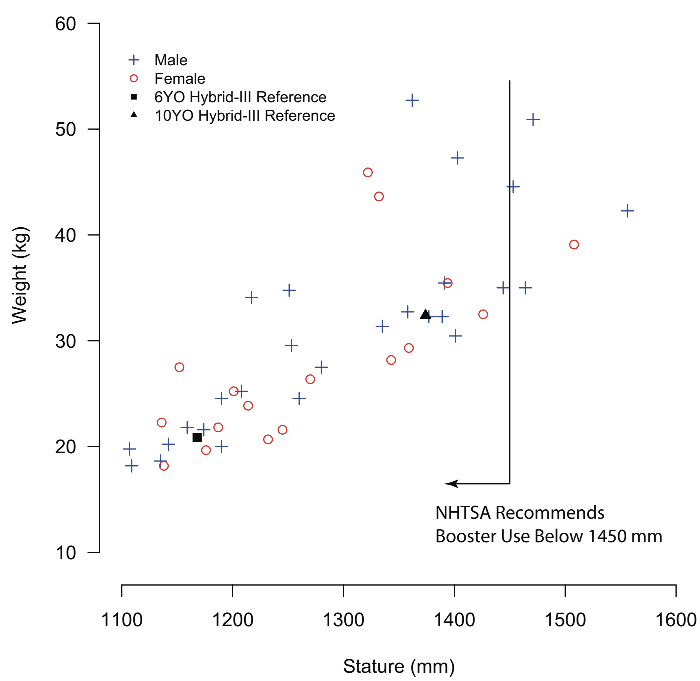


Figure 7. Stature and body weight for subject pool (17 girls and 27 boys) along with reference stature and weight for the 6YO and 10YO Hybrid-III ATDs from Mertz et al. (2001).

2.6 Three-Dimensional Anthropometry

The three-dimensional locations of body landmarks were measured using a FARO Arm coordinate digitizer (FARO Technologies, Lake Mary, FL). The procedures were very similar to those used previously in many studies of adult and child posture and position (Reed et al. 1999, Reed et al. 2005, Reed et al. 2006). The experimenter located the desired landmark by palpation, placed the tip of the FARO Arm probe on the landmark, and pressed a button to record the location. All data were expressed in a laboratory coordinate system with the X-axis positive rearward, Y-axis positive to the right, and Z-axis positive upward. Landmark data were recorded in each of the test conditions in Table 6 and while the participant sat in a specially constructed laboratory *hardseat*. The hardseat, shown in Figure 8, is designed to produce a posture similar to a vehicle-seated posture but to provide access to posterior landmarks on the spine and pelvis.

Table 8a lists the body landmarks that were recorded during the vehicle-seat and hardseat trials. Table 8b lists the reference points on the seat, CRS, and belt that were recorded where applicable. The reference points allow the body landmark data to be referenced to a seat or CRS coordinate system. Points were digitized on the belt where it crossed over the sternum, clavicle, and the lateral positions of the left and right anterior-superior iliac spines (ASIS). Points on the participant were sufficient to define the three-dimensional locations of the major skeletal components, including the head, thorax, pelvis, clavicles, and the right humerus and femur. Figure 9 shows the landmarks schematically. In the hardseat, surface landmarks over the C7, T4, T8, T12, L3, and L5 spinous processes were recorded along with the locations of the left and right posterior-superior iliac spines (PSIS). Combined with the ASIS points, the PSIS points give the three-dimensional position and orientation of the pelvis.

A low-profile inclinometer capable of measuring orientation with respect to gravity on two axes was taped to the skin over the sacrum. Thin-film pressure transducers under the inclinometer plate provide compensation for changes in orientation due to pressure on the transducer. During the hardseat landmark measurements, the inclinometer pressure compensation was calibrated by pressing on the inclinometer with a range of pressure levels and gradients. Figure 10 shows the inclinometer on a participant's sacrum. The data from the ASIS and PSIS locations measured in the hardseat were used to convert the inclinometer-measured angles to a three-dimensional representation of the orientation of the bony pelvis (Reed et al. 2006).

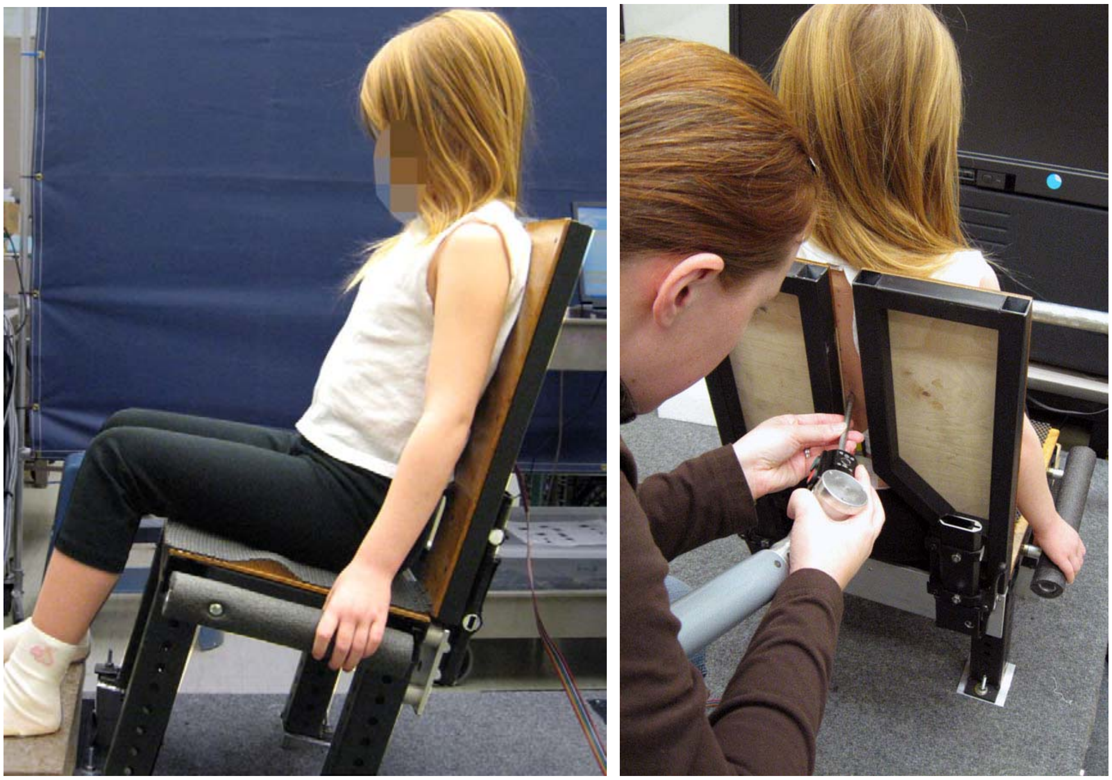


Figure 8. Laboratory hardseat used to obtain posterior and anterior body landmarks in same posture.

Table 8a
Body Landmarks

Recorded each time the child donned the belt		
Recorded each time the child sat down		
Recorded in the hardseat		
Acromion (R) Suprasternale Substernale ASIS (L, R)	Glabella Center of Eye (R) Corner of Eye (R) Tragion (R) Medial Clavicle (R) Lateral Clavicle (R) Lat. Humeral Epicondyle (R) Wrist (R) Suprapatella (R) Lat. Femoral Condyle (R) Lateral Malleolus (R) Heel (R) Ball of Foot (R) Toe (R) Point streams over lap	PSIS (L, R) Spine: (C7, T4, T8, T12, L3, L5) Back of Head Top of Head Center of Eye (L) Corner of Eye (L) Acromion (L) Lateral Clavicle (L) Medial Clavicle (L) Chest Circumference Height Abdomen Circumference Height Point streams over shoulder, chest, and lap

Table 8b
Buck and Booster Reference Points

Recorded each time the child donned the belt	
Recorded each time the child sat down	
Booster Reference (3)	Booster Head Restraint (3) References (3) Buck Seatback References (2) Buck Seatpan References (2)

Table 8c
Belt Points

Anchorages	Shoulder belt margins where it…	Lap belt margins where it …
D-ring Ref. (3) Inboard Anchor Outboard Anchor	Crosses the clavicle Leaves the shoulder Crosses midline of body Crosses the body at the height of the suprasternale	Crosses ASIS (L, R) Leaves the body

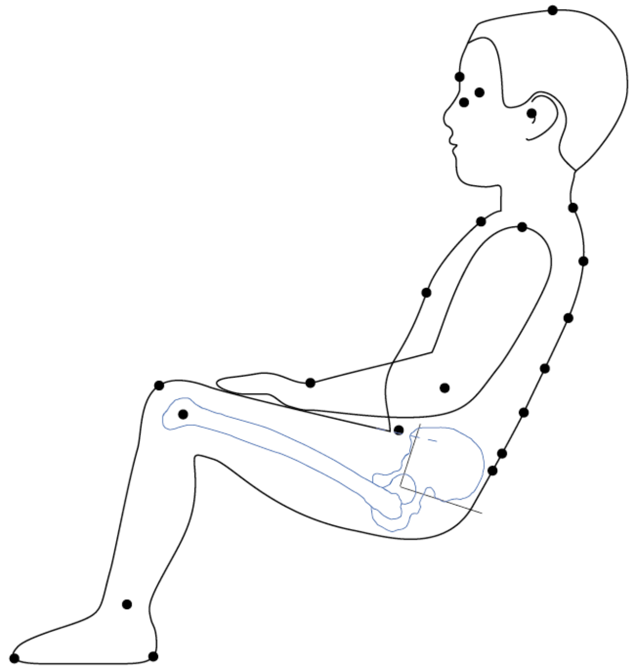


Figure 9. Schematic depiction of body landmarks that were digitized (see Table 8). Posterior landmarks were digitized only in the hardseat.

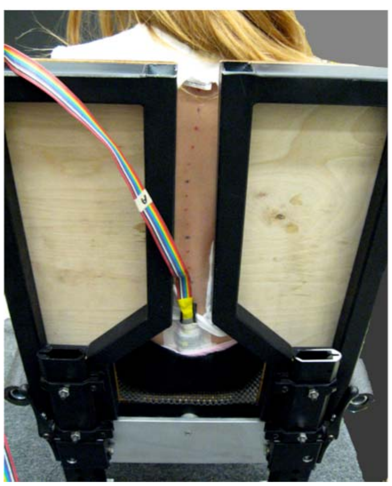


Figure 10. Pelvis inclinometer on participant's sacrum. Some tape has been removed to provide a better view of the sensor.

2.7 Protocol

The test protocol was approved by an institutional review board at the University of Michigan. Written informed consent was obtained from the parent or guardian of each participant and each child assented orally. The parent or guardian was present during testing and was paid $12 per hour for participating. The child changed into thin test garments (a t-shirt and form fitting leggings) that provided access to posterior landmarks (see Figure 8). The experimenter recorded standard anthropometric dimensions. The child sat in the hardseat (Figure 8) and the experimenter applied the pelvis inclinometer to the skin on the child's sacrum with medical tape. The experimenter then used the FARO Arm to digitize the landmarks listed in Table 8 while the child held a relaxed, sagittally symmetric posture. The landmarks were digitized in several overlapping sets. If the child moved appreciably during a set, the set was repeated. The data from each set were aligned to the first set using the repeated points.

The anterior-superior and posterior-superior iliac spine landmarks were used to define a pelvis coordinate system using the methods in Reed et al. (1999). The angular offset between the measurements obtained from the pelvis inclinometer and the pelvis coordinate system was calculated for use in determining the pelvis orientation from the inclinometer data in subsequent test conditions.

The participant was then tested in the conditions listed in Table 6. At the beginning of testing, the subject was shown the seat belt latch plate and buckle. Prior to testing with each booster, the investigator adjusted the booster according to the manufacturer's instructions listed in Appendix A. Booster-specific instructions were given to the participant following the scripts in Appendix A. The investigator acted as a conscientious caregiver following the manufacturer's instructions for each booster as closely as possible. The child was not instructed to assume a particular posture or to route the belt in a particular manner, beyond following the instructions.

The experimenter recorded the locations of the landmarks listed in Table 8 using the FARO Arm while the participant sat approximately motionless. The children were usually able to hold the posture during measurement as well as adult participants in similar studies. Two digital photographs were taken of every test trial. Testing required approximately three hours for each participant, with breaks taken as needed. Test conditions were blocked in groups of conditions with the same seat configuration (cushion angle, back angle, and length) and booster condition. The subject stood up after each block so the conditions could be set for the next block. After sitting in the new combination and donning the belt for the first time, the points in the first and second column of Table 8a were recorded. After removing the belt, the sagittal contours of the lap at the lateral location of the left and right ASIS point were digitized from below the pectoris to mid thigh as illustrated in Figure 11.

2.8 Belt Fit Measures

The lap and shoulder belt fit measures were computed from the FARO Arm data recorded during each trial. Lap belt measures were computed using a methodology that was designed to produce results comparable to those that could be measured on a crash dummy, while preserving a meaningful relationship to the child's pelvis position. Overall, the goal was to measure the location of the belt "below" the ASIS landmarks. Because of the shape of the body at the thigh abdominal junction, "below" can also mean "forward of" the ASIS. Due to this complexity, some computation was necessary to arrive at a lap belt score. Similarly, shoulder belt fit was assessed relative to anatomical landmarks using belt locations measured in each trial based on calculations designed to provide consistency across subjects and reference to the crash dummy measures.

Lap Belt Fit — Each time the child sat down in a new condition, a continuous "stream" of points was recorded at the lateral positions of both ASIS landmarks. These sagittal lap streams were digitized from high on the abdomen down to mid thigh as illustrated in Figure 11. The ASIS points were also digitized and the orientation of sacrum inclinometer was recorded in this posture. For each of the belt conditions that followed during the test condition bloc, the locations of the ASIS landmarks were recorded again. During data processing, the lap stream data were translated to align with the ASIS location measured at the time the lap stream was taken.

Figure 11. Digitizing the lap streams on a participant.

The lap stream data were somewhat noisy due to bunching of the clothing in the thigh/abdominal region. Consequently, the contours were smoothed using a spline fitting procedure. Appendix C describes the procedure in detail. In brief, the data were truncated to similar dimensions for each trial. A Bezier curve was fit to the data in side view so that irregularities were bridged. The ASIS and belt locations were projected into the Bezier curve. The lap belt score (LBS) was computed as the distance along the curve from the projected ASIS point to the projected belt point (upward or rearward edge of the belt) as shown in Figure 12. The score was positive (better) if the projected belt point was below or forward of the projected ASIS point. A negative lap belt score indicates that the belt extended above the ASIS.

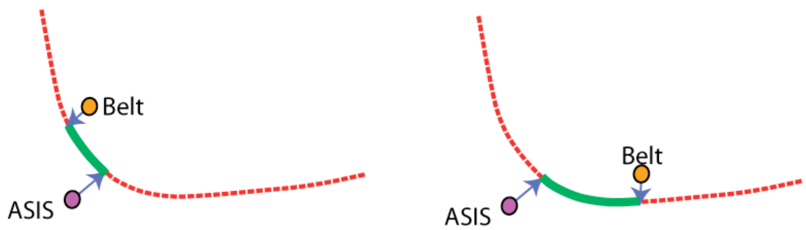


Figure 12. Projecting the ASIS and top edge of the belt onto the spline and calculating the distance (green) between the projected points along the length of the spline (dashed red). The image on the left shows a negative lap belt score and the image on the right shows a positive lap belt score.

Shoulder Belt Score – The shoulder belt score was computed as the distance in millimeters between the suprasternale and the point on the inboard side of the belt at the height of the suprasternale. During testing, the investigator digitized the inboard edge of the belt where it crossed the clavicle and where it appeared to be at the height of the suprasternale. Since the belt was often some distance from the suprasternale or not resting on the thorax, the investigator had to approximate the correct height. To reduce the error that this approximation created, the belt location at the height of the suprasternale was calculated by fitting a two-dimensional line in the YZ plane between the two digitized belt points. The line was then solved for Y at the suprasternale Z value, as illustrated in Figure 13. The belt score was given a positive value if the belt was outboard relative to the suprasternale and a negative value if inboard, as shown in Figure 14.

