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Optimizing Protection for Rear Seat Occupants: Assessing Booster Performance With Realistic Belt Geometry Using the Hybrid III 6YO ATD

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16. Abstract

A series of sled tests was conducted to examine the performance of booster seats under belt geometries representing the range found in the rear seats of current vehicles. Twelve tests were performed with the standard 6YO Hybrid III ATD and 29 tests were performed with a modified version of the 6YO ATD. The modified dummy has a pelvis with more realistic shape and flesh stiffness, a gel abdomen with biomechanically-based stiffness characteristics, and a custom neoprene jacket. Shoulder belt upper anchorage was set at the FMVSS No. 213 belt anchorage location and 64 mm inboard and outboard from this location. Lap belt anchorage locations were chosen to span the range of lap belt angles permitted under FMVSS 210, using the FMVSS No. 213 belt anchorage locations and forward belt anchorage locations that produce a much steeper lap belt angle. Four booster seats that provide a range of static belt fit were used. The ATDs were positioned using either the standard FMVSS No. 213 seating procedure or an alternate UMTRI procedure that produces postures closer to those of similar-size children.

Kinematic results for the standard and modified dummies under the same test conditions were more similar than expected. The current version of the modified 6YO is less sensitive to lap belt geometry than the prototype version of the dummy. The seating procedure had a greater affect on kinematic results. The UMTRI seating procedure produced greater knee-head excursion differences and less forward torso rotation than the FMVSS No. 213 procedure.

Shifting the shoulder belt upper anchorage 128 mm laterally produced minimal variations in kinematics for a given booster seat/lap belt condition, likely because the belt-routing features of the booster seats limited the differences in static shoulder belt score to less than 10 mm. Moving the lap belt geometry from rearward (shallow angle) to forward (steep angle) produced less desirable kinematics with all booster seats tested. The forward position of the lap belt anchorage allows greater forward translation of the booster and ATD before the belt engages the pelvis. Steeper belt angles are associated with better lap belt fit for children sitting without boosters, so designing rear seat belts for children who sit with and without boosters may involve a performance tradeoff.

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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/in²	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)				
°C	Celsius	1.8C+32	Fahrenheit	°F
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)

Acknowledgments

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1.0 Introduction

A larger percentage of U.S. children than ever before are using age appropriate child restraints and sitting in rear seats. Rear seating of 0-4 year olds was 98% in 2008 compared to less than 90% in 2002, and changed from 71% to 88% of 4-7 year olds over the same time period. Much of the recent increase in restraint use has come through increased booster use by children from four to eight years old, which was 15% in 2000 and 63% in 2007 (NOPUS 2008). Forty-seven states have passed laws mandating child restraint use for older children. NHTSA recommends that children aged 8-12 years use a booster seat until they are big enough to fit in a seat belt properly, but most of the laws use criteria stating that a child no longer must use a booster once they achieve a particular age (6-9) or a target stature or body weight (often 4'9" or 80 lb based on outdated recommendations.) Although some caregivers will continue to use boosters beyond these mandated limits, most U.S. children older than about 7 years of age will be riding without boosters even if 100% compliance with the new laws is assumed. This implies that rear seats of vehicles, if designed to accommodate the population of children who use them, must be designed to accommodate children in this age range both with and without booster seats.

Recent research at UMTRI suggests that these children, ages 6 to 12 and smaller than 5th-percentile adult women by stature, experience a restraint environment that poorly suits them. Huang and Reed (2006) measured second-row seat dimensions and found that the median rear seat cushion length of 455 mm exceeds the thigh length of nearly all children and adults less than 60 inches tall. Essentially, the seat geometry in most vehicles precludes sitting in a comfortable posture without slouching, and slouching leads to poor belt fit.

In recent research for NHTSA, seated postures and belt fit were recorded for children between ages 5 and 12 with statures from 1100 to 1550 mm (43 to 61 inches). In a typical rear seat and belt configuration without a booster, the average lap belt fit experienced by the largest of these children was poor, with more than half of the width of the lap belt extending above the top of the pelvis. Moreover, the data show only a small effect of body size on lap belt fit. The improvement in belt fit between the smallest and largest children was small compared to the benefit of putting any of the children in a typical booster. The results indicate that moving even the largest children out of boosters is likely to substantially degrade their lap belt fit in most vehicles, increasing the risk of submarining and belt-induced injuries.

Moving children out of boosters also is likely to result in much poorer shoulder belt fit in many vehicles. The same study showed a wide range of shoulder belt fit results from the large range of D-ring (upper anchorage) locations observed in second-row seats of vehicles. Whereas well-designed high-back boosters have belt routing features that can produce good shoulder belt fit even when the vehicle belt geometry is poor, a child not using a booster may experience poor belt fit for both portions of the belt. Of particular concern is that the poor fit will lead to misuse, such as the child putting the torso portion of the belt behind the back or under the arm.

In previous research for NHTSA, the effects of belt geometry on frontal-crash sled test outcomes with the Hybrid-III 10YO ATD were investigated (Klinich et al 2009). The results showed that poor lap or shoulder belt fit leads to adverse kinematic outcomes, including submarining and torso rollout. Children experiencing the same kinematics would be at increased risk of abdominal and head injuries compared to children with better belt fit.

This research program is part of a project intended to understand the optimal rear seat environment for child passengers who use the vehicle belt for primary restraint. Testing was performed with the standard and modified 6YO Hybrid III ATDs to evaluate the effects of booster seat design across different realistic belt conditions and with seating procedures producing different postures. In prototype testing with the modified dummy components (developed jointly by UMTRI, Ford, and NHTSA), the new components have improved the sensitivity of the 6YO ATD to lap belt fit (Klinich et al. 2010).

2.0 Methods

2.1 Selection of booster seats

When this project was originally formulated, the intent was to test the booster seats that were used in the program involving child volunteers (Reed et al. 2009) to allow direct comparison of the static fit produced by volunteer children and the dynamic performance of the same boosters. However, two of the four seats used in the earlier child seats were discontinued and no longer available for purchase. Of the two remaining seats, the Cosco Alpha Omega had been slightly redesigned, and the Graco TurboBooster had modifications to the padding.

To ensure that testing would be performed using booster seats that provided a range of belt fits, the newer versions of the Cosco Alpha Omega and Graco TurboBooster were installed in a laboratory seating buck and the median shoulder belt and lap belt scores were calculated using procedures described in Reed et al. (2009). These belt configurations and seating buck were those used in the testing with volunteer children, and all of these measurements used the UMTRI seating procedure to position the Hybrid III 6YO ATD (Appendix 1). Two other booster seats were selected for dynamic testing based on their shoulder and lap belt scores measured in the same seat. Table 1 lists the belt fit scores for these four seats in the laboratory seating buck, indicating that they provide a range of belt fits when installed in a realistic vehicle seat with belt geometry varied over the range found in vehicles.

Table 1. Median belt fit scores of selected booster seats

Booster	*SBS**	*qualitative*	*LBS**	*Qualitative*
Compass B510	-29	Inboard	-1	Marginal
Evenflo Comfort Touch	-8	Good	-7	Poor
Graco TurboBooster	3	Good	23	Good
Cosco Alpha Omega	25	Outboard	-4	Poor

* Shoulder belt score and lap belt score (see Reed et al. 2009).

The boosters used in testing are shown in Table 2. Throughout this report, they are referred to by designations Booster A through D as indicated in the table.