The ideal shoulder belt score is dependent on the size of the child. A good belt position places the belt at the center of the shoulder. The belt fit data from children were analyzed to determine the relationship between shoulder belt score and the belt location with respect to the center of the shoulder.

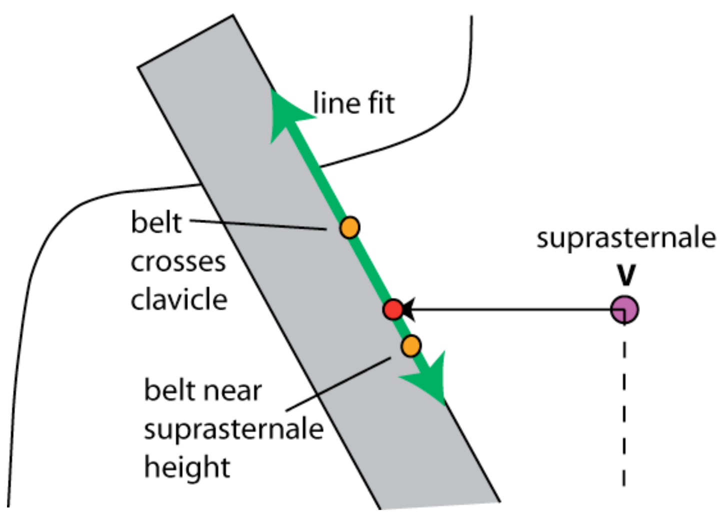


Figure 13. Calculating the location of the inboard side of the belt at the height of the suprasternale by fitting a two dimensional line between two points digitized on the belt and solving for the lateral position of the line at the height of the suprasternale landmark.

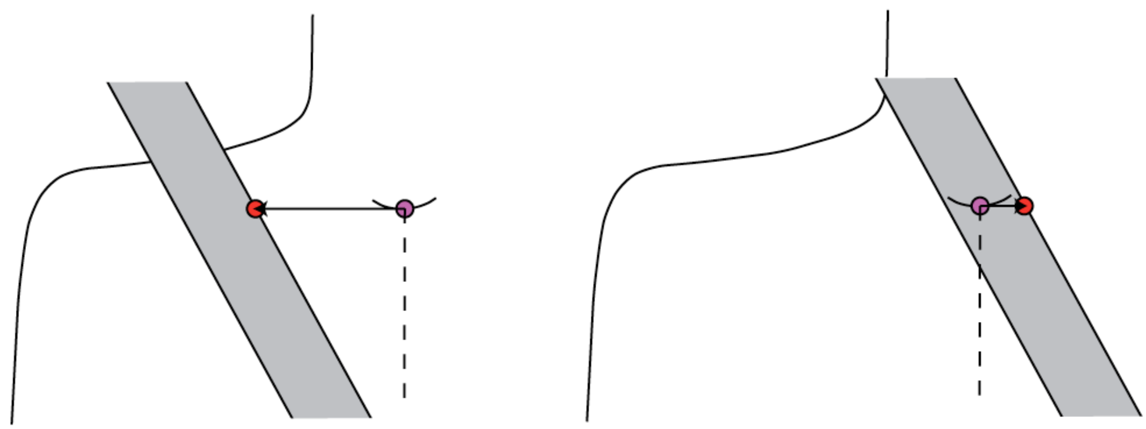


Figure 14. Shoulder belt score, showing a positive value (left) and a negative value (right).

2.9 ATD Belt Fit Measures

An important goal of this project was to understand the relationship between belt fit on children and analogous measures on ATDs. Ideally, ATD belt fit measures could be used to predict belt fit scores for children so that ATD testing could substitute for time-consuming and expensive testing with child volunteers. In previous work at UMTRI, a procedure for installing ATDs was developed that produced hip and head locations in booster seats that are similar to those of similar-size children (Reed et al. 2006). A standardized belt routing procedure was subsequently added to provide a repeatable method for measuring belt fit. The procedure, described in detail in Appendix B, involves placing the ATD on the booster (or seat) in a standardized sequence, applying uniform loads to the pelvis and chest, and routing the belt using a standardized sequence of motions. The procedure produces belt fit measures directly analogous to those described in section 2.8 for children. The lap belt score is the distance of the belt below the ASIS along the abdomen/pelvis/thigh profile. (On the ATDs, the top of the pelvis bone is taken to represent the ASIS location.) The shoulder belt score is the distance of the inboard edge of the belt from the ATD centerline at the height of the bib/neck-bracket junction, which is roughly the height of the suprasternale landmark on children.

Following testing with children, belt fit measures were made in each test condition (see Table 6) using both the 6YO and 10YO ATDs. These measures were compared to child belt fit measures to assess the extent to which ATD belt fit scores are related to child belt fit.

RESULTS

3.1 Overview

The data were analyzed as a series of sub-experiments examining particular aspects of belt fit.

- Belt fit was compared across boosters in the nominal belt and seat condition.

- The effects of lap belt angle on belt fit in two boosters and without the booster were quantified.

- The effects of D-ring (upper anchorage) location on belt fit in two booster conditions and without the booster were examined.

- The effects of belt geometry on ATD belt fit were examined.

- The relationships between ATD and child belt fit were quantified.

For each analysis, the effects of participant body dimensions and potential interactions between the independent variables and body size were examined.

3.2 Lap Belt Fit Across Booster Conditions

Data from condition 2 (nominal values on all seat and belt variables — see Table 6) were extracted for a comparison of lap belt fit across all booster conditions. On average, the right (outboard) belt fit score was 6 mm higher than the left belt fit score. The standard deviation of the left-right difference was 12 mm and consistent across booster conditions. All subsequent lap belt fit analyses use the mean of the left and right lap belt scores.

Table 9 lists the means and standard deviations of lap belt score in condition 2 across boosters, including the no-booster condition, for all subjects. All pairwise comparisons of mean value among the conditions were statistically significant ($p<0.01$, Bonferroni) except that the scores for the Parkway and backless TurboBooster were not significantly different. On average, the belt fit was worst (lowest score) without a booster, with the belt extending an average of 23 mm above the participant's ASIS locations. The belt width is 48 mm, so approximately half of the belt, on average, is above the ASIS in the no-booster condition. The best average lap belt fit was observed in the TurboBooster Backless, with the upper edge of the belt 17 mm below the ASIS. The Parkway performed similarly, with an average score of 13 mm. The Intera belt fit was the worst among the boosters, with the belt extending 15 mm above the ASIS, on average.

Figure 15 shows that all but two of the subjects had the belt below their ASIS landmarks on the TurboBooster Backless and more than 75% achieved that level of fit in the Parkway, but 75% failed to achieve that level in the Intera and most did not reach that level in the Alpha Omega. Figure 16 shows photographs of one child in each of the booster conditions, illustrating the range of lap belt fit. The photos show that the lap belt is oriented near vertical when it crosses the lap belt guides on the Intera, resulting in positioning of the belt across the child's abdomen. In contrast, the belt guides on the TurboBooster and Parkway hold the belt orientation closer to horizontal, and the belt passes primarily over the thighs rather than the lower abdomen.

Table 9
Mean and Standard Deviation of Lap Belt Score in Condition 2

Booster*	Mean (mm)	Standard Deviation (mm)
TurboBooster Backless	16.5	8.0
Parkway	13.4	10.8
TurboBooster	4.9	7.5
Alpha Omega	-6.2	10.3
Intera	-14.8	10.9
None	-22.5	12.6

* Rank ordered by mean score (higher scores indicate better belt fit).

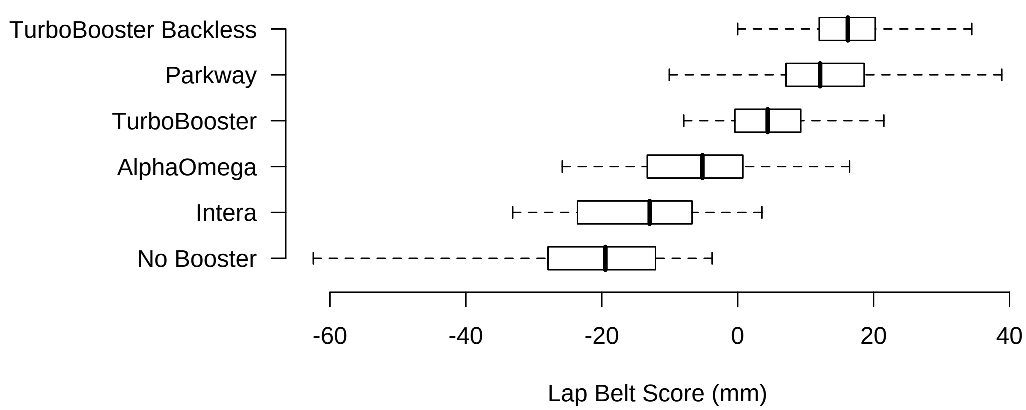


Figure 15. Box plots of lap belt scores in condition 2. Box spans 25th to 75th percentile with central line at median. Whiskers show range of data.

No Booster

Safety 1st Intera

Cosco Alpha Omega

TurboBooster Highback

Graco TurboBooster Backless

Britax Parkway

Figure 16. Belt fit across booster conditions for one child.

Lap belt fit was significantly affected by child body size. Figure 17 shows a scatter plot of lap belt scores from condition 2 by stature (erect standing height) and booster. A regression analysis showed a statistically significant effect of stature (p<0.01) and no interaction between stature and booster type. That is, the effect of stature on lap belt fit was the same across booster conditions (including no booster), so children of all sizes experienced approximately the same improvement in lab belt fit in each booster, relative to the no-booster condition. After subtracting off the individual booster means, the stature effect has a slope of 0.0345 mm/mm and a root-mean-square error of 8.5 mm.

Average stature increases from about 1030 mm at age four to 1270 mm at age eight, an increase of 240 mm. Multiplying this stature change by the slope of the stature effect on lap belt fit indicates that the typical eight year old will experience lap belt fit only 8.3 mm better than the typical four year old under these conditions. This difference is only 21 percent of the difference in mean lap belt score between the no-booster condition and the best performing booster, and only 27 percent of the difference between the best-performing and worst-performing boosters on lap belt fit. Hence, this analysis indicates that booster design is a more important factor than body size in determining lap belt fit in boosters.

Moreover, the analysis indicates that body size alone does not produce good belt fit on the vehicle seat. Children at the 1450-mm stature cutoff for booster use recommended by NHTSA achieved an average lap belt score of -18 mm when sitting on the vehicle seat alone, based on the regression analysis. Children as short as 1100 mm tall sitting on all but the worst-performing booster exceeded this average score. These results suggest that being 1450 mm tall does not guarantee good lap belt fit in a typical rear-seat belt configuration.

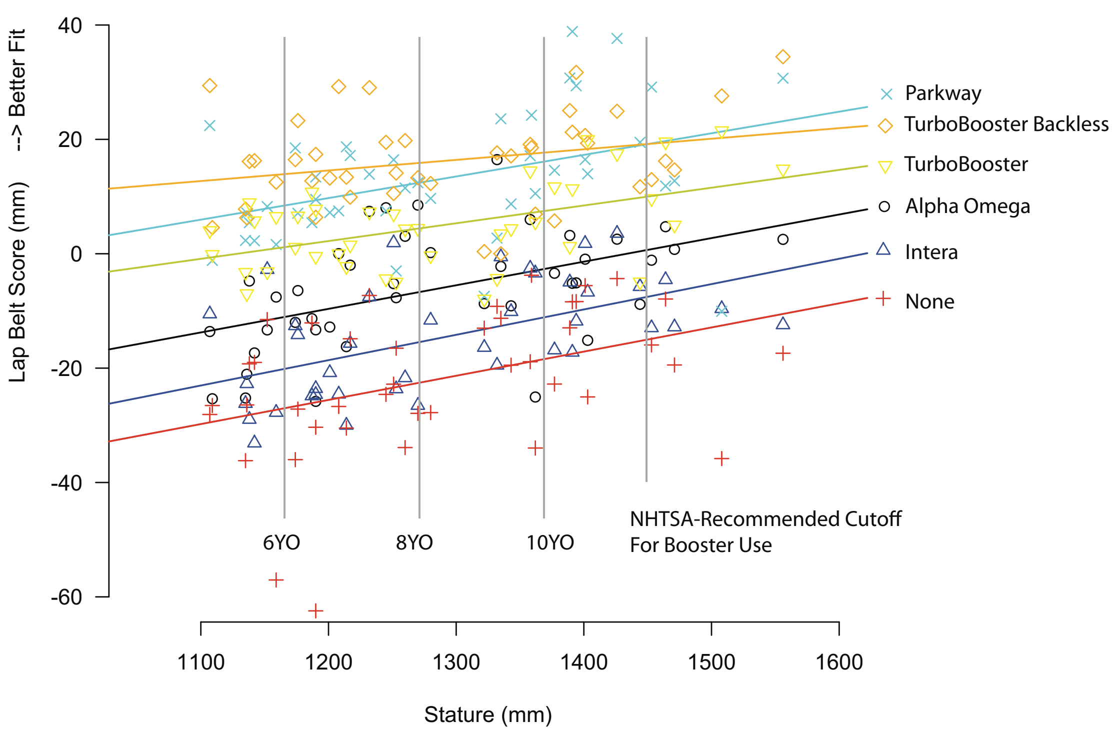


Figure 17. Lap belt score relative to stature across boosters in condition 2. Vertical lines show average stature for children ages 6, 8, and 10 based on analysis of data from Snyder et al. (1977).

3.3 Effects of Lap Belt Angle on Lap Belt Score

The four lap belt angles were presented with nominal values of other variables for the TurboBooster highback, Alpha Omega, and in the no-booster condition (conditions 2, 4, 6, and 23 in Table 6). Data from these conditions were analyzed to assess the effects of lap belt angle on lap belt fit. As noted before, pilot testing had shown little effect of D-ring location on lap belt fit.

Table 10 lists the means and standard deviations of lap belt score for the three booster conditions and four lap belt angles. Figure 18 shows the same data graphically. In the no-booster condition, lap belt angle had an approximately linear relationship with lap belt score, with the change in belt angle from 30 to 68 degrees (flattest to steepest) producing an average improvement in lap belt score of 17 mm. In contrast, no significant effect of lap belt angle on lap belt score was observed for the TurboBooster and Alpha Omega, indicating that these boosters effectively isolated the lap belt fit from the belt anchorage geometry.

Table 10
Effects of Lap Belt Angle: Means (Standard Deviations) of Lap Belt Scores in Conditions 2, 4, 6, and 23

Booster Condition	Lap Belt Angle*			
	30°	35°	51.5°	68°
TurboBooster	2.6 (9.7)	1.8 (8.4)	4.8 (7.6)	6.2 (8.0)
Alpha Omega	-9.2 (9.6)	-7.1 (8.9)	-6.3 (10.1)	-4.9 (9.5)
None	-29.5 (14.2)	-28.2 (12.3)	-21.9 (12.7)	-12.1 (10.0)

* Angle of line from anchorage to H-point in side view with respect to horizontal forward.

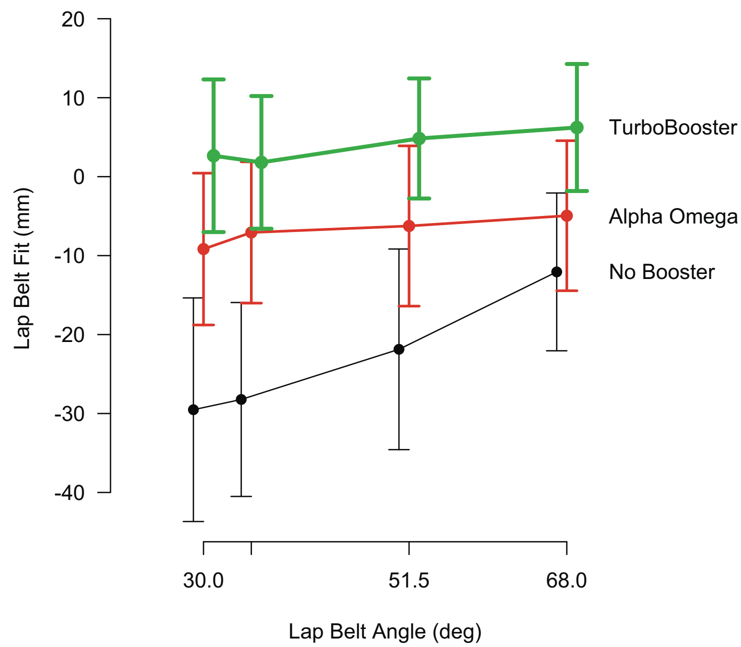


Figure 18. Effect of lap belt angle on lap belt score in two boosters and the no-booster condition. Plot shows condition means and standard deviations. Points are offset on the horizontal axis for clarity.

For the no-booster condition, an additional regression analysis was conducted to determine the extent to which body size might affect the relationship between belt angle and belt fit. The interaction between stature and lap belt angle (LBA) was not significant, but both were significant independent predictors ($p<0.001$):

LBS, No Booster (mm) = -93.8 + 0.0388 Stature + 0.455 LBA, R^2adj = 0.34,
RMSE = 11.5 (1)

where RMSE is the root-mean square error (standard deviation of the residuals). A second-order term was not significant, nor was the interaction between lap belt angle and stature. On average, a 10-degree increase in lap belt angle resulted in a 4.5 mm improvement in lap belt fit, the same average difference in belt fit experienced by children with statures differing by 116 mm, approximately the difference between average 6YO and 10YO statures. The inclusion of BMI as a potential predictor did not add significantly to the fit, and the R^2 value for a regression using body weight rather than stature was identical ($R^2_{adj} = 0.34$).

3.4 Effects of Cushion Angle and Cushion Length on Lap Belt Score

Several test conditions were designed to evaluate the effects on belt fit of cushion angle and cushion length on the vehicle seat without a booster. Conditions 18-21, 24, and 25 used the midrange D-ring locations and three lap belt angles (30, 35, and 68 degrees) across 11- and 18-degree cushion angles. The comparison of conditions 2 and 22 assesses the effect of changing the seat cushion length.

Cushion angle did not have a significant effect on lap belt score across the range of lap belt angle, as shown in Figure 19. Figure 20 shows the distribution of lap belt score with two cushion lengths. Using both the paired t-test and the non-parametric Wilcox signed-rank test, lap belt score was significantly higher ($p<0.01$, mean difference 4 mm) in the shorter-cushion condition.

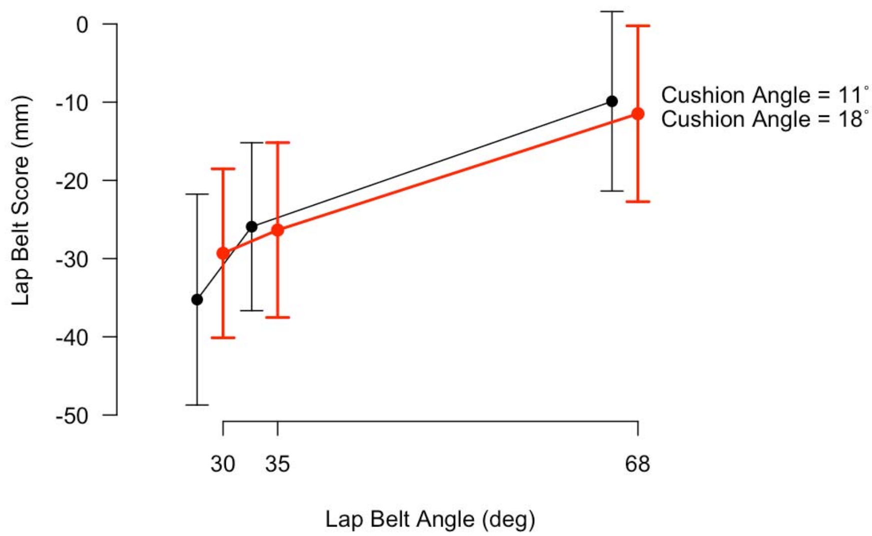


Figure 19. Effects of cushion angle and lap belt angle on mean lap score with no booster (conditions 18, 19, 20, 21, 24, and 25. Plot shows condition means and standard deviations (offset on the horizontal axis for clarity).

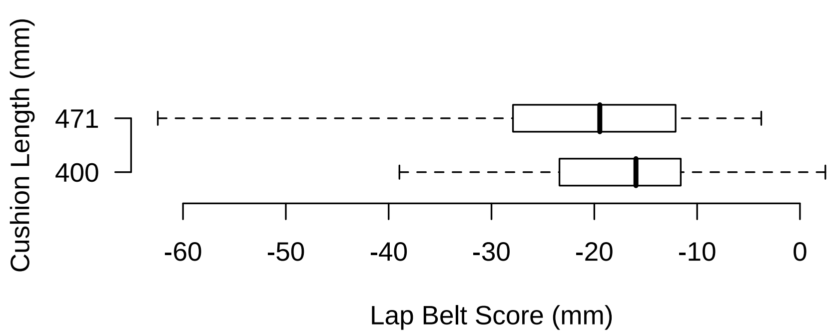


Figure 20. Effect of cushion length on lap belt score in the nominal belt condition (conditions 2 and 22) with no booster.

3.5 Effects of Booster on Shoulder Belt Fit

The shoulder belt score (SBS) is the distance from the inner boundary of the belt to the midline of the child at the height of the suprasternale landmark (see Figure 14). On average, an SBS of 30 mm places the belt in the middle of the shoulder (midway between the acromion landmark at the outer edge of the shoulder and the midline of the body), but the optimal value depends in part on the subject's shoulder height and the angle of the belt. This definition of SBS was chosen in part because a directly analogous measure can be obtained using the Hybrid-III 6YO and 10YO ATDs (see Appendix B).

All of the boosters were evaluated in the mid-range D-ring and lap conditions (condition 2). Table 11 compares the shoulder belt scores across boosters in this condition. Figure 21 shows a box plot of the same results, showing the large skew in results with the Alpha Omega. Unlike the other highback boosters, the Alpha Omega lacks a height adjustment on the shoulder belt routing clip (see Figure 16), instead providing two fixed-position routing loops.

The contrast between the results for the backless TurboBooster and the no-booster condition shows the effects on torso belt fit of raising the child, even in the absence of shoulder belt routing. The average SBS is approximately 25 mm higher (further outboard) on the booster compared with the no-booster condition.

Table 11
Mean and Standard Deviation of Shoulder Belt Score in Condition 2

Booster*	Mean (mm)	Standard Deviation (mm)
None	20.3	24.4
TurboBooster	31.6	17.7
Parkway	35.8	20.2
Intera	36.0	23.2
TurboBooster Backless	56.8	26.9
Alpha Omega	103.3	60.4

* Rank ordered by mean score (higher scores indicate belt is further outboard).

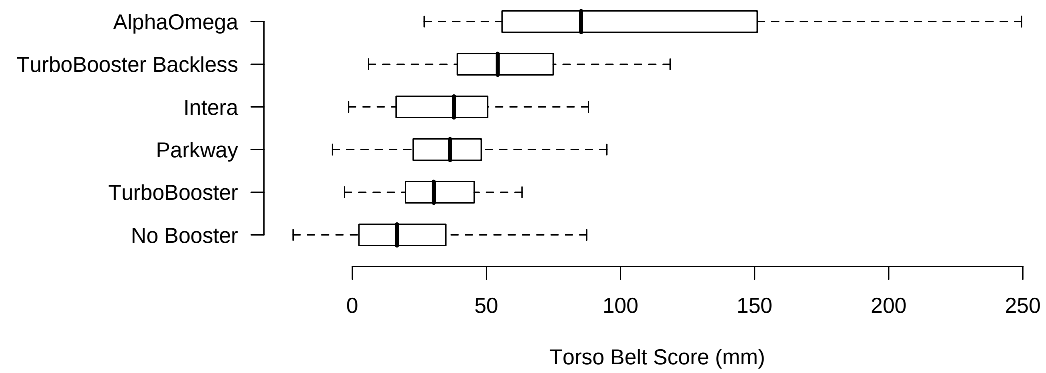


Figure 21. Box plot of shoulder belt score by booster. Boxes show median and interquartile range. Whiskers show full range of data.

3.6 Effects of Body Size on Shoulder Belt Fit

Most of the variability in shoulder belt score in Table 11 and Figure 21 (data from condition 2 only) is due to differences in participant body size. In generally, children with larger sitting height would be expected to have more-outboard shoulder belt fit in a particular test condition, unless the shoulder belt routing is adjustable for body size.

The effects of body size on shoulder belt fit are masked in part by subject posture effects. In particular, subjects often leaned slightly to the right or left, which had a direct effect on the shoulder belt scores. To clarify body size effects, a corrected shoulder belt score was calculated by adding or subtracting the amount of torso lean at the suprasternale landmark from the shoulder belt score. For example, if a subject were leaning 15 mm to the right during a trial (toward the belt), 15 mm would be added to the shoulder belt score. For the highback booster condition, the amount of lean was calculated by computing the distance from the suprasternale landmark to the centerline plane of the booster. For the backless TurboBooster and no-booster conditions, the lean was calculated with respect to the centerline of the seating position. The lean-corrected shoulder belt score is termed SBS_{Corr}.

Figure 22 shows SBS_{Corr} in condition 2 by booster as a function of stature. SBS_{Corr} was independent of stature except in the Alpha Omega highback booster, the backless TurboBooster, and in the no-booster condition. The outlying performance of the Alpha Omega resulted from its unusual fixed-position shoulder belt routing clip. In contrast, the adjustable positioning features of the Parkway and TurboBooster provided shoulder belt scores that were independent of participant size. The photos in Figure 23 show shoulder belt fit across booster conditions for a small participant (stature 1138 mm).

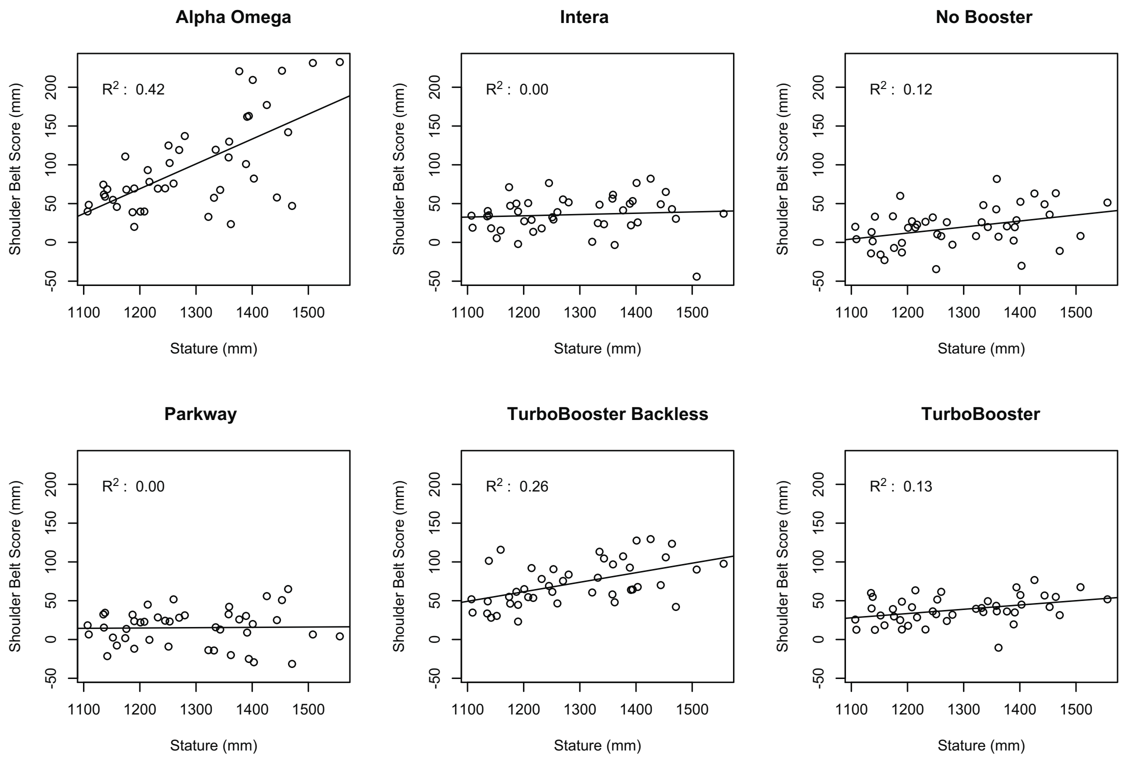


Figure 22. Shoulder belt score (lean-corrected) versus stature in condition 2 by booster.

Alpha Omega Intera None

Parkway TurboBooster Backless TurboBooster

Figure 23. Shoulder belt fit in condition 2 for a participant with stature of 1138 mm.

3.7 Effects of D-Ring (Upper Anchorage) Location on Shoulder Belt Fit

For analysis, the D-ring location was parameterized by the angle of the H-point-to-D-ring vector in side view (XZ angle) and front view (YZ angle). Two boosters (TurboBooster backless and Alpha Omega) were tested three D-ring positions (test conditions 1-3). The TurboBooster backless and no-booster conditions were tested with 7 D-ring positions.

Figure 24 shows the shoulder belt score for all D-ring conditions identified by XZ (side) and YZ (front) plane angles. The shoulder belt routing provided by the Alpha Omega negated the effect of the D-ring location. The average shoulder belt fit was poor, however, with the inboard edge of the belt lying more than 100 mm from the participant's midline. In the backless-booster and no-booster conditions, YZ (front) plane angle was more consistently related to shoulder belt score than XZ (side) plane angle. Increasing the YZ plane angle by moving the D-ring outward, down, and forward (see Figure 4) increased shoulder belt score, with a larger effect observed in the TurboBooster backless condition due to the higher occupant position. The nonlinear shift in shoulder belt score between 23 and 25 degrees YZ plane angle is due to a shift in XZ plane angle from 35 to 48 degrees. The D-ring location changed on all three axes between these conditions (see Tables 2 and 6).

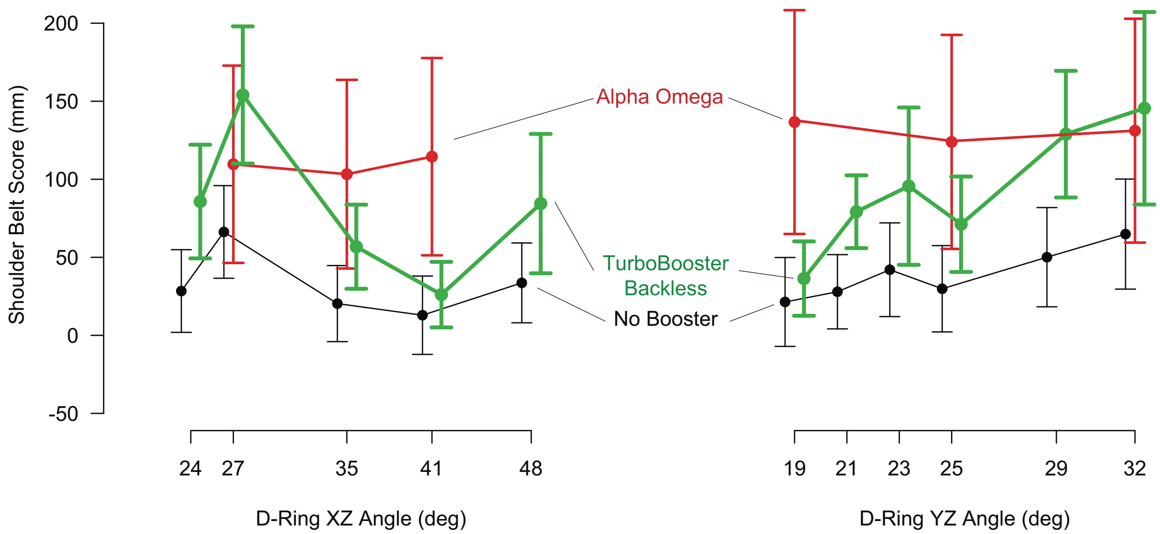


Figure 24. Effect of XZ (side-view) and YZ (front-view) D-ring location angle on Shoulder Belt Score for Alpha Omega, TurboBooster backless, and no booster (test conditions 1, 2, 3, 12, 13, 14, 15). Plot shows means and standard deviations at each D-ring condition. Points are offset slightly on horizontal axis for clarity.