Table 2. Boosters and designations used in testing.

Graco TurboBooster	*Evenflo Comfort Touch*	*Compass B510*	*Cosco Alpha Omega*
A	B	C	D
			
			

2.2 Configuring anchorage geometry

In previous series of sled tests using the 10YO Hybrid III ATD, the belt geometry was selected such that it provided a range of belt fit scores on the dummy. However, some of the anchorage locations were outside of the range permitted by FMVSS 210 for vehicles. FMVSS 210 specifies that the side-view lap belt angle should range from 30 to 75 degrees with respect to horizontal when measured from the lap belt anchorage location to the vehicle seat's H-point using the manikin and procedures described in SAE J826. Figure 1 illustrates the range of lap belt geometries measured in 55 late-model vehicles, together with the FMVSS 210 corridors. For the UMTRI FMVSS No. 213 seating buck, the location of the anchorages specified in FMVSS N. 213, also shown on the plot, fall just outside the legal range of the FMVSS 210 specifications. [Note that the FMVSS NO. 213 belt anchorage locations are defined relative to the undeflected seat contour rather than with respect to H-point.] For the current test series, the FMVSS N. 213 lap belt anchorage location was selected to represent a condition with a rearward anchorage location and shallow lap belt angle. Choosing these anchorages also allowed comparison of the current data to other testing using the FMVSS No. 213 belt geometry. Two other anchorage locations were selected that provided lap belt angles of 50 and 75 degrees. Because the length of belt from the anchorage to H-point can affect kinematics, these two anchorages were located so the distance between anchorage and H-point was similar (~161 mm in side view), creating an “arc” of belt anchorages providing different angles but similar lengths of belt around the occupant. The right side of the figure shows the implementation in hardware.

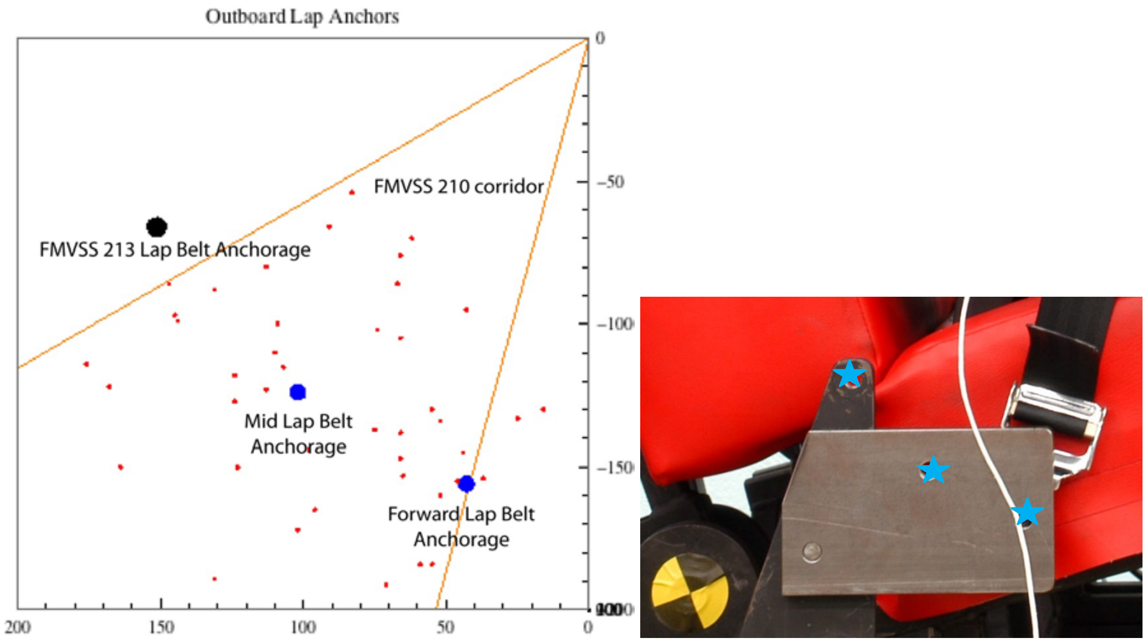


Figure 1. Side view of lap belt anchorage locations from vehicle rear seats (small dots) and anchorages selected for testing. Origin of plot is SAE J826 H-point. Forward is to the right. Photo illustrates hardware implementation with stars indicating belt anchorage locations.

An effort was made to locate anchorages so they created the same lap belt angle on the inboard and outboard side, even though this is not always the case in production vehicles. To do this, an access hole was cut in the cover of the FMVSS No. 213 seat, and a small section of foam was cut from the inboard side to allow installation of the inboard anchorages in the desired location. The edge of the cover was held in place with tape as shown in Figure 2.

Figure 2. Implementing inboard lap belt anchorage locations.

For the shoulder belt anchorage, the location was shifted inboard and outboard of the FMVSS No. 213 shoulder belt anchorage location by 64 mm. As shown in Figure 3, these anchorages span the range of rear-seat shoulder belt positions found in the rear seats of 55 late model vehicles.

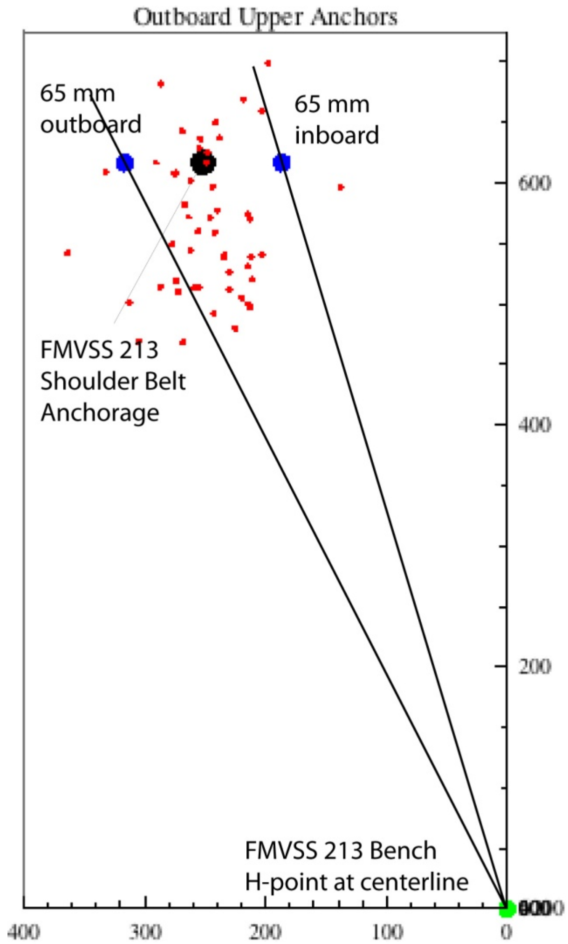


Figure 3. Front view of shoulder belt anchorage locations from vehicle rear seats (small dots) compared with FMVSS No. 213 shoulder belt anchorage and inboard and outboard shoulder belt anchorages. Origin is SAE J826 H-point on the centerline of the outboard seating position on the FMVSS No. 213 bench.

2.3 Modified 6YO ATD

The tests in this series were performed using a standard 6YO Hybrid III ATD and a modified 6YO ATD. Development of the modified 6YO pelvis is described by Klinich et al. (2010). A production version of the pelvis has been developed as shown in Figure 4. ASIS load cells were manufactured by DentonATD to fit the new profile of the modified pelvis.