Figures 22 and 24 suggest that both stature and D-ring position have important effects on shoulder belt fit. A regression analysis was conducted using SBS from the no-booster condition, considering stature, D-ring XZ angle, and D-ring YZ angle, along with potential squared effects and two-way interactions, as potential predictors. D-ring X-, Y-, and Z-axis locations were also considered as potential predictors. The best model based on adjusted R^2 value was

$$\text{Shoulder Belt Score, No Booster (mm)} = -144.9 + 0.0824\ \text{Stature} + 2.731\ \text{DRingYZAngle},\ R^2_{adj} = 0.31,\ \text{RMSE} = 25.3 \quad (2)$$

The model accounts for only about 30 percent of the variance in the data, leaving a relatively large residual. A similar model was fit to the data from the TurboBooster backless condition, yielding

Shoulder Belt Score, TurboBooster Backless (mm) = -143.9 + 0.0452 Stature + 6.336 DRingYZAngle, R^2_{adj} = 0.39, RMSE = 40.2 (3)

A combined analysis with both no-booster and TurboBooster backless data showed a significant interaction ($p<0.001$) between booster and DRingYZAngle (significantly different DRingYZAngle slopes in the two booster conditions) but no significant interaction between booster condition and stature.

3.8 Effects of Seat Back Angle

In testing without a booster, the effects of seat back angle (SAE A40) were investigated for three D-ring locations and the nominal lap belt angle (conditions 1, 2, 8, 10, 16, and 17). Because the most-rearward D-ring location was unrealistic with the most-upright seat back angle, the 19-degree seat back angle was used with the same D-ring locations used at the 23-degree seat back angle, while the 31-degree seat back angle was tested at the center and most-rearward D-ring locations.

Neither D-ring location nor seat back angle had a significant effect on lap belt score. Figure 25 shows significant effects of DRingYZAngle, but the effects of D-ring location are not significantly different across seat back angles.

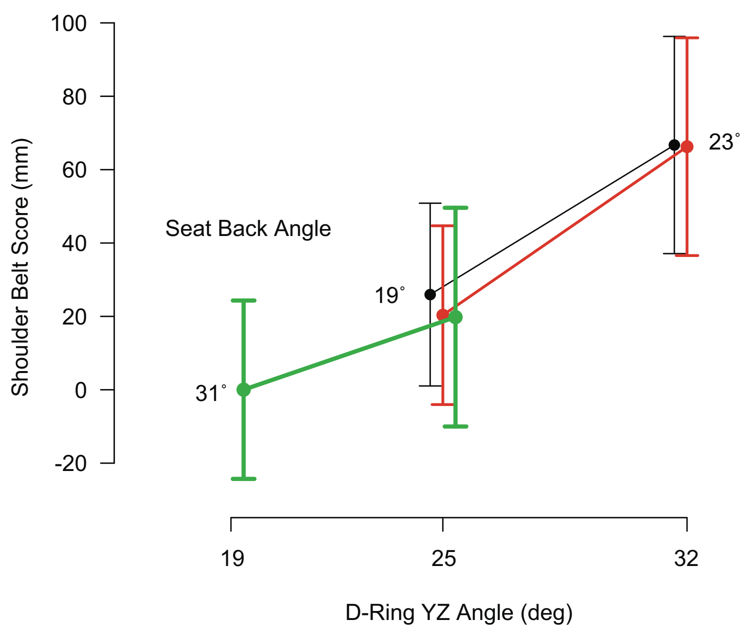


Figure 25. Effects of seat back angle and D-ring YZ angle on shoulder belt score in the no-booster condition. Plot shows means and standard deviations. Points are offset on the horizontal axis for clarity.

3.9 ATD Belt Fit

Lap and shoulder belt fit were measured in each test condition with both the 6YO and 10YO Hybrid-III ATDs using the UMTRI belt-fit measurement procedure (see Appendix B). Lap belt angle and D-ring position had significant effects on ATD lap belt score and shoulder belt score, respectively. Figure 26 shows LBS and SBS for the no-booster condition in the lap belt sub-matrix (conditions 2, 4, 6, and 23) and in the D-ring-position submatrix (conditions 1, 2, 3, 12, 13, 14, 15) for both ATDs. In each case, the within-ATD regression analysis was significant ($p<0.001$). On average, LBS was 31 mm higher (better belt fit) for the 10YO ATD than for the 6YO ATD in the no-booster condition. The SBS was higher (shoulder belt further outboard) for the 10YO ATD than for the 6YO ATD due to the higher shoulder position of the ATD. Table 12 shows regression analysis results for the ATD belt scores in the no-booster condition (both LBS and SBS) and in the TurboBooster backless (SBS) conditions.

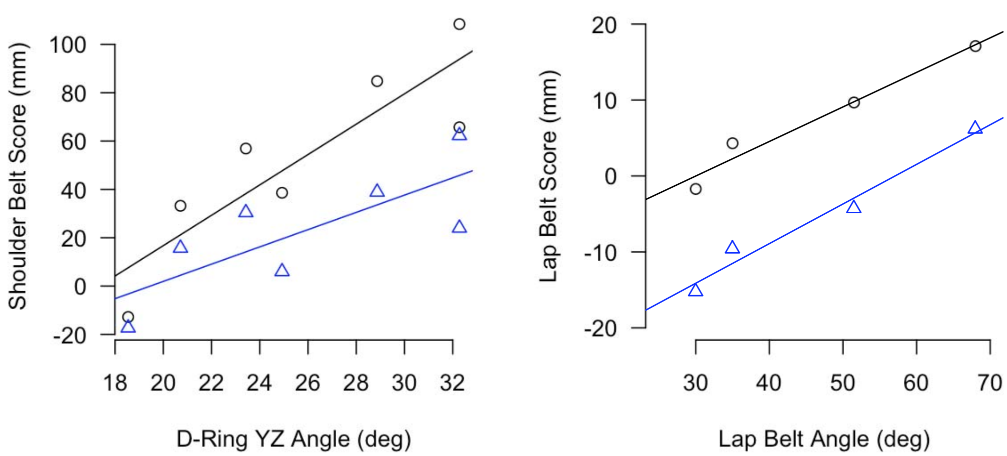


Figure 26. Relationship in the no-booster condition between lap belt and D-ring angles and lap belt score (left) and shoulder belt score (right) for the 10YO (circles) and 6YO (triangles) Hybrid-III ATDs.

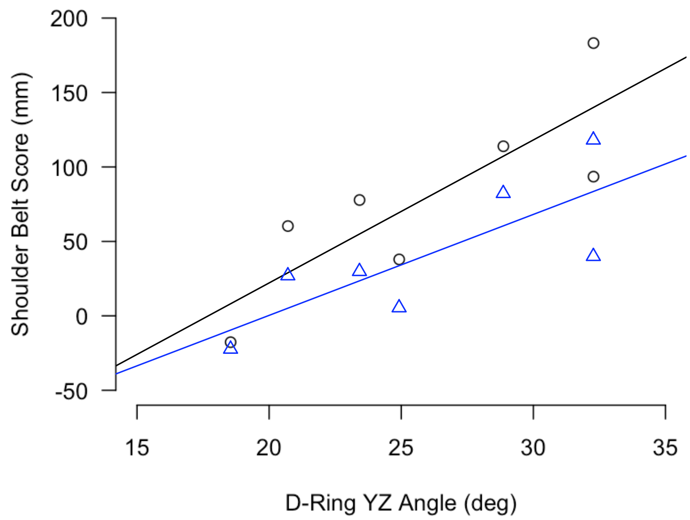


Figure 27. Relationship in the TurboBooster backless condition between D-ring angle and shoulder belt score for the 10YO (circles) and 6YO (triangles) Hybrid-III ATDs.

Table 12
Regression Results Predicting ATD Belt Fit from Belt Anchorage Locations

Condition	Measure	ATD	Regression Function*	R^2	RMSE
No Booster	SBS	6Y0	-69.5 + 3.572 YZ	0.51	17.6
	SBS	10YO	-108.9 + 6.283 YZ	0.72	20.7
	LBS	6Y0	-29.8 + 0.5221 LBA	0.96	1.9
	LBS	10YO	-13.7 + 0.4552 LBA	0.94	1.9
TurboBooster Backless	SBS	6Y0	-135.3 + 6.781 YZ	0.54	31.8
	SBS	10YO	-169.9 + 9.604 YZ	0.63	38.0

* Models significant with p<0.001. YZ = D-ring YZ plane angle; LBA = lap belt angle in side view, measured from anchorage to H-point (see text).

3.10 Comparison Between Child and ATD Lap Belt Fit

On average, the mean child lap belt score was 14 mm lower (worse) for the children than for the 6YO ATD, and 29 mm lower for the children than for the 10YO ATD. This reflects differences in pelvis geometry and particularly ASIS position, which is much lower relative to the thigh/abdomen junction on children than on the ATD.

Nonetheless, ATD lap belt scores were closely related to child lap belt scores. For each ATD, the correlation between the ATD lap belt fit and mean child LBS was 0.93 across all conditions. A close examination of the data showed offsets between the relationships for the booster and no-booster conditions, as shown in Figure 28. Children sat more slumped in the no-booster conditions, resulting in a lower ASIS position relative to the ATD and consequently lower (poorer) lap belt scores. Table 13 lists the regression equations for each condition. R^2 values exceeded 0.8, except for the no-booster condition with the 10YO ATD. More importantly, the root-mean-square error values were below 5 mm when booster and no-booster conditions fit separately.

Table 13
Regression Results Predicting Mean Child Lap Belt Score from ATD Lap Belt Score (mm)

Condition	ATD	Regression Function*	R^2_{adj}	RMSE
No Booster	6Y0	-17.3 + 0.851 ATDLBS	0.82	2.6
	10YO	-28.1 + 0.712 ATDLBS	0.58	4.0
Booster	6Y0	-5.1 + 0.644 ATDLBS	0.95	2.5
	10YO	-16.2 + 0.640 ATDLBS	0.85	4.3
All Conditions	6Y0	-13.1 + 0.915 ATDLBS	0.87	5.8
	10YO	-26.8 + 0.876 ATDLBS	0.87	5.8

* Models significant with $p<0.001$. ATDLBS = ATD Lap Belt Score

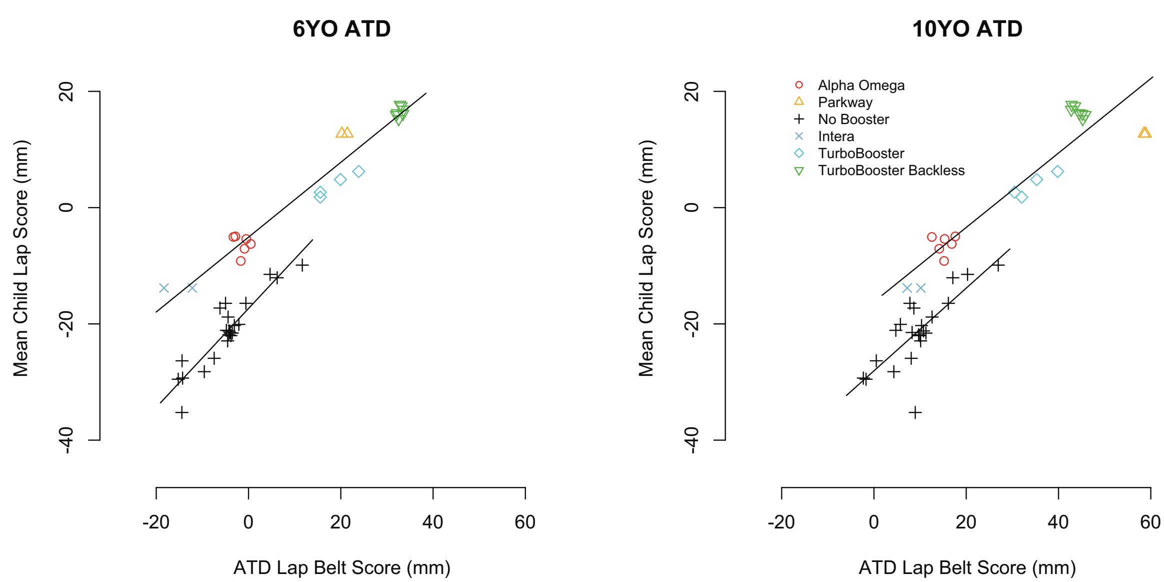


Figure 28. Association between mean child lap belt score and the ATD lap belt score. Data points show the mean child lap belt score for each condition.

Assessing the ability of the ATDs to predict child belt fit is aided by adjusting the child data to match the reference anthropometry of the ATDs. From Mertz et al. (2001), the reference statures for the 6YO and 10YO Hybrid-III ATDs are 1168 mm and 1374 mm, respectively. From equation 1, the slope of the stature effect on lap belt score is 0.0388 mm/mm (taller children experiencing better belt fit). The mean stature of the participant population is 1289 mm, so the mean expected belt fit for children the size of the 6YO ATD is 0.0388*(1289 – 1168) = 4.7 mm worse (smaller LBS) than the mean value for children as a whole. Children the size of the 10YO ATD have average lap belt fit 0.0388*(1374-1289) = 3.3 mm better than the average participant value.

These relationships can be used to predict the mean expected lap belt score for children in the measured stature range. For example, if the lap belt score measured on a booster with the 6YO Hybrid III is 20 mm, the average lap belt score for children midway in stature between the 6YO and 10Y0 ATDs (1271 mm) is predicted to be -5.1 + 0.644 (20) + 0.0388 (1271 - 1289) = 7 mm.

Alternatively, the ATD lap belt scores corresponding to a target lap belt score for children of a particular size can be computed. For example, the 6YO ATD lap belt score on a booster corresponding to the mean expected lap belt score for children the size of the 6YO ATD is given by

6YOCHILDLBS = MEANCHILDLBS – 4.7 = (-5.1 + 0.644 ATDLBS) – 4.7

= -9.8 + 0.644 ATDLBS

For a LBS target value of 0 mm for children with the same reference body dimensions as the 6YO ATD, the corresponding 6YOATDLBS = 15 mm.

Repeating the same calculations for the 10YO ATD and similar-size children on boosters gives

10YOCHILDLBS = MEANCHILDLBS + 3.3 = (-16.2 + 0.640 ATDLBS) + 3.3

= -12.9 + 0.644 ATDLBS

For a LBS target value of 0 mm for children with the same reference body dimensions as the 10YO ATD, the corresponding 10YOATDLBS = 20 mm.

3.11 Comparison Between Child and ATD Shoulder Belt Fit

The comparison between child and ATD shoulder belt score is more complicated than for the lap belt score because of postural differences between children and ATDs and differential effects of stature across booster conditions. As was shown in Figure 22, stature affects shoulder belt score differently across booster conditions, with the largest effect observed in the Alpha Omega. Consequently, the child mean shoulder belt scores were adjusted using the booster-specific stature slope to match the reference stature of each ATD. For example, the slope of the stature effect in the Alpha Omega (using SBS_{Corr}) was 0.321 mm/mm, so the mean child shoulder belt score was adjusted by 0.321*(1168-1289) = -38 mm for comparison to the 6YO ATD.