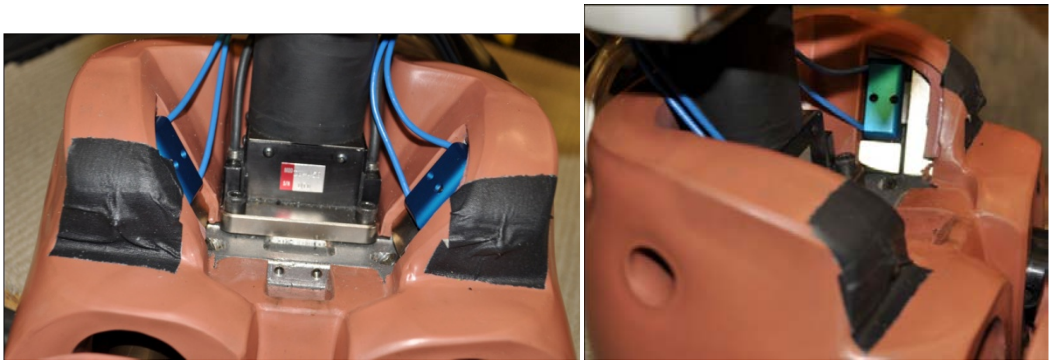


Figure 4. Production version of modified pelvis.

The gel abdomen used in this test series is shown installed in the ATD in Figure 5. The abdomen contained instrumentation hardware to measure deflection that was not fully functional, so displacement data were not collected. Compared to the gel abdomen used in prototype testing, the gel abdomen was updated so its stiffness better matched the target corridors developed from dynamic loading of pediatric porcine subjects (Kent et al. 2006). The current version is also slightly bigger to fit better within the modified pelvis and abdomen, and was designed to mount to the top of the pelvis with a metal bracket and to the bottom of the rib cage with Velcro strips as shown in Figure 5.

The top attachment method was modified after the first test because the Velcro was separated but still glued to each component post-test. A modified method of securing the top of the abdomen was developed and worked consistently for 25 tests. The new method involves extending the Velcro flaps so they are also clamped to the plate at the bottom of the rib cage. In addition, loops made from silicone strips were glued to the sides of the abdomen and a cable tie was routed between the loops behind the lumbar spine. This attachment method is illustrated in Figure 6.

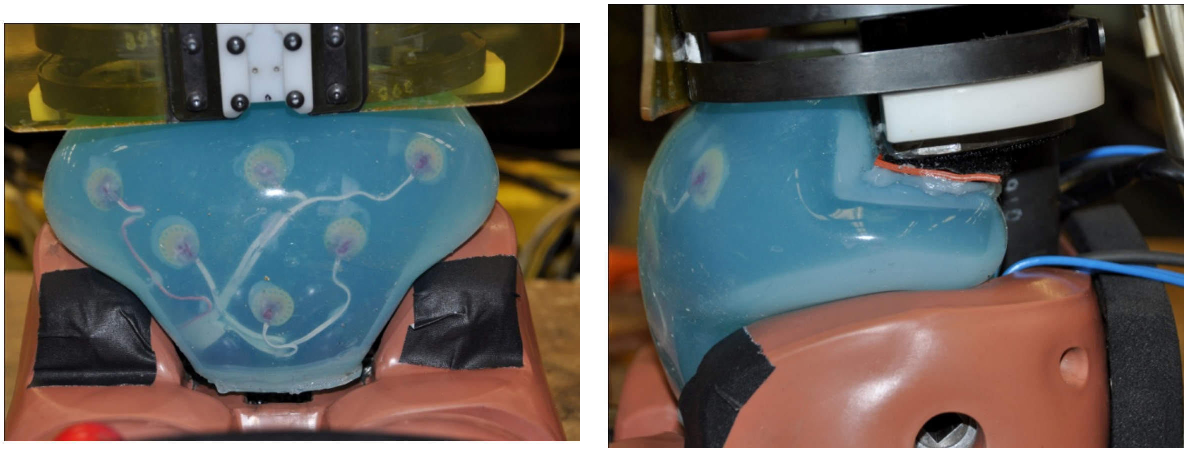


Figure 5. Gel abdomen installed in pelvis.

Figure 6. Method of attaching top of gel abdomen.

During prototype testing (Klinich et al. 2010), a Q3 dummy jacket was used, but the current testing used a custom jacket that fits the dummy more tightly. The assembled seated modified dummy is shown in Figure 7. During testing, the jacket was slightly damaged in the area under the shoulder belt where it was not reinforced by Kevlar. Duct tape was applied to the jacket surface when needed in areas of damage.

Figure 7. Custom jacket for modified 6YO ATD.

2.4 Test matrix

Table 3 lists the test matrix used in this series. Test NT0915 was rerun under the conditions of NT0911 as a replacement test, because the neck cable of the dummy broke in test NT0911; the data from NT0911 are not valid and not included in this report. The table is color coded according to different belt geometry conditions. In addition, the colors are darker when FMVSS No. 213 seating procedure was used instead of UMTRI seating procedure. Test results are available from the NHTSA biomechanics database and can be located by entering "TestID" in the "Test Reference" cell of the database query tool.

Table 3. Test matrix

Test ID	ATD Configuration*	Booster	Seating Procedure	Lap Belt Anchorage	Shoulder Belt Anchorage
NT0901	Standard	TB	213	213 (rear)	213
NT0902	Standard	Chase	213	213 (rear)	213
NT0903	Standard	B510	213	213 (rear)	213
NT0904	Standard	AO	213	213 (rear)	213
NT0905	Standard	TB	UMTRI	213 (rear)	2.5” OB
NT0906	Standard	AO	UMTRI	213 (rear)	2.5” OB
NT0907	Standard	TB	UMTRI	213 (rear)	2.5” IB
NT0908	Standard	AO	UMTRI	213 (rear)	2.5” IB
NT0909	Standard	TB	UMTRI	Forward	2.5” IB
NT0910	Standard	AO	UMTRI	Forward	2.5” IB
NT0915	Standard	AO	UMTRI	Forward	2.5” OB
NT0912	Standard	TB	UMTRI	Forward	2.5” OB
NT1001	Mod: ab secure 1	TB	UMTRI	213 (rear)	213
NT1002	Mod: ab secure 2	B510	UMTRI	213 (rear)	213
NT1003	Mod: ab secure 2	Chase	UMTRI	213 (rear)	213
NT1004	Mod: ab secure 2	AO	UMTRI	213 (rear)	213
NT1005	Mod: ab secure 2	TB	UMTRI	213 (rear)	2.5” IB
NT1006	Mod: ab secure 2	AO	UMTRI	213 (rear)	2.5” IB
NT1007	Mod: ab secure 2	TB	UMTRI	213 (rear)	2.5” OB
NT1008	Mod: ab secure 2	AO	UMTRI	213 (rear)	2.5” OB
NT1009	Mod: ab secure 2	TB	UMTRI	Forward	2.5” OB
NT1010	Mod: ab secure 2	AO	UMTRI	Forward	2.5” OB
NT1011	Mod: ab secure 2	TB	UMTRI	Forward	2.5” IB
NT1012	Mod: ab secure 2	AO	UMTRI	Forward	2.5” IB
NT1013	Mod: ab secure 2	B510	UMTRI	213 (rear)	2.5” IB
NT1014	Mod: ab secure 2	Chase	UMTRI	213 (rear)	2.5” IB
NT1015	Mod: ab secure 2	B510	UMTRI	213 (rear)	2.5” OB
NT1016	Mod: ab secure 2	Chase	UMTRI	213 (rear)	2.5” OB
NT1017	Mod: ab secure 2	B510	UMTRI	Forward	2.5” OB
NT1018	Mod: ab secure 2	Chase	UMTRI	Forward	2.5” OB
NT1019	Mod: ab secure 2	TB	213	Forward	2.5” OB
NT1020	Mod: ab secure 2	AO	213	Forward	2.5” OB
NT1021	Mod: ab secure 2	None	UMTRI	213 (rear)	213
NT1022	Mod: ab mixed foam	None	UMTRI	213 (rear)	213
NT1023	Mod: ab soft foam	None	UMTRI	213 (rear)	213
NT1024	Mod: ab soft foam	AO	UMTRI	Forward	2.5” OB
NT1025	Mod: ab soft foam	TB	UMTRI	Forward	2.5” OB
NT1026	Mod: ab secure 2	TB	213	213 (rear)	213
NT1027	Mod: ab secure 2	B510	213	213 (rear)	213
NT1028	Mod: ab secure 2	Chase	213	213 (rear)	213
NT1029	Mod: ab secure 2	AO	213	213 (rear)	213

2.5 Seating procedure

Test conditions included using both the standard FMVSS No. 213 procedure and a procedure developed at UMTRI. The FMVSS No. 213 seating procedure involves pushing the dummy's buttocks against the rear of the booster seat, tightening the lap belt to 67 N (12-15 lbf) of tension and 7-18 N (2-4 lbf) in the torso portion of the belt. The lap-belt tension is carried over from earlier FMVSS No. 213 procedures for testing harness restraints.

The UMTRI seating procedure is based on child posture data and produces more representative hip and head CG locations than the FMVSS No. 213 procedures (Reed et al. 2006). The procedure uses several positioning aids to achieve these postures. A positioning pad is placed on the back of the ATD's buttocks to shift the pelvis forward in a repeatable manner. When the standard ATD is used, a lap shield is taped to the front of the ATD to prevent the lap belt from falling into the gap between the pelvis and thighs. The lap shield is not used with the modified ATD because its jacket design prevents this problem, and use of the lap shield would interfere with the modified abdomen. The UMTRI seating procedure tightens both the lap belt and the shoulder belt to 7-18 N (2-4 lbf), based on results from a previous UMTRI laboratory study of child volunteers that measured the belt tensions the children produced when they donned the belt themselves (Reed et al. 2009).

Prior to each test, a 3-D coordinate measurement system (FARO Arm) was used to record the posture of the ATD and the position of the booster seat and belt restraints. Some of these measurements were used to calculate a shoulder belt score (SBS), and lap belt score (LBS), which quantify the position of the belt relative to ATD landmarks. The shoulder belt score (SBS), illustrated in Figure 8, is defined as the lateral distance between the inboard edge of the shoulder belt and the centerline of the neck/bib landmark at the height of the centerline landmark. The lap belt score, illustrated in Figure 9, is the distance from the ASIS to the top of the lap belt, measured at the same lateral location of the ASIS. Results present the mean of the left and right lap belt scores for each test condition. Because the ASIS location is significantly lower on the modified pelvis compared to the standard pelvis, lap belt scores will differ for the same booster/belt geometry conditions when different ATDs are used.

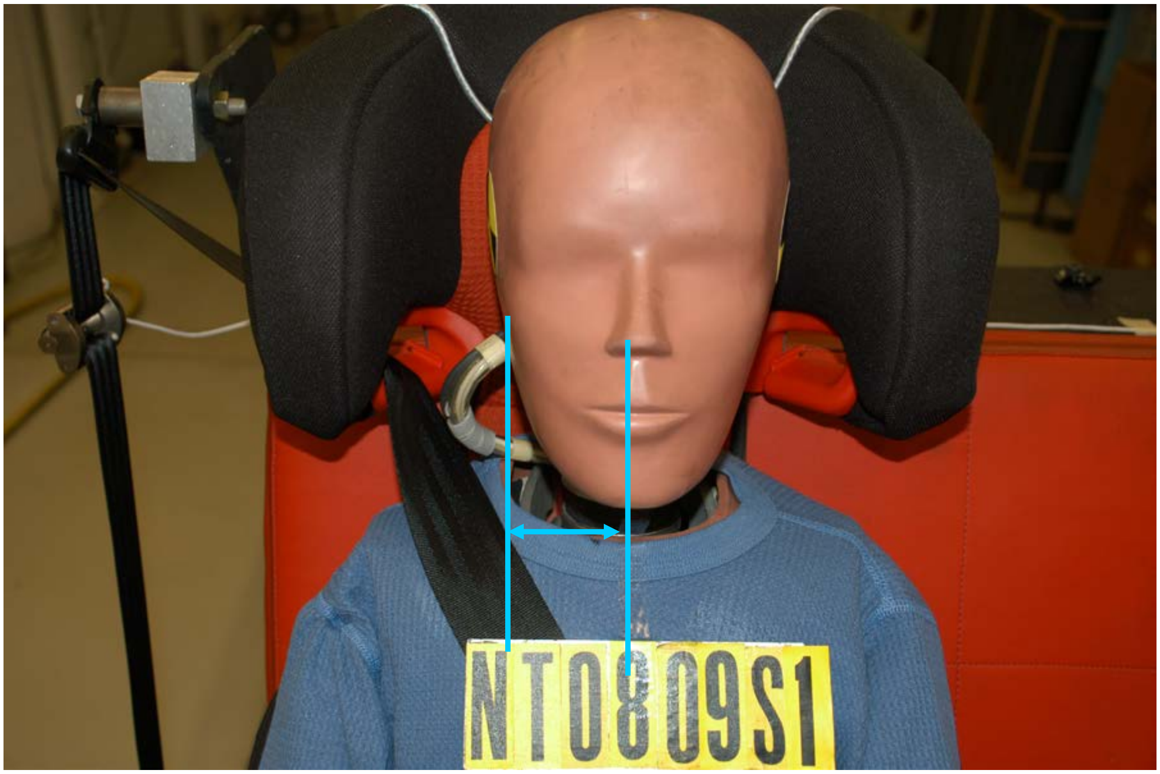


Figure 8. Illustration of shoulder belt score (SBS) measurement.

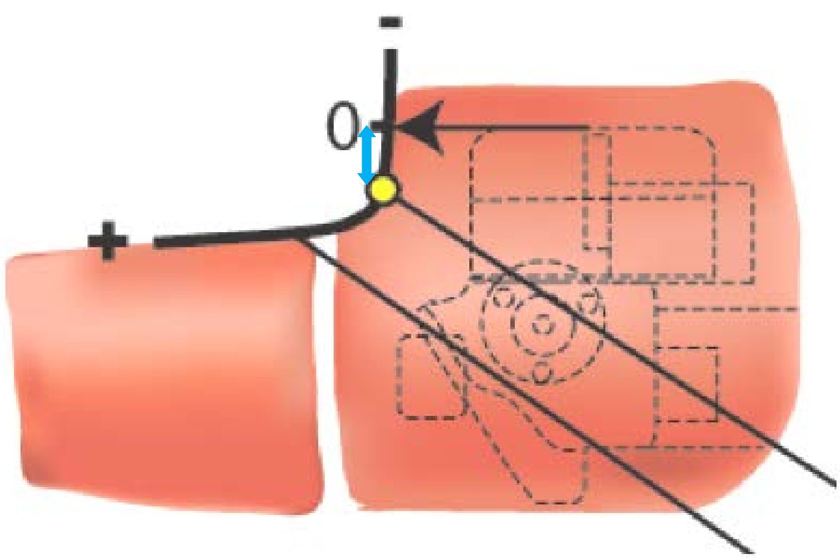


Figure 9. Illustration of lap belt score (LBS) measurement.