Figure 29 shows the stature-adjusted shoulder belt scores across all test conditions relative to ATD shoulder belt score. As with the lap belt scores, a different linear relationship is observed for booster and no-booster conditions. In effect, slumping results in the children having a shorter sitting height in the no-booster condition, so the shoulder belt routes closer to their necks. The ATDs do not slump realistically in the no-booster condition, so the ATDs scores show a smaller decrease in shoulder belt score when the booster is removed than do the children. Figure 30 shows this effect with one small subject in comparison to the 6YO ATD. Note that the difference in head location with respect to the seat back between the child and ATD is larger in the no-booster condition.

To assess this posture effect quantitatively, child hip and head CG locations were calculated from posture data using the methods described in Reed et al. (2006). In trials with the 23-degree seat back angle, child head CG was located an average of 444 mm above the hips on the vehicle seat and 460 mm above the hips on the TurboBooster backless, indicating a greater amount of lumbar spine flexion when sitting without a booster. As another indicator of greater slumping in the no-booster condition, the mean child head CG location was 57 mm below the 10YO ATD head CG location in the no-booster condition, but only 40 mm below the 10YO ATD head CG on the backless TurboBooster, indicating that the children were sitting 17 mm more erect on the booster.

Table 14 lists regression results predicting mean stature-adjusted child shoulder belt score from ATD shoulder belt scores. The high R^2 values indicate that the ATD shoulder belt scores are good predictors of child belt fit across the range of conditions studied. More importantly, the root-mean square error values are small relative to the range of shoulder belt scores produced by testing in different boosters and varying the belt geometry. Most of the variability in child shoulder belt scores is due to changes in the D-ring location, and the ATD shoulder belt scores track these changes accurately.

The 10YO ATD shoulder belt scores for the Alpha Omega were considerably more extreme than the stature-adjusted mean child scores. An examination of photos from testing in that booster showed qualitatively different belt routing behavior for the children. As shown in Figure 31, the torso portion of the belt lay well off the shoulder for the 10YO ATD and some children, but other children tended to push the belt up by raising their arms, reducing the shoulder belt score. Noting that the belt fit provided by the Alpha Omega for children the size of the 10YO ATD was clearly poor, the Alpha Omega data were excluded from the regression analysis for that ATD to avoid adversely affecting the performance of the regression model for other booster conditions.

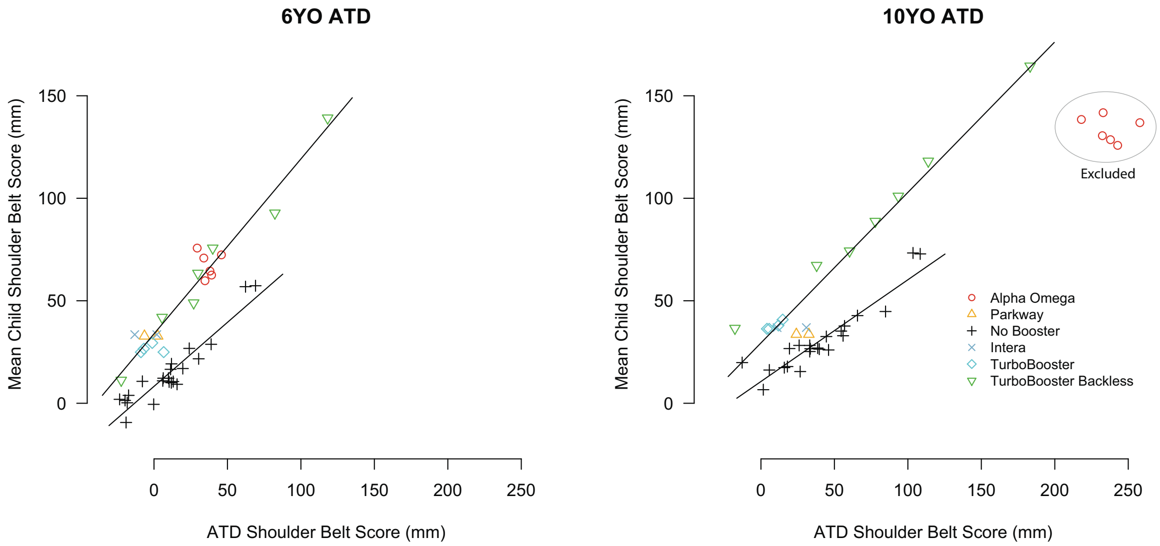


Figure 29. Association between ATD shoulder belt score and mean child shoulder belt score for the 6YO (left) and 10YO (right) Hybrid-III ATDs across all test conditions. Child data have been adjusted for stature differences between the children and ATDs.

Figure 30. Comparison of shoulder belt fit for the 6YO ATD and one child in the backless TurboBooster and no-booster conditions, showing the effect of slumping on sitting height for the child.

Table 14
Regression Results Predicting Shoulder Belt Score for Children with the Same Stature as the Reference Stature of the ATD from ATD Shoulder Belt Score (mm)

Condition	ATD	Regression Function*	R^2_{adj}	RMSE
No Booster	6Y0	8.2 + 0.625 ATDSBS	0.87	5.9
	10YO	10.6 + 0.496 ATDSBS	0.85	6.3
Booster	6Y0	33.9 + 0.853 ATDSBS	0.94	7.5
	10YO†	29.6 + 0.729 ATDSBS	0.93	10.3
All Conditions	6Y0	19.2 + 0.873 ATDSBS	0.71	16.3
	10YO†	15.2 + 0.672 ATDSBS	0.71	17.1

* Models significant with p<0.001. ATDSBS = ATD Shoulder Belt Score
† Data from Alpha Omega excluded

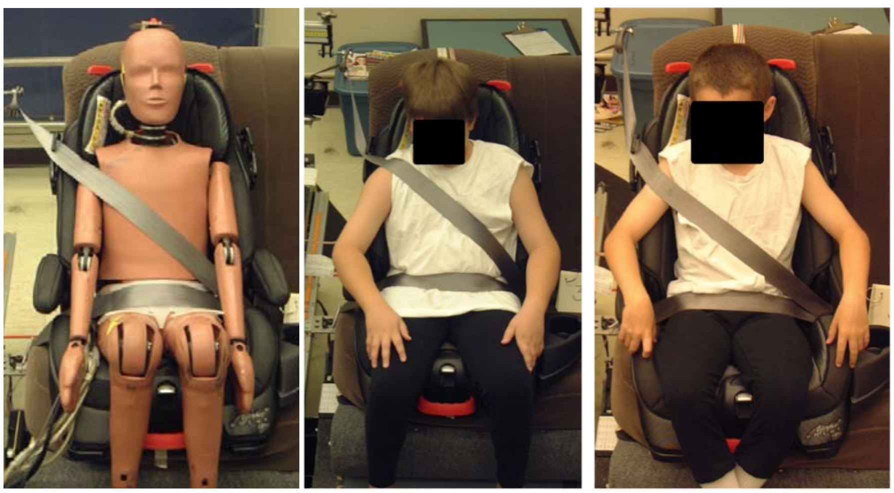


Figure 31. Comparing shoulder belt routing for the 10YO ATD and two large children in the Alpha Omega.

3.12 Ideal Shoulder Belt Fit

Good shoulder belt fit is characterized by belt centered on the shoulder. If the belt is too close to the neck, the resulting discomfort might cause a child to lean away from the belt or to put the belt behind the back or under the arm. This type of misuse has been associated with an increased risk of abdominal injury. If the belt is too far outboard on the shoulder, the occupant will tend to roll out of the belt, leading to poor torso restraint and increased head excursion. Hence, the belt should be as close to the neck as possible without causing discomfort. Given the relatively narrow shoulders of children relative to belt webbing width, the ideal belt position is effectively centered on the shoulder. This definition could be refined to consider the articulation of the shoulder (locating the belt inboard enough that the child can flex the shoulder without hindrance from the belt), but in practical terms the "center" of the shoulder is an appropriate target that places the belt on the clavicle.

Because larger children have wider shoulders, on average, the shoulder belt score that constitutes ideal belt fit is dependent on body size. The shoulder belt score analyzed above was chosen to be directly comparable between children and ATDs, which lack accurate shoulder anatomy. To relate the SBS to child shoulder belt fit, a second shoulder belt measure was computed in the child data. The midpoint of the belt at the height of the suprasternale was determined from digitized points. The Y (lateral) coordinate of the belt centerline was compared to the lateral midpoint between the suprasternale (top of sternum) and acromion (outer margin of scapula) landmarks. This new measure, $SBS_{centered}$, gives the belt location with respect to the lateral center of the shoulder. A regression analysis across all test conditions yielded

$$SBS_{centered} = 7.0 + 0.956\ SBS - 0.0280\ Stature,\ R^2_{adj} = 0.93,\ RMSE = 13.3 \quad (4)$$

Setting this equation to zero gives the child SBS that centers the belt as a function of stature:

$$\text{Child SBS (ideal)} = -7.3 + 0.0293\ \text{Stature} \quad (5)$$

for stature in mm. For children the size of the 6YO ATD (stature = 1168 mm), the ideal SBS is 27 mm. Using the equation in Table 14 for booster conditions and the 6YO ATD, the ideal ATD SBS is –8 mm. As shown in Figure 29, these are approximately the average stature-corrected child and 6YO ATD SBS scores for the TurboBooster and Parkway. For children the size of the 10YO ATD (stature = 1374 mm), the ideal SBS is 33 mm and the corresponding 10YO ATD score (in boosters) is 5 mm.

Because of the posture differences between booster and no-booster conditions, ATD scores identifying ideal belt fit for children are different without the booster. For example, the 6YO ATD score for ideal shoulder belt fit for children the size of the ATD on a vehicle seat without a booster is 30 mm, 38 mm further outboard than for booster conditions.

Figure 32 shows several examples of children in the backless TurboBooster with shoulder belt scores within one mm of the ideal SBS for their stature calculated using equation 5. The belt is centered on the shoulder, in each case. The belt is closest to the neck for the shortest subject, who has the smallest shoulder breadth, but is not touching the neck. For the taller children, the belt is approximately midway between the neck and the outer margin of the shoulder.

Figure 32. Children with a range of stature in trials with shoulder belt score within one mm of the ideal SBS calculated from equation 5.

The calculations above target the lateral center of the shoulder as the ideal location for the shoulder belt, but some deviation from this position would likely provide equivalent performance. However, a belt that is too far inboard would contact the child's neck and cause discomfort, potentially leading to misuse, and a belt too far outboard would be more likely to slide off the shoulder during a crash, or even to fail to engage the shoulder at all.

The range of functionally equivalent belt scores depends on the size of the child. Older children with wider shoulders can tolerate a larger range of belt scores, whereas the smallest children in the current data have only a narrow range of acceptable shoulder belt positions. Qualitative observations in the current data indicate that, for children about the size of the 6YO ATD, little margin is available between the most medial position that avoids neck contact and the most outboard position that keeps the belt inboard of the anterior deltoid muscle at the glenohumeral joint (see Figure 32). If the belt lies over the deltoid muscle, it will interfere with normal arm motions and may slide off the shoulder during a crash.

Assuming no lateral margin for the 6YO, the functionally equivalent range of belt fit scores for larger children can be estimated based on the rate of increasing shoulder breadth with stature. The standard anthropometric data obtained in the current study include biacromial breadth, a measure of bony shoulder breadth. To apply more directly to the current analysis, half of biacromial breadth (HBB) is computed as a function of stature:

Half Biacromial Breadth (mm) = 5.7 + 0.0955 Stature, $R^2 = 0.76$, RMSE = 6.3 mm

HBB for the 6YO reference stature of 1168 mm is 117 mm, increasing to 137 mm for the 10YO. Under the rationale described here, torso belt scores in a range of 20 mm centered on the ideal belt score of 33 mm (i.e., from 23 to 43 mm) would be considered equivalent for children the size of the 10YO ATD. Using the relationships in Table 14 for boosters, the corresponding 10YO ATD SBS range would be from -9 to 18 mm.

3.13 Belt Tension

Belt tension in the lap portion of the belt was measured using a load cell at the outboard lower anchorage. Data were recorded to the nearest 0.1 lb. Figure 33 shows the cumulative distributions of belt tension across all belt and seat conditions for each of the booster conditions. Belt tensions in the Intera, TurboBooster backless, and no-booster conditions were significantly higher than in the other three conditions (Mann-Whitney, $p<0.01$). The highest median belt tension (1 lb) was observed in the no-booster condition. For all booster conditions, 95% of the observations were less than 2.5 lb (11 N).

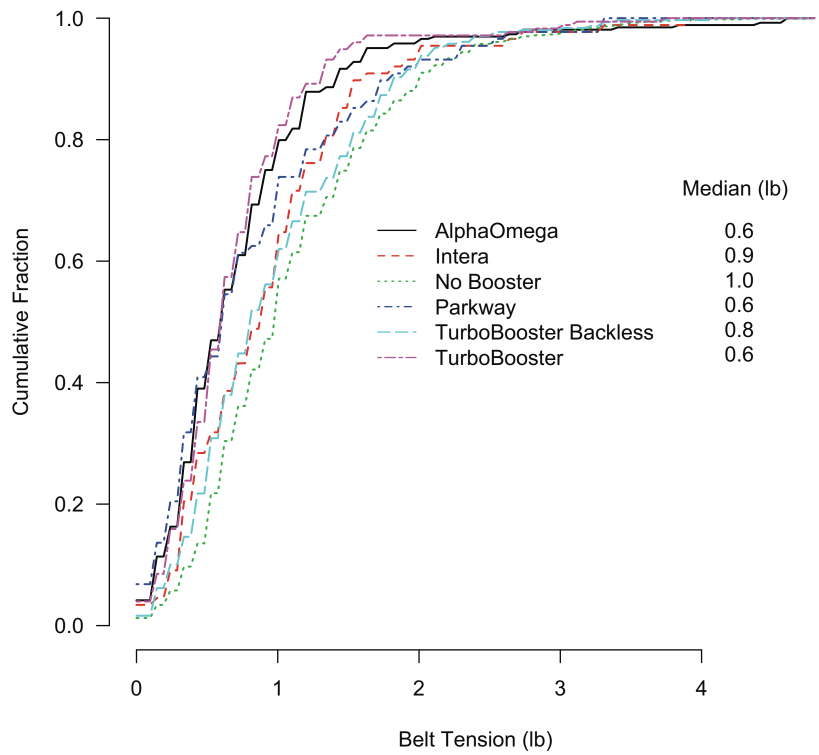


Figure 33. Cumulative distributions of belt tension at the lower outboard anchorage by booster condition.

4.0 DISCUSSION AND CONCLUSIONS

4.1 Primary Observations

- Boosters can differ substantially in the belt fit that they provide to children.
- The effects of body size on belt fit are smaller than the differences across boosters. The smallest children experienced approximately the same average lap belt fit in the worst-performing booster as the largest children did without a booster.
- Lap belt angle and D-ring location have large effects on lap and shoulder belt fit, respectively, when no booster is used.
- Boosters isolated the child from the effects of lap belt angle.
- In the absence of shoulder belt routing by the booster, the range of upper belt anchorage (D-ring) locations used in this study produce a wide range of shoulder belt fit.
- In trials without a booster, changing seat cushion angle did not have a significant effect on belt fit.
- In trials without a booster, shortening the seat cushion length by 71 mm produced a small but statistically significant improvement in lap belt fit, approximately the same average improvement that could be achieved by increasing the lap belt angle by 10 degrees.
- Belt fit measures obtained with the 6YO and 10YO Hybrid-III ATDs were strongly correlated across test conditions with the mean child belt fit scores.
- ATD lap belt scores of 15 mm (6YO) and 20 mm (10YO) were associated with mean lap belt scores of zero or better (indicating good belt fit) for children the size of the ATDs.
- ATD shoulder belt scores of -8 mm (6YO) and 5 mm (10YO) were associated with the shoulder belt being centered on the shoulder, on average, for children the size of the ATD.