In all tests using the UMTRI seating procedure, hip offset tools shown in Figure 10 were inserted in the pelvis to allow reliable measurement of pelvis position and orientation. These tools did not interfere with belt routing, and remained in place during dynamic testing. They did not have any discernable effect on instrumentation signals, including pelvis acceleration.

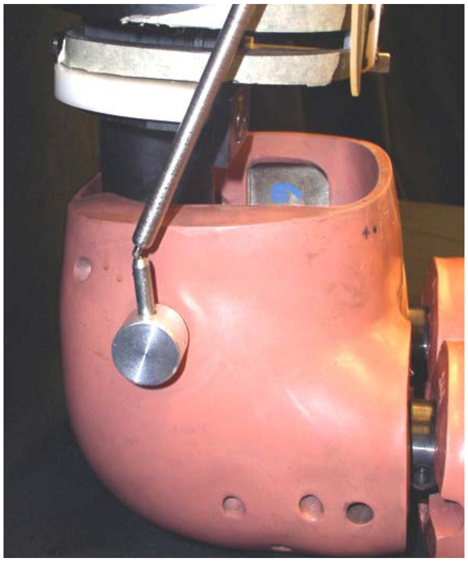


Figure 10. Illustration of hip offset tool to facilitate measurement of pelvis orientation using the FARO arm.

3.0 Results

3.1 Baseline Conditions

Table 4 and Figure 11 summarize key results from the baseline tests of four booster seats using FMVSS No. 213 belt geometry and seating procedure. The head responses (peak g, HIC 36, excursion) are similar for the two booster only seats (A [TurboBooster] and B [Compass]) and the two combination booster designs (C [Chase] and D [Alpha Omega]). The test with booster C had chin-to-chest contact that contributed to HIC, while the other three tests did not. This is also true of the shoulder belt scores produced by these boosters when the dummy is seated using FMVSS No. 213 procedures. The lap belt score produced by booster A is better than the other three boosters, which are similar. These associations with style of booster seat are not reflected in the chest and pelvis responses and the knee excursions. Chest accelerations (3-ms clip) range from 39 to 44 g across the four booster seats. One of the combination boosters (Chase) had the lowest value of peak resultant pelvis accelerations, while the other combination booster (Alpha Omega) had the highest value, with the two booster-only styles in between.

Figure 14 shows the final torso angle (initial head-to-hip angle plus measured change in torso angle, measured on the spine box by integration of angular rate) vs. the difference between knee and head excursion for each baseline test condition. The kinematics of the two combination booster designs are similar to each other, as are the two booster-only tests. The initial and peak frames for each of these tests are shown in Table 5.

Table 4. Summary of baseline tests for each booster

Test ID	ATD	Booster	Belt Geometry	Seating	HIC (36 ms)	Head R (g)	Chest 3 ms (g)	Pelvis R (g)	Head	Knee	Knee-head	Final Torso Angle	SBS	LBS
NT0901	S	A	RM	213	550	54	39	46	576	619	43	-28	39	47
NT0903	S	B	RM	213	661	59	44	43	574	655	81	-13	33	20
NT0902	S	C	RM	213	980*	75	42	38	609	645	36	-29	54	18
NT0904	S	D	RM	213	1079	76	44	49	616	708	92	-11	61	23

*chin-to-chest contact that affected HIC

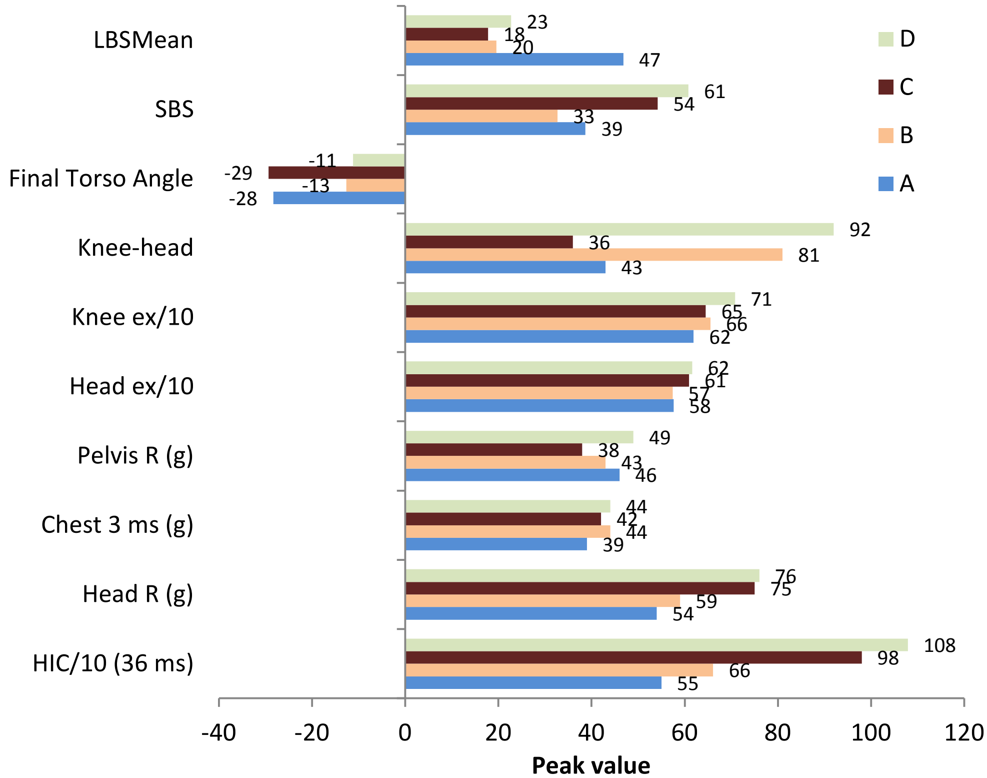


Figure 11. Peak values of outcome measures for each booster under FMVSS No. 213 baseline conditions.

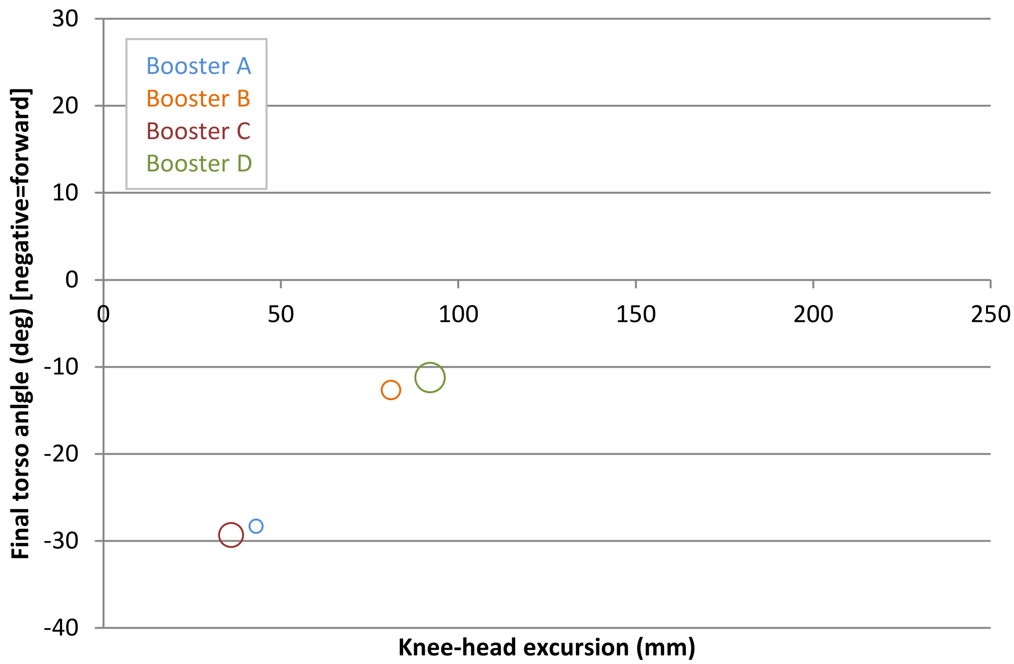


Figure 12. Final torso angle (deg) vs. knee-head excursion (mm) for baseline testing of four boosters using FMVSS No. 213 procedures.

Table 5. Shoulder belt fit at time zero and peak excursion for each booster under baseline FMVSS No. 213 test conditions

Booster	*T0*	*Peak*
A		
B		
C		
D		

3.2 Effect of Modified ATD

Table 6 summarizes results from twelve paired test conditions in which the standard 6YO ATD and the modified 6YO ATD were run using the same booster, belt geometry, and seating procedures.

Table 6. Summary of results for tests examining differences between standard and modified ATDs

Test ID	ATD	Booster	Belt Geometry	Seating	HIC (36 ms)	Head R (g)	Chest 3 ms (g)	Pelvis R (g)	Head	Knee	Knee-head	Final Torso Angle	SBS	LBS
NT1011	M3	A	FI	U	720*	65	52	58	588	770	182	7	29	-4
NT0909	S	A	FI	U	736*	80	53	59	604	766	162	2	35	21
NT1012	M3	D	FI	U	1499*	101	55	82	675	845	170	7	47	-26
NT0910	S	D	FI	U	1808*	102	55	58	662	845	183	8	43	-3
NT1009	M3	A	FO	U	703*	64	47	*	610	768	158	-7	31	-5
NT0912	S	A	FO	U	661*	86	48	55	618	754	136	-11	35	19
NT1010	M3	D	FO	U	1486*	99	54	69	660	851	191	15	56	-27
NT0915	S	D	FO	U	1529*	198	50	59	650	861	211	-3	41	-4
NT1005	M3	A	RI	U	820	65	48	55	547	671	124	-5	26	-10
NT0907	S	A	RI	U	738	63	49	50	560	660	100	-13	27	22
NT1006	M3	D	RI	U	1562	89	53	58	644	749	105	-7	55	-29
NT0908	S	D	RI	U	1573	84	45	48	622	752	130	-1	37	-4
NT1026	M3	A	RM	213	563	54	50	52	552	624	72	-17	42	-6
NT0901	S	A	RM	213	550	54	39	46	576	619	43	-28	39	47
NT1027	M3	B	RM	213	566	58	46	46	565	662	97	-15	49	-11
NT0903	S	B	RM	213	661	59	44	43	574	655	81	-13	33	20
NT1028	M3	C	RM	213	317	121	54		657	712	55	-23	41	-13
NT0902	S	C	RM	213	980*	75	42	38	609	645	36	-29	54	18
NT1029	M3	D	RM	213	907*	88	50	52	587	664	77	-32	83	-15
NT0904	S	D	RM	213	1079	76	44	49	616	708	92	-11	61	23
NT1007	M3	A	RO	U	975	78	44	60	602	673	71	-27	33	-8
NT0905	S	A	RO	U	793	69	44	54	592	658	66	-28	30	20
NT1008	M3	D	RO	U	1098	71	51	56	616	749	133	-5	56	-27
NT0906	S	D	RO	U	1376	80	46	54	622	761	139	-2	46	7

Bold: FMVSS No. 213 seating procedure, normal: UMTRI seating procedure
Italic: Standard ATD, normal: Modified ATD with gel abdomen
Blue: FMVSS No. 213 belt geometry (rear, mid); Purple: Rear, outboard; Green: rear, inboard; Orange: forward, inboard; Pink: forward, outboard
*Chin-to-chest contact that affects HIC calculation

The shoulder belt scores between the two ATDs are expected to be similar for the same belt and booster conditions. The average difference across all paired test conditions is 4 mm, with larger differences seen with booster D compared to booster A. Because the lap belt score is measured relative to the ASIS, and the ASIS on the modified pelvis is approximately 25 mm lower than that on the standard pelvis, lap belt scores between the two conditions would be expected to differ by about 25 mm. The average difference for tests using the UMTRI procedure is 27 mm. Using the FMVSS No. 213 seating procedure, which uses a higher lap belt tension that pulls the belt lower against the dummy, the mean difference in lap belt score is 38 mm.

Figure 13 shows the average values for the standard and modified ATDs for all of the outcome parameters listed in Table 6. (Mean values of HIC, head excursion, and knee excursion are divided by 10 to allow better visualization on the same chart.) Across all conditions where both the modified and standard ATDs were tested, mean values of all outcomes were quite similar, except for the average lap belt score which is expected to be different as described above. The average head excursions, knee excursions, and final torso angles were all very similar.

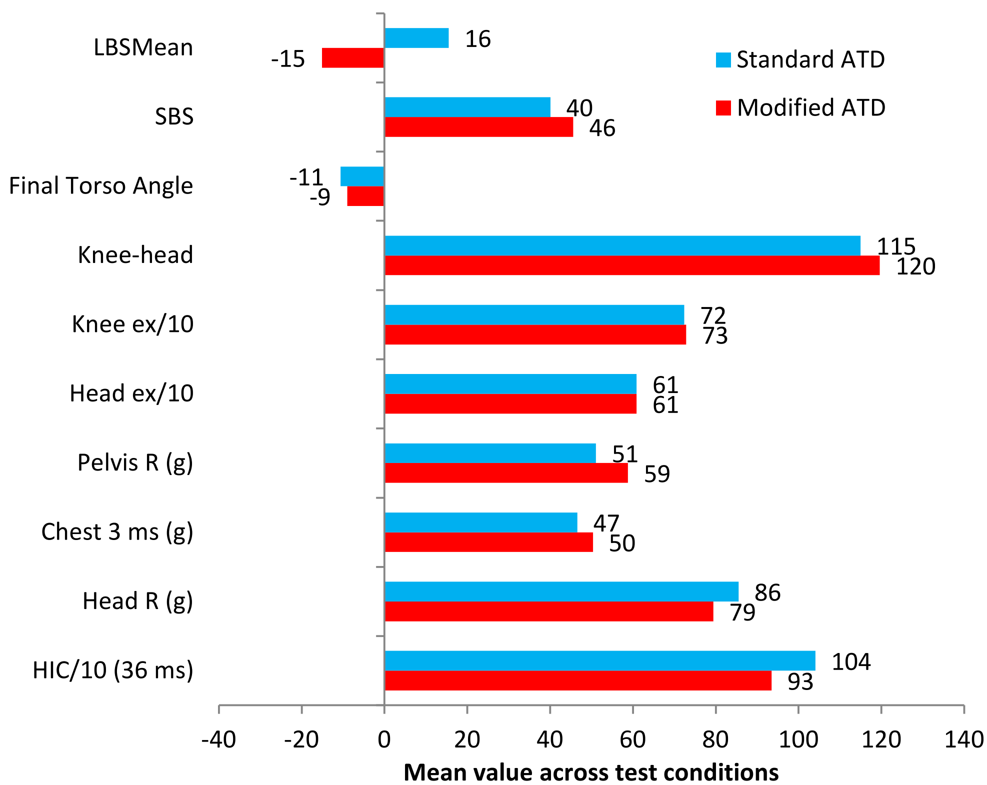


Figure 13. Mean values of outcome measures for standard and modified ATDs for all paired test conditions.