Through detailed measurements and a relatively large sample size, this study was able to find statistically significant differences in lap belt fit between booster and belt conditions that are nonetheless small in absolute terms. Referring to Table 9, the difference in average lap belt fit between the best-performing booster and no booster (39 mm) was less than the width of the belt (48 mm). Moreover, intersubject variability was large, with the within-booster range of lap belt fit approximately as large as the mean difference between the best and worst-performing boosters. And, in all boosters, the average belt fit put more than half of the belt “below” the ASIS landmarks.

A critical issue in interpreting these data is what constitutes good lap belt fit. Is it sufficient for the belt to lie "over" the ASIS or must the belt be "below" the ASIS, i.e., on the thighs? Chamouard et al. (1996) and others have proposed that the lap belt should be fully below the ASIS to provide good lap belt fit. From considerations of child pelvis geometry and posture, we believe that the belt must start out fully below the ASIS to have a high probability of remaining engaged with the pelvis during a frontal crash. This corresponds to a lap belt score (LBS) greater than or equal to zero mm. Only three of the tested booster conditions produced belt fit meeting that criterion for the majority of the children tested.

Yet, consideration of field experience with boosters in the context of the current results does not provide a strong clarification of which, if any, of the booster conditions constitute good lap belt fit. Children ages 4 to 8 using three-point belts without a booster have been found to be at greatly elevated risk of abdominal injury due to belt interaction (Durbin et al. 2003) relative to children using belt-positioning boosters. No difference in field performance between different booster models, or between highback and backless boosters, has been shown. The results of the current study, however, show a substantial overlap in lap belt fit between the no-booster condition and two of the boosters (Alpha Omega and Intera), raising the question of whether improved lap belt fit alone accounts for the benefits of boosters seen in field data.

Much of the benefit of boosters in reducing the risk of abdominal injury may derive not from the relatively small improvement in lap belt fit demonstrated in the current study, but rather from a reduction of the incidence of very poor lap belt fit, essentially misuse of the belt. For example, misuse of the torso portion of the belt, either placing the belt under the arm or behind the back, has been implicated in some of the cases of serious abdominal injury to children using a three-point belt without a booster (Arbogast et al. 2005). This perspective is bolstered by the observation that older children (ages 9 to 15) experience a much lower risk of abdominal injury when using a three-point belt than do children ages 4-8 (Durbin et al. 2003). This difference has been widely assumed to be due to an increase in body size resulting in better lap belt fit, but the results of the current study show that even children the size of small adults do not achieve the same level of lap belt fit in typical belt conditions that the smallest children obtain in boosters. Hence, body size is shown not to be a substitute for a booster with respect to lap belt fit. Combining the field observation with the lab findings strengthens the argument that behavioral (including postural) differences, rather than belt-fit differences resulting from body size, may account for a substantial part of the improved performance of three-point belts for children ages 9-15.

This analysis has emphasized the importance of positioning the lap belt on the thighs, rather than on the lower abdomen. Using the current measurement approach scale, higher lap belt scores are better, but at some point a higher score would represent a decrement in performance. A straightforward quantitative justification for recommending a maximum value for LBS has not been identified. Conceptually, the lap belt to be as close to the pelvis as possible while still ensuring that it will engage the pelvis and not slide into the abdomen during impact. However, a forward belt position would allow the pelvis to translate farther during a frontal impact before substantial restraint force is generated. If torso restraint were applied earlier, the occupant would tend to recline in the early phases of the event, increasing the risk of submarining.

One observation from the current data is that the backless TurboBooster placed the belt fully below the ASIS (score of 0 or better) for all children in the midrange condition (see Figure 15). Starting from this observation, we could recommend that LBS measured with the 6YO ATD not be larger than the mean 6YO ATD LBS in this booster (35 mm) plus some margin (say, 15 mm) intended to account for increased postural variability in the field compared to the lab. Using this reasoning, we would recommend that boosters produce a lap belt score with the 6YO ATD no greater than 50 mm.

As demonstrated in section 3.10, ATD lap belt scores greater than 15 mm (6YO) and 20 mm (10YO) are associated with mean LBS of zero (the threshold for good belt fit) children the size of the ATD. However, because the child belt fit scores are approximately normally distributed, approximately half of children the size of the ATD would have the belt extending above the ASIS into the abdomen region at these target ATD belt scores. Consequently, a higher target LBS score would be needed to ensure that a large percentage of children would achieve good lap belt fit.

The current analysis has focused on the effect of the belt routing features in improving lap belt fit, but the data also show that simply raising the child and shortening the effective seat cushion length (as all boosters do) has substantial benefits for improving belt fit. Raising the child increases lap belt angle, which provides improved belt fit. In a backless booster, the child also sits substantially rearward on the seat, relative to the no-booster condition, again improving effective lap belt angle (Reed et al. 2006). The current analysis shows a reduction in slumping in boosters, relative to the vehicle seat alone. A more-upright pelvis posture will increase the likelihood that the belt will engage the pelvis during a crash.

These considerations are important when considering how to improve protection for all children using the belt for primary restraint, not just those using boosters. In most states, children ages 8 and older may legally be restrained using only a three-point belt. The data from the current study suggest that, in most vehicles, the belt fit these children obtain will be poor. Based on the current results, improvements to belt fit for these children should focus on steeper lap belt angles, shorter seat cushions, and more appropriate D-ring locations.

4.2 Design Features That Produce Good Belt Fit

Figure 34 shows close-up views of the lap and shoulder guides, highlighting characteristics that produce good or poor belt fit. A good lap belt routing guide, such as that on the TurboBooster or Parkway, has the following characteristics:

- The lower edge of the guide is at the same height as the seating surface, not elevated above it.

- The rear edge of the guide is forward of the back of the booster to hold the belt adjacent to the sitter's thighs. More-rearward guides allow the belt to move onto the abdomen with flatter lap belt angles.

- The guide has an upper component that limits upward movement of the lap belt at disadvantageous (relatively flat) lap belt angles.

In contrast, poor lap belt guides hold the belt up, rather than down, and may angle the belt toward the abdomen rather than toward the thighs. These recommendations are in agreement with those proposed by Chamouard et al. (1996).

Good shoulder belt guides are close to the child's shoulder, as shown in Figure 33, rather than at the outboard edge of the restraint. The shoulder belt guide should be adjustable vertically over a wide range to accommodate children with a wide range of shoulder height.

Good Poor

Figure 34. Illustration of good (left) and poor (right) belt routing guide designs for the shoulder portion of the belt (top) and lap portion (bottom.

4.3 Study Limitations

The principal limitation of this study is that all testing was conducted in a laboratory environment rather than in vehicles. Measuring child postures and belt fit in the laboratory allowed greater efficiency in testing because belt and seat geometry could be varied quickly and independently. Children who were not aware of being observed might have exhibited a larger range of behaviors. These behaviors, such as slouching, twisting, or leaning, would probably be more likely to result in poorer rather than better belt fit. The current study also did not consider the effects of heavy clothing, which would be likely to degrade lap belt fit.

This study included only a small number of boosters. However, these boosters were selected from among a sample of over 30 boosters for which ATD belt fit measures were available to be typical of those producing good and poor lap and shoulder belt fit. The findings from the current study allow the ATD-based measures of other boosters to be interpreted in terms of child belt fit.

The effects of D-ring location on shoulder belt fit were confounded to some extent by interaction between the seat and the belt, which has the effect of reducing the applicability of the regression analyses to other environments. This interaction was reduced by eliminating the outboard seat back bolster, but was still present for some subjects in the most-rearward D-ring location. Belt/seat interaction is common in vehicle second rows, so more research is needed to determine appropriate ways for accounting for this interaction in predicting belt fit. Direct measurement of belt fit using the ATDs (or computer simulations) using the methods in Appendix B may be a good way to assess belt fit, provided that the ATD results are referenced to child data via the results of the current study.

The current study used relatively high lap belt anchorage locations (see Figure 4). High belt anchorages probably increase the effects of body size on lap belt fit, because the lap belt angle changes more rapidly with the fore-aft position of the pelvis than would be the case with lower lap belt angles. In a vehicle with lower anchorages, child body size would have even less of an effect in determining lap belt fit for children than was the case in this study, in which only a small effect was observed.

In a previous study (Reed et al. 2006), child-selected postures were found to be less erect than postures measured after standardized instructions. In the current study, children chose their postures and donned the belt themselves, following standardized oral instructions based on the instruction manuals provided by the booster manufacturers (see Appendix A). The variability in posture and belt fit observed in the current study is probably smaller than would be observed in a sample of children in vehicles.

This research addresses only static belt fit. The dynamic performance of a restraint system, with or without a belt-positioning booster, depends on many factors, including the crash severity and impact direction. This study is part of a broader research program that addresses child occupant protection through studies with child volunteers, development of improved crash dummy components, and physical and computational crash simulations. This additional research is needed to determine the dynamic implications of the static belt fit differences observed in the current study.

As noted above, a critical consideration in interpreting the results of this study is the evidence from the field that belt-positioning boosters are effective in reducing the incidence of severe abdominal injuries relative to three-point belts alone. Although the current study suggests that many children using current-production boosters are obtaining relatively poor lap belt fit, the incidence of abdominal injury in booster-seated children in the field is low. Using data from a large-scale field survey of crash-involved children, Nance et al. (2004) reported no abdominal injuries among children 4 to 7 years of age who were using child restraints or belt-positioning boosters. Yet, abdominal injuries typical of those due to submarining have been observed in children using boosters. Analyzing a newer sample from the same survey, Jeremakian et al. (2007) reported three cases of children in belt-positioning boosters who sustained abdominal injuries in frontal impacts.

Although published reports suggest that the incidence of abdominal injuries in booster-seated children ages 4 to 8 is lower than for similar-age children using belts alone, data from the current study indicate that lap belt fit is improved only slightly by the use of some boosters. One interpretation of this conflict is that boosters improve belt load distribution on the child substantially, relative to belts alone, even when the boosters do not produce optimal belt fit. This improved load distribution may increase the crash speed at which the likelihood of an abdominal injury exceeds some threshold (say, 50%). Another possibility is that most abdominal injuries to children using three-point belts without boosters occur in part due to gross belt misuse (putting the belt under the arm or behind the back) rather than poor belt fit without gross misuse. In that case, a substantial part of the observed effectiveness of boosters in preventing abdominal injury relative to three-point belts alone may be due to a reduction in gross belt misuse, perhaps due to improved child comfort.

Nonetheless, the current study demonstrates that it is possible to design a booster to provide good lap and shoulder belt fit, which should be the primary objective of any booster design. Good belt routing features can position the lap portion of the belt on the thighs, rather than on the abdomen, and can keep the torso portion of the belt centered on the shoulder. Booster evaluation procedures should include belt fit assessments to encourage manufacturers to produce boosters that produce good belt fit for children.

4.4 Applications

The data and results from this study will have utility for a variety of purposes. The most apparent application is to the design of improved boosters that produce better belt fit. These results document important differences in belt fit between three models, and those differences are strongly linked to design features. Child restraint manufacturers can use this information, and the test procedures documented in this report, to assess and to improve their current designs.

A previous analysis of similar data (Reed et al. 2006) produced an ATD positioning procedure that has been used in sled testing and to obtain the belt fit measurements in this report. Further analysis of the posture data from the current study could document ways in which ATD postures could be made more realistic. For example, children's lumbar spine postures vary across booster and seat conditions, but the 6YO Hybrid-III lacks a lumbar spine adjustment.

The data also have applicability to the design of rear compartments of vehicles to improve child occupant protection. The belt conditions used in the current study were selected to span the range of belt anchorage locations measured in a study of vehicle second-row seating positions. Children experience a wide range of belt geometry in the current vehicle fleet, and the results of the current study show that this variance can result in large differences across vehicles in belt fit.

The data also show that typical seat and belt layouts are inadequate for children who are larger than those for whom boosters are recommended. Even at the NHTSA-recommended stature of 1450 mm, approximately half the width of the lap belt is above the child's ASIS, on average. Submarining would be likely with this initial belt position even with a steep lap belt angle.

An assumption underlying current booster recommendations is that children above a certain size "fit" well enough in the vehicle seat and belt and can safely dispense with booster use. The current results show that not only is there no bright line above which children fit, but that the fit received by the largest children is poor for many belt configurations that comply with FMVSS 210. The results also highlight the problem of excessive seat cushion length, which was noted qualitatively by Klinich et al. (1994) and documented quantitatively by Huang and Reed (2006). The average second-row seat cushion length is longer than the thighs of nearly all children under 1450 mm tall, making it difficult for them to sit comfortably against the seatback. In the current study, shortening the seat cushion by 71 mm from the median cushion length for passenger cars (471 mm) improved lap belt fit significantly.

The results of this study can also be used to support the use of ATD-based belt-fit assessments. The regression relationships reported in Section 3 can be used to calculate target ATD belt fit scores that are associated with desired levels of child belt fit. The example calculations in Section 3.10 showed that, on boosters, a 6YO ATD lap belt score of 15 mm is associated with a lap belt score of 0 mm for similar size children, indicating that at, on average, the belt is fully below/forward of the ASIS. Note that a higher score would be necessary to target greater than 50% of such children achieving an LBS of 0 mm.

4.5 Future Work

This research highlights the need to improve design standards and evaluation procedures for belt-positioning boosters. Current FMVSS 213 testing does not provide a meaningful evaluation of belt-positioning boosters. In particular, the Hybrid-III 6YO ATD is insufficiently sensitive to poor belt fit, such that submarining is not observed even when the lap belt is positioned in such a way that submarining would be likely with similar-size children. This lack of sensitivity to submarining is characteristic of adult-size Hybrid-III ATDs as well (Couturier et al. 2007). Work is underway to implement a new pelvis and abdomen assembly for the Hybrid-III 6YO based on realistic child anthropometry. Prototype evaluations suggest that the new components will improve the ability of the ATD to evaluate belt fit through dynamic testing.

This report suggests a range of shoulder belt scores that may produce equivalent performance for children the size of the 10YO ATD, but more research is needed to determine what range around the ideal, centered belt position is acceptable. Volume II of this report describes sled testing with Hybrid III 10YO ATD that examines ATD performance with outboard torso belt routing. The results indicate that the belt must be routed relatively far outboard, corresponding to an ATD SBS of 70 mm, before torso rollout is observed. However, the ATD shoulder is known to lack biofidelity, particularly with respect to contour in the belt-interaction areas, so it is difficult to assess the significance of these results for children. More research is needed to determine the range of ATD SBS that produce acceptable shoulder belt fit with children, both with and without boosters.

The current research shows that children who are larger than those typically using booster seats (ages 8 and up) obtain poor belt fit in a wide range of realistic rear-seat belt geometries. The lap portion of the belt is prepositioned on the abdomen, rather than fully engaged with the pelvis, and the shoulder portion of the belt is either too close to the neck or too far outboard on the shoulder. These findings indicate that children who “graduate” from a booster to the vehicle seat are likely to be experiencing a substantial degradation in crash protection. Improved evaluation procedures for rear-seat restraint systems and improved design standards for restraint systems in these seating positions are needed to better protect these children.

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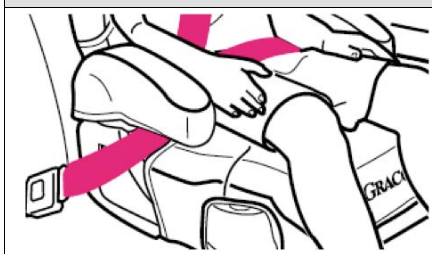
APPENDIX A
Booster Use Instructions

MANUAL INSTRUCTIONS		
TurboBooster	**Item**	**Action**
	Component Adjustments	To ensure the correct head support height is obtained, the bottom of the headrest MUST be even with the top of child's shoulders as and the shoulder belt must be positioned in the red zone. If the belt lays across child's neck, head or face, readjust head support height.
	Shoulder Belt	Belt must pass underneath the armrests. Position shoulder belt through the shoulder belt guide. Fasten buckle and pull up on the shoulder belt to tighten. If the belt lays across child's neck, head or face, readjust support height.
	Lap Belt	Lap portion of lap/shoulder belt MUST be low and snug on hips, just touching thighs. The lap belt portion MUST pass under the armrests and be positioned low on the hips.
IN LAB INSTRUCTIONS		
		Adjust head rest so that it looks like this image.
		Check belt fit at mid settings. Shoulder belt must be in router. Lap belt must be under arm rests. Shoulder belt must be under inboard arm rest. If child does not try to tighten belt, ask them to do so. If lap belt has more than 2 inches of slack, ask the child to tighten it again.