Figure 14 shows the final torso angle (initial head-to-hip angle plus measured change in torso angle, measured on the spine box by integration of angular rate) vs. the difference between knee and head excursion for test conditions in which the standard ATD (circles) and modified ATD (triangles) were used. As indicated by the overlap between the thin black oval around the modified data points and the thick gray oval around the standard data points, these kinematic results were very similar between the two ATDs. In all test conditions, the difference in knee-head excursion between the two ATDs was 30 mm or less, with eight of the twelve conditions having differences of 20 mm or less. When considering the final torso angle, nine of the twelve conditions had differed by eight degrees or less using the two different ATDs. The two conditions with the largest differences both used booster D, but one was the forward/outboard (FO) condition with UMTRI seating procedure (largest filled pink), while the other was the rear/mid (RM) condition with FMVSS No. 213 seating procedure (largest open blue). In the FO condition, the modified ATD had a less upright final posture, while in the RM condition, the standard ATD had a less upright final posture. In the RM condition with booster A (smallest open blue), the modified ATD final torso angle was 11 degrees more upright than that of the standard ATD.

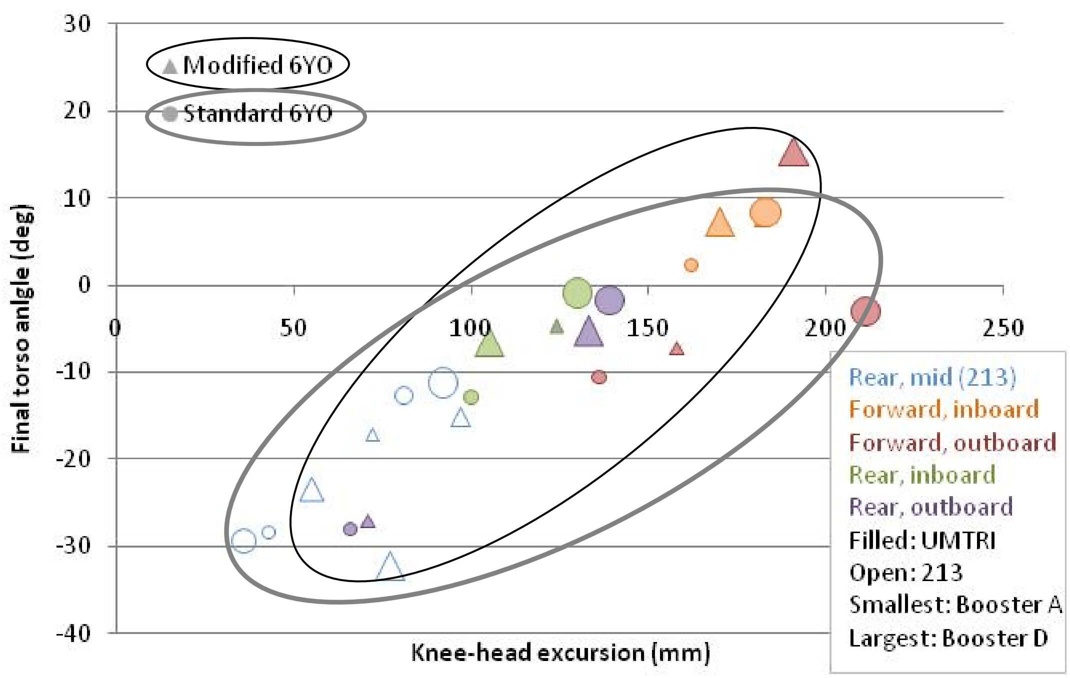


Figure 14. Final torso angle (deg) vs. knee-head excursion (mm) for standard ATD and modified ATD with gel abdomen.

Because the modified ATD performed differently than expected compared to the prototype version (less sensitivity to lap belt angle), sled tests were run in several conditions in which the gel abdomen was replaced with a mixed foam or soft foam abdomen. The goal of these tests was to try to identify whether changes in response were due to changes in the pelvis, jacket, or abdomen compared to the prototype version. The soft foam abdomen was constructed of two layers of the softer FMVSS No. 213 seat foam, while the mixed foam abdomen used one layer each of the two types of FMVSS No. 213 foam.

Results plotting final torso angle vs. head-knee excursion are shown in Figure 15. The modified ATD was tested using the FMVSS No. 213 belt geometry and seating procedure without a booster (blue triangle), because this was a condition where the prototype ATD submarined decisively, while the standard ATD did not. Results were mixed, as the torso did not rotate forward past vertical, but the knee-head excursion difference was well below the proposed submarining threshold of 200 mm (Klinich et al. 2010). Tests were repeated with mixed foam (blue square) and soft foam (blue diamond) abdomens. The final torso angles were similar to that of the gel abdomen, but the knee-head excursion difference increased with softer abdomens. Two booster test conditions were repeated using the soft foam abdomen (FO with boosters A and D). Results with booster A were similar for the standard, gel abdomen, and soft foam abdomen ATDs. Excursion differences were similar with all three ATD versions in tests with booster D, but the standard ATD had a more upright final torso angle.

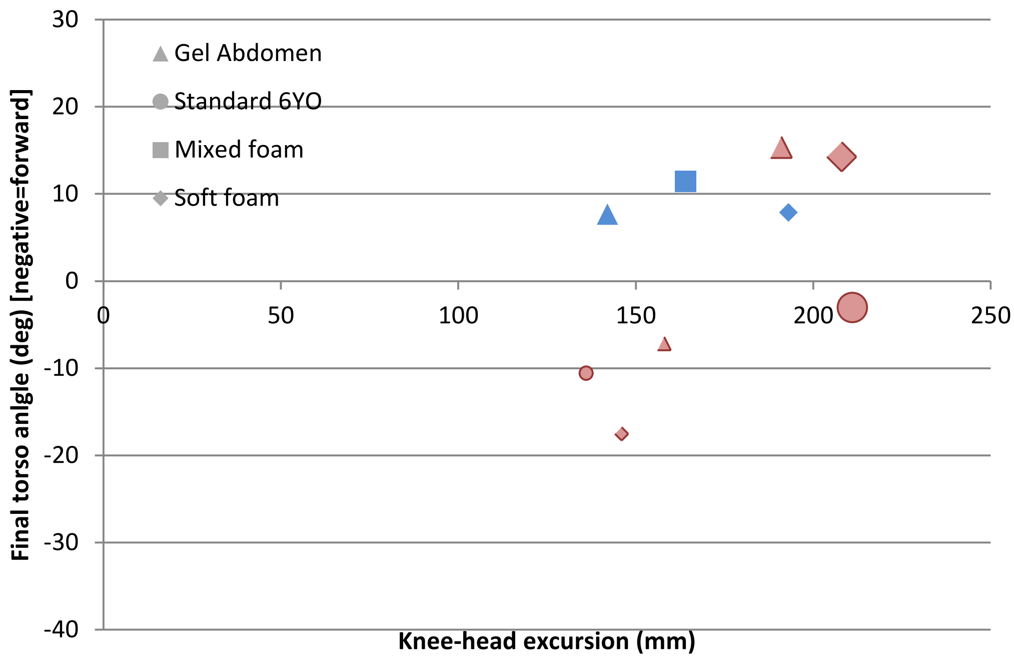


Figure 15. Final torso angle (deg) vs. knee-head excursion (mm) for standard ATD and modified ATD using gel and foam abdomens