Script:
- On your right side the lap belt goes under the armrest.
- On your left side both the lap and shoulder belt goes under the armrest.
- Make sure the shoulder belt goes through this guide. (It will be in the guide already)
- Pull up on the shoulder belt to tighten.

MANUAL INSTRUCTIONS		
TurboBooster (Backless)	**Item**	**Action**
	Component Adjustments	
	Shoulder Belt	The shoulder belt MUST lay across the child's shoulders in red zone as shown. IF shoulder belt lays outside this zone, the shoulder belt positioning clip MUST be used.
	Lap Belt	The lap belt position MUST pass under the armrest and be positioned low on the hips. The belt MUST NOT be twisted.

IN LAB INSTRUCTIONS	
	Lap belt must be under arm rests. Shoulder belt must be under inboard arm rest. Do not use the shoulder belt clip. If child does not try to tighten belt, ask them to do so. If lap belt has more than 2 inches of slack, ask the child to tighten it again. If the child cannot tighten the belt on their own, help – but let the child select the final tightness.

Script:

- On your right side the lap belt goes under the armrest.
- On your left side both the lap and shoulder belt goes under the armrest.
- Pull up on the shoulder belt to tighten.

<table>
<tr><th colspan="3">MANUAL INSTRUCTIONS</th></tr>
<tr><th>Intera</th><th>Item</th><th>Action</th></tr>
<tr><td rowspan="3"></td><td>Component Adjustments</td><td>No written description of headrest height in manual.</td></tr>
<tr><td>Shoulder Belt</td><td>Secure the shoulder belt behind the headrest. The belt should cross the base of the child's neck and lie across the chest, not the face or neck. Pull up on the shoulder belt to tighten. The shoulder belt must always be adjusted snugly across the child's chest.</td></tr>
<tr><td>Lap Belt</td><td>Place lap belt across child's thighs. Lock buckle.</td></tr>
<tr><th colspan="3">IN LAB INSTRUCTIONS</th></tr>
<tr><td colspan="2"></td><td>Adjust the headrest to look like this drawing.
Shoulder belt should be behind the headrest when possible.
If the shoulder belt does not stay behind the hook after trying, leave it.
If child does not try to tighten belt, ask them to do so.
If lap belt has more than 2 inches of slack, ask the child to tighten it again.
If the child cannot tighten the belt on their own, help – but let the child select the final tightness.</td></tr>
<tr><td colspan="3">Script:
• Place the lap belt across your thighs.
• Pull up on the shoulder belt to tighten.
• The shoulder belt should go behind this hook.</td></tr>
</table>

MANUAL INSTRUCTIONS		
Alpha Omega	**Item**	**Action**
	Component Adjustments	Child restraint must be in the full upright position.
	Shoulder Belt	Secure the shoulder belt through one of the notches in the shoulder belt guides. The belt should cross the base of the child's neck and across the chest (not the face or neck). Pull up on the shoulder belt to tighten. The shoulder belt must always be adjusted snugly across the child's chest.
	Lap Belt	Place lap/shoulder belt across child's thighs. Lock buckle.
IN LAB INSTRUCTIONS		
		Check shoulder belt fit at mid settings. Select shoulder router that gives the best fit. The shoulder belt should be routed through one of the routers for every condition. It the belt does not stay in the router despite trying, leave it. If child does not try to tighten belt, ask them to do so. If lap belt has more than 2 inches of slack, ask the child to tighten it again. If the child cannot tighten the belt on their own, help – but let the child select the final tightness.

Script:

- Place the lap belt across your thighs.
- Pull up on the shoulder belt to tighten.
- The shoulder belt should go though this hook.

APPENDIX B
Method for Measuring Belt Fit with ATDs

1.0 Preparing the ATD

The Hybrid-III ATDs have an unrealistic flesh contour in the lap area that complicates the measurement of belt routing. As shown in Figure B1, the large gap between the pelvis flesh and thigh flesh can catch the lap portion of the belt. Note that the ATD was tested without clothing, which differs from standard dynamic testing procedures.

To eliminate this problem, a flexible lap form was developed (Figure B1). Constructed of 50A-durometer, 1/8-in-thick silicone rubber, the lap form provides a smooth contour and uniform friction in the critical area at the thigh/abdomen junction. The lap form was attached to the upper edge of the pelvis flesh using double-sided tape. The portions of the lap form over the thigh flesh were not attached to the ATD (Figure B2).

The ATD pelvis was fitted with removable measurement fixtures on each side, inserted into the square holes on the sides of the ATD pelvis (Figure B3). Each fixture has two reference landmarks that were measured at each trial to characterize the position and orientation of the ATD pelvis. An indelible marker was used to identify the positions of the left and right anterior-superior margins of the pelvic bone of the ATD on the exterior flesh surface. These points were referenced in the measurement of the belt location as described below.

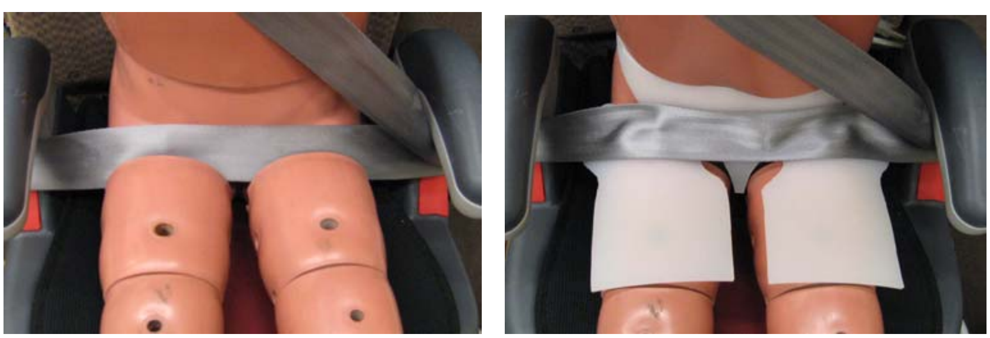


Figure B1. Gap between the pelvis flesh and thigh flesh without and with the lap form.

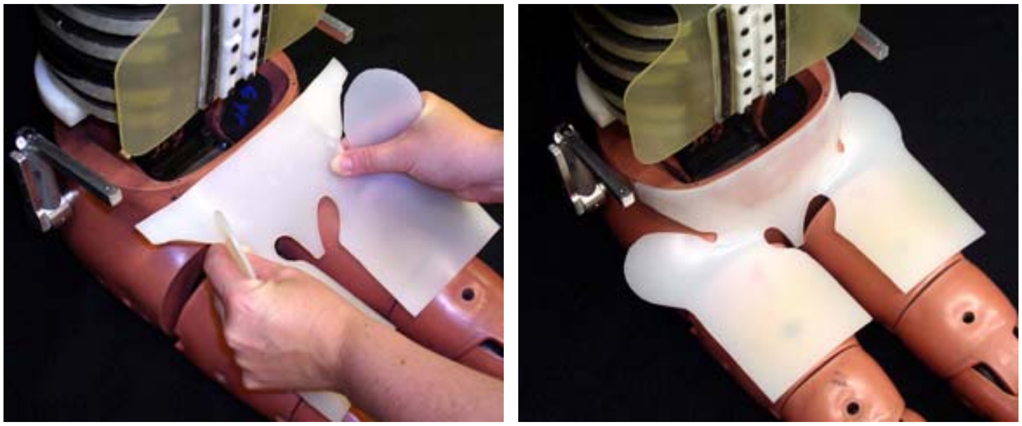


Figure B2. Attaching the lap form to the ATD.

Figure B3. Removable pelvis measurement fixture.

2.0 Belt-Fit Measurement Method

The belt fit measurement procedure has the following five components.

1. Preparing the Booster

The manufacturer's installation and usage instructions were reviewed and documented. The lateral centerlines on the top and back of the booster were marked to aid in positioning the booster on the seat. Any adjustable components were set according to the manufacturer's instructions for children the size of the ATD. To accomplish these adjustments, the booster was placed on the seat according to the instructions below, the ATD was placed in the seat, and the components were adjusted. For example, many boosters instruct that the back height be adjusted so that the torso belt routing is at the shoulder height. This adjustment was accomplished with the ATD in position. After completing adjustments of booster components, the ATD and booster were removed from the vehicle seat.

2. Positioning the Booster

The booster was placed on the seat so that the lateral centerline plane of the booster was coincident with the lateral centerline of the seating position. A force of 133 N was applied to the front of the booster seat pan directed rearward along the plane of the seating surface. The manufacturer's instructions about how the booster should be placed in the seat, such as specified points of contact, were followed. If the booster obstructed access to the buckle, the booster was moved outboard until the buckle was accessible. During this movement, the lateral centerline plane of the booster was maintained parallel to the centerline plane of the seating position as much as possible.

3. Installing the ATD

The ATD installation procedure was derived from the positioning procedures developed from child posture data (Reed et al. 2006). This positioning procedure was intended to put the hips and head of the ATD in positions representative of those of similar-size children. A foam pad was placed on the back of the ATD pelvis, as shown in Figure 4, so that a hip location representative of similar-size child occupants was obtained (see Reed et al. 2006).

The ATD was installed through a series of steps shown in Figure 5. The ATD was placed in an initial position on the seat by moving the ATD rearward just above the seat pan until the pelvis pad was in minimal contact with the back of the booster, or the seat back for backless boosters. The ATD was then set on the booster and the torso of the ATD allowed to lean against the back of the booster. A hand-held force gage was used to apply 177 N to the pelvis and thorax of the ATD in sequence, using a force-application tool with a flat, square surface as specified in FMVSS 213. The outer edges of the knees are set to 180 mm apart and the upper extremities were set to extend straight forward from the shoulders. The ATD was checked to verify that the ATD midsagittal plane was coincident with the lateral centerline plane of the booster. No further adjustment of the ATD posture, such as attempting to level the head, was performed.

A piece of tape was placed on the thorax of the ATD to mark the measurement location for torso belt fit. This procedure was performed after the ATD was installed, because the jacket of the ATD, which represents the thorax flesh, can shift during installation. Figure 6 shows the procedure for locating a point on the surface lying directly over the junction between the hard plastic "bib" of the thorax assembly and the neck on the ATD midline. A piece of tape oriented horizontally was placed at this height on the ATD. The tape was located approximately at the position of the clavicle in the human, but the Hybrid-III ATD shoulder lacks a clavicle component.

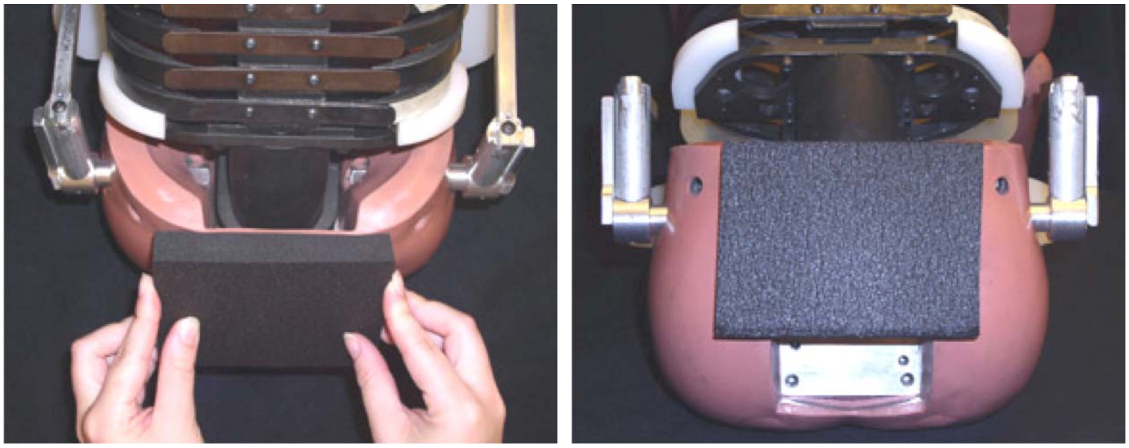
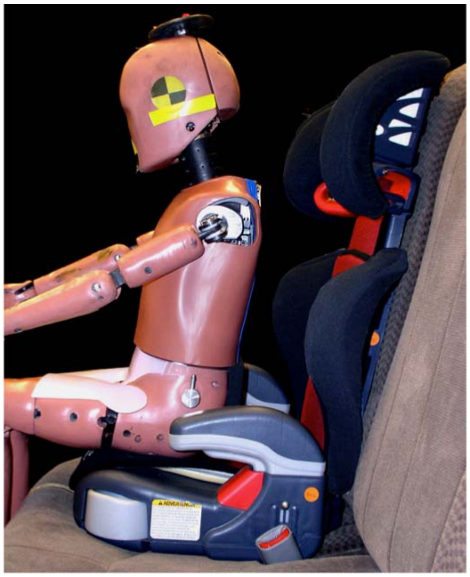


Figure B4. Attaching the pelvis positioning pad.

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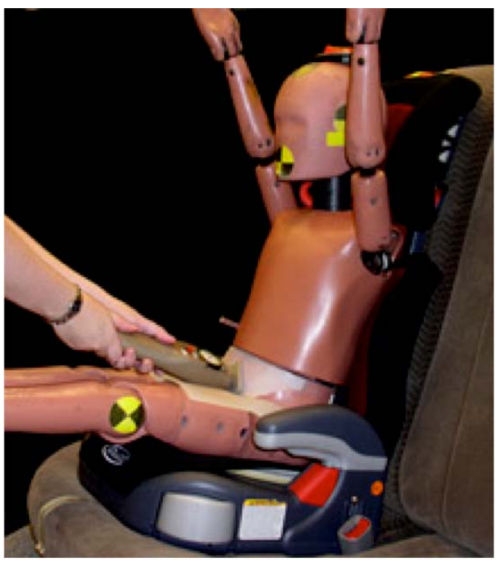



c d

Figure B5. Steps in positioning the ATD. (a) Placing the ATD in the booster; (b) Leaning the ATD against the back of the booster; (c) applying 177 N to the pelvis; (d) applying 177 N to the thorax.

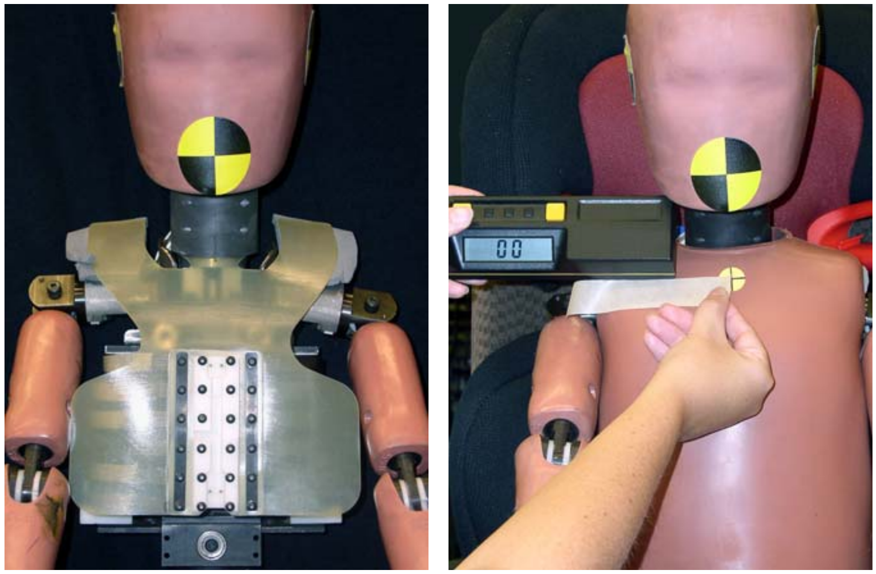
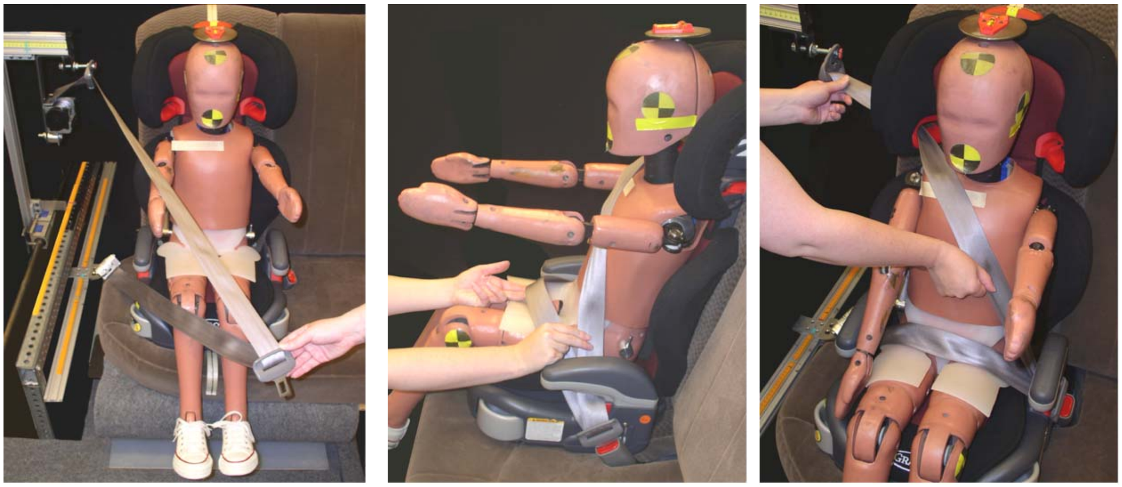


Figure B6. Applying tape used to measure the fit of the shoulder belt

4. Deploying the Belt

The method of placing the belt on the ATD was developed to approximate the donning procedure a child would use while also producing repeatable and reproducible routing. The steps are illustrated in Figure 7. The latchplate was pulled forward at the vertical level of the ATD abdomen until the latchplate was over the buckle-side foot of the ATD. If the booster had a back with a belt-routing feature, the belt was placed through the guide. The latchplate was inserted into the buckle and the slack in the lap portion of the belt was controlled by the investigator’s left hand (see Figure B7B) while the right hand pulled the belt through the latchplate to tighten the lap portion of the belt. The belt was pulled only until it stopped moving against the lap form. The torso portion of the belt was then placed snugly against the chest by pulling the belt outward at the upper anchorage (D-ring) while gently adjusting the belt position against the chest. The goal was to achieve the belt routing requiring the least belt webbing, i.e., the minimum distance routing.



A B C

Figure B7. Steps in deploying the belt: (A) pulling the latchplate out to fore-aft position of the ATD feet; (B) controlling the lap portion of the belt while pulling the torso portion through the latchplate after buckling, and (C) establishing the minimum-distance routing over the torso.

5. Recording Belt Fit

A FARO Arm coordinate digitizer was used to record the routing of the belt at the chest and pelvis as shown in Figure B8. The inboard and outboard edges of the torso portion of the belt were digitized where they passed over the tape placed on the ATD's chest. The upper and lower edges of the lap portion of the belt were recorded where the belt passed over the lateral positions of the anterior-superior iliac spines (ASIS) landmarks of the ATD pelvis bone. The locations of landmarks on the ATD pelvis, chest, head, and extremities were recorded to quantify the posture and position of the ATD and reference points on the booster were digitized.

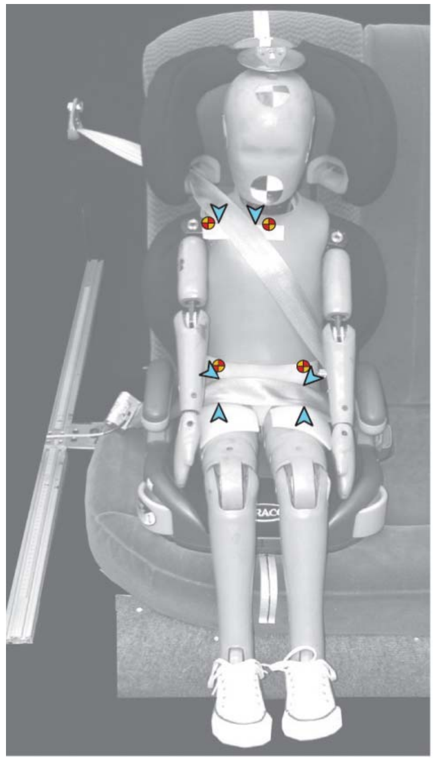


Figure B8. Landmark locations measured to quantify belt fit (arrows). Circles mark reference points on the ATD from which belt fit was measured.

4.0 Dependent Measures

Torso belt fit was quantified as the position, relative to the ATD centerline, of the medial edge of the belt where it passes over the tape line on the upper chest. The fit measurement is shown schematically in Figure B9. A higher value indicates that the belt is more lateral (outboard). Lap belt fit is quantified relative to the projection of the ASIS of the ATD pelvis bone onto the surface of the ATD skin. The lap belt score is the distance below/forward of the ASIS of the upper/rearward edge of the belt along the side-view profile of the pelvis and thighs at the lateral position of the ASIS. Figure B9 shows how the measurement was calculated. The distance was taken along the curved profile and was computed rather than directly measured. Separate scores were computed for the inboard (buckle) and outboard sides. A higher lap belt score indicates that the belt is lower or more forward. A score of approximately 35 mm for the 6YO ATD indicates that the belt is lying fully on the thighs at the thigh abdominal junction.

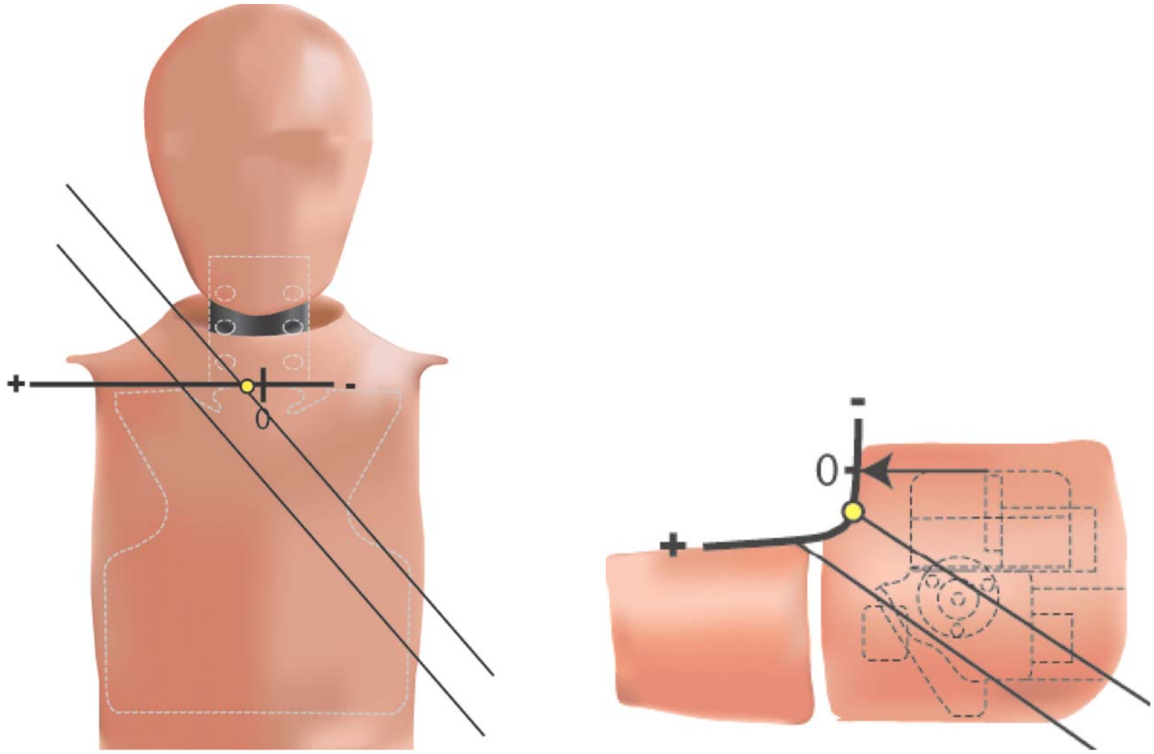


Figure B9. Calculation of lap belt scores. The yellow dot indicates the digitized landmark that was used to compute the score. The score is the distance along the indicated contour from the origin (marked with 0).

APPENDIX C
Computing Child Lap Belt Score

The calculation of child lap belt fit started with stream data measured along a sagittal plane at the lateral location of the ASIS, along with measured ASIS and belt locations. The belt location was represented by the upper/rearward edge of the belt in the same plane. All analysis of the lap stream data was conducted side view. Figure C1 shows the streams schematically.

Figure C1. Digitizing the lap streams on a participant.

Prior to computing lap belt scores, the stream data were truncated so that the lengths of the streams were similar across conditions and subjects. Starting from a point on the stream closest to the digitized ASIS point, the stream data further than 100 mm forward and 70 mm above were cut off as illustrated in Figure C2. The end points of the truncated stream were used as the end points when fitting a cubic Bezier spline to the stream points.

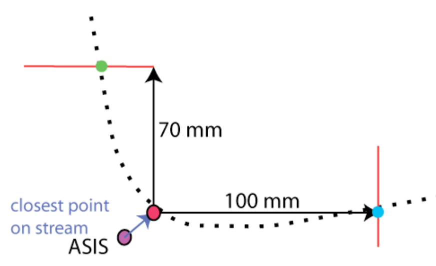


Figure C2. Truncating the lap stream data

A cubic Bezier spline is a parametric curve that interpolates its end points (controls 1 and 4 in Figure C3). The interior shape of the curve is controlled by two points (controls 2 and 3) that define the gradients at the end points. While fitting the spline to the lap stream data, the angular orientations of the interior control points (controls 2 and 3) relative to the end points were fixed values, but their distances from the end points were not. Points within 60 mm along the length of the stream from the end point on the thigh (control 1) were used to fit a line along which control 2 would be located. The angle formed between control 4, 1 and 2 was called *angle 1*.

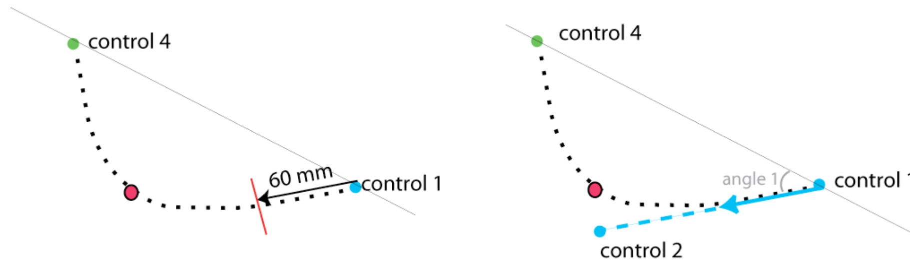


Figure C3. Using the the line fit to the thigh end of the stream to determine the angle formed by controls 4-1-2.

A line perpendicular to the line between controls 1 and 2 was constructed and moved rearward along the line between controls 1 and 2 until it intersected the stream at or above the point on the stream closest to the ASIS. This point of intersection created *angle 2* between controls 1-4-3, as shown in Figure C5. With angles 1 and 2 fixed, the distances of controls 2 and 3 relative to controls 1 and 4 respectively were allowed to vary along the vectors defined by these angles while using the least-squares method to find the best fit of a Bezier spline to the stream data. Figure C6 illustrates spline fits to lap stream data. Splines fit in this way tended to bridge indentations in the stream contours, providing a smooth transition from abdomen to pelvis.

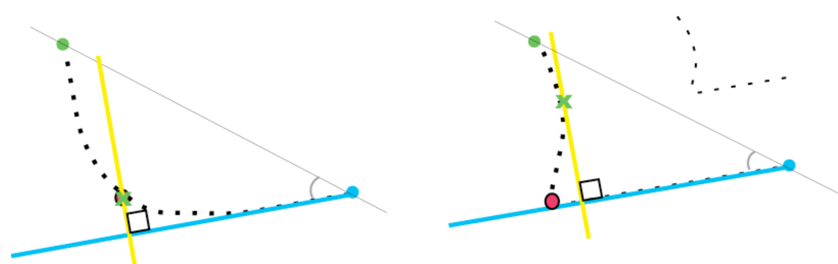


Figure C4. Using the intercept between the stream above the projected ASIS and a perpendicular to the line between controls1 and 2 to determine the angle formed by controls 1-4-3 for two different lap contours. A vector perpendicular to the thigh tangent was moved rearward until contacting the abdomen portion of the stream.

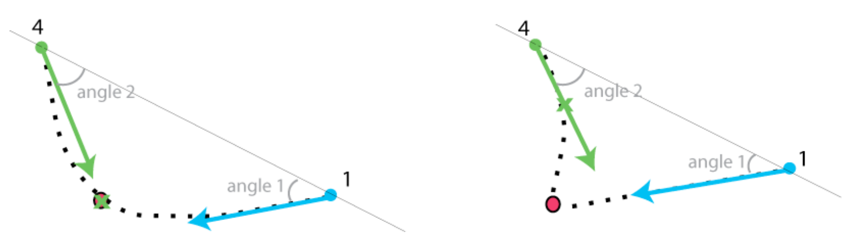


Figure C5. Setting the direction of the vector from control 4 to control 3 for two different lap contours.

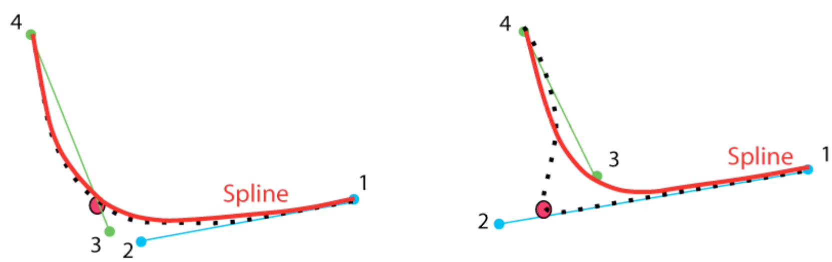


Figure C6. Fitting a spline (red) by varying the distance between controls 3 and 4 and between 2 and 1 and optimizing fit using least squares. Lap stream data are shown with black points and the spine is shown as a red line.

After fitting the spline, the ASIS location was projected into the spline by taking (in side view) the point on the spline closest to the measured ASIS location. The upper/rearward edge of the belt, measured at the lateral location of the ASIS, was also projected into the spline. As shown in Figure 12f, the lap belt score was computed as the distance in millimeters along the spline between the projected ASIS and belt points. The belt score is positive if the belt is below/forward of the projected ASIS location. The belt score is negative if the belt is above the ASIS along the spline.

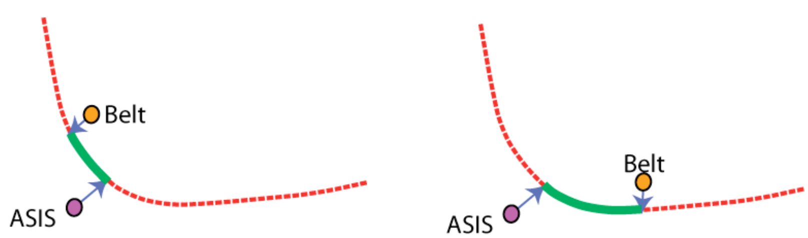


Figure C7. Projecting the ASIS and top edge of the belt onto the spline and calculating the distance (green) between the projected points along the length of the spline (dashed red). The image on the left shows a negative lap belt score and the image on the right shows a positive lap belt score.