3.3 Variations with Seating Procedure

Table 7 summarizes results for six test conditions using the modified 6YO that compare the effect of seating procedure on outcomes.

Table 7. Summary of results for tests examining seating procedure

Test ID	*ATD*	*Booster*	*Belt Geometry*	*Seating*	*HIC (36 ms)*	*Head R (g)*	*Chest 3 ms (g)*	*Pelvis R (g)*	*Head*	*Knee*	*Knee-head*	*Final Torso Angle*	*SBS*	*LBS*
NT1019	**M3**	**A**	**FO**	**213**	**723***	**103**	**47**	**76**	**613**	**746**	**133**	**-17**	**39**	**10**
NT1009	M3	A	FO	U	703*	64	47	x	610	768	158	-7	31	-5
NT1020	**M3**	**D**	**FO**	**213**	**1558***	**86**	**52**	**76**	**671**	**746**	**75**	**1**	**45**	**-16**
NT1010	M3	D	FO	U	1486*	99	54	69	660	851	191	15	56	-27
NT1026	**M3**	**A**	**RM**	**213**	**563**	**54**	**50**	**52**	**552**	**624**	**72**	**-17**	**42**	**-6**
NT1001	M2	A	RM	U	730	61	57	56	530	680	150	-3	31	-4
NT1027	**M3**	**B**	**RM**	**213**	**566**	**58**	**46**	**46**	**565**	**662**	**97**	**-15**	**49**	**-11**
NT1002	M3	B	RM	U	889	70	48	55	554	716	162	3	36	-18
NT1028	**M3**	**C**	**RM**	**213**	**317**	**121**	**54**		**657**	**712**	**55**	**-23**	**41**	**-13**
NT1003	M3	C	RM	U	1147	73	53	51	578	703	125	-7	47	-23
NT1029	**M3**	**D**	**RM**	**213**	**907***	**88**	**50**	**52**	**587**	**664**	**77**	**-32**	**83**	**-15**
NT1004	M3	D	RM	U	1320*	75	53	57	617	745	128	-3	62	-26

Bold: FMVSS No. 213 seating procedure, normal: UMTRI seating procedure
Blue: FMVSS No. 213 belt geometry (rear, mid); Pink: forward, outboard
*Chin-to-chest contact that affects HIC

Figure 16 shows mean values of outcome measures for the modified ATD when it was seated using UMTRI and FMVSS No. 213 seating procedures. On average, HIC (36 ms) was about 270 higher with the UMTRI seating procedure, due to head contact with the chest in some tests. With the UMTRI seating procedures, average knee excursions are 50 mm larger and head excursions are about 20 mm smaller than with the FMVCSS No. 213 seating procedure, resulting in an average difference between knee and head excursions of almost 70 mm. The average final torso angle is 0 degrees for tests with the UMTRI seating procedure and -17 degrees (with negative values indicated forward rotation) for the FMVSS No. 213 seating procedure. The average lap belt score is -17 using the UMTRI seating procedure and -9 using 213, showing how the higher belt tension of the FMVSS No. 213 procedure produces a lap belt fit lower on the ATD.

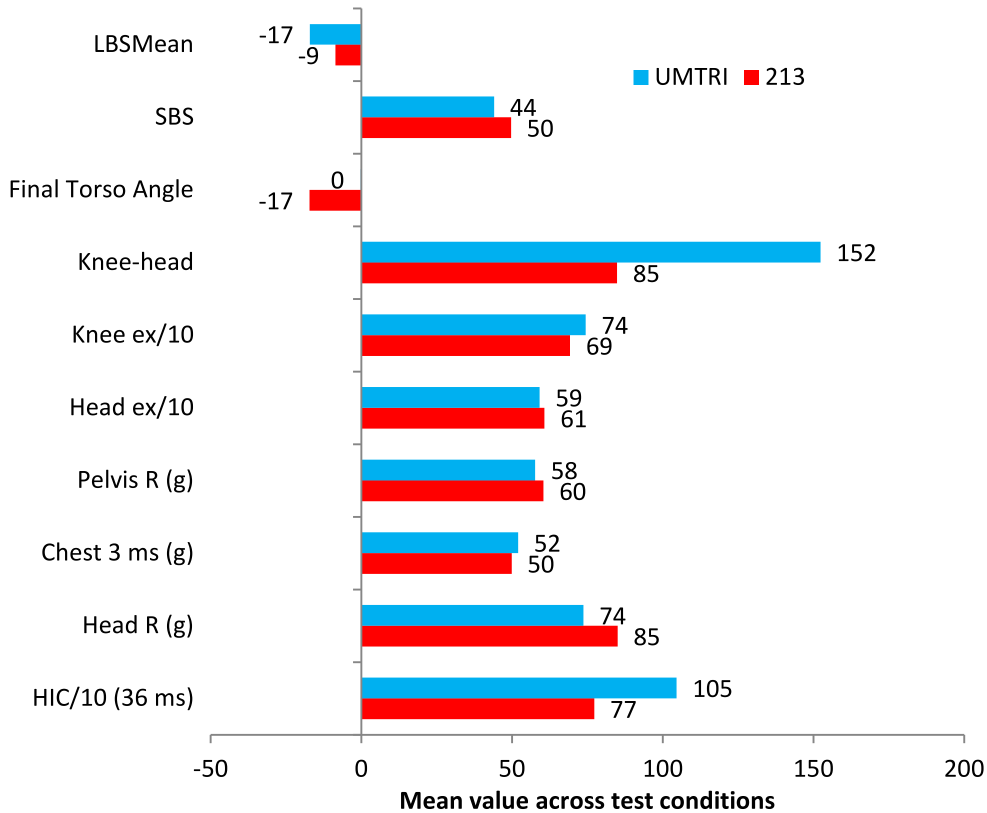


Figure 16. Mean values of outcome measures for FMVSS No. 213 and UMTRI seating procedures using the modified ATD.

Figure 17 illustrates the final torso angle vs. knee-head excursion for six paired test conditions using the UMTRI and FMVSS No. 213 seating procedures. The tests using the UMTRI seating procedure (filled, outlined with thin black oval) have less forward torso rotation and higher knee-head excursion values than those using the FMVSS No. 213 seating procedure (open, outlined with thick gray circle). Table 8 shows the initial and final positions of the ATD under four of the conditions, showing the differences in kinematics from the different initial seating procedures.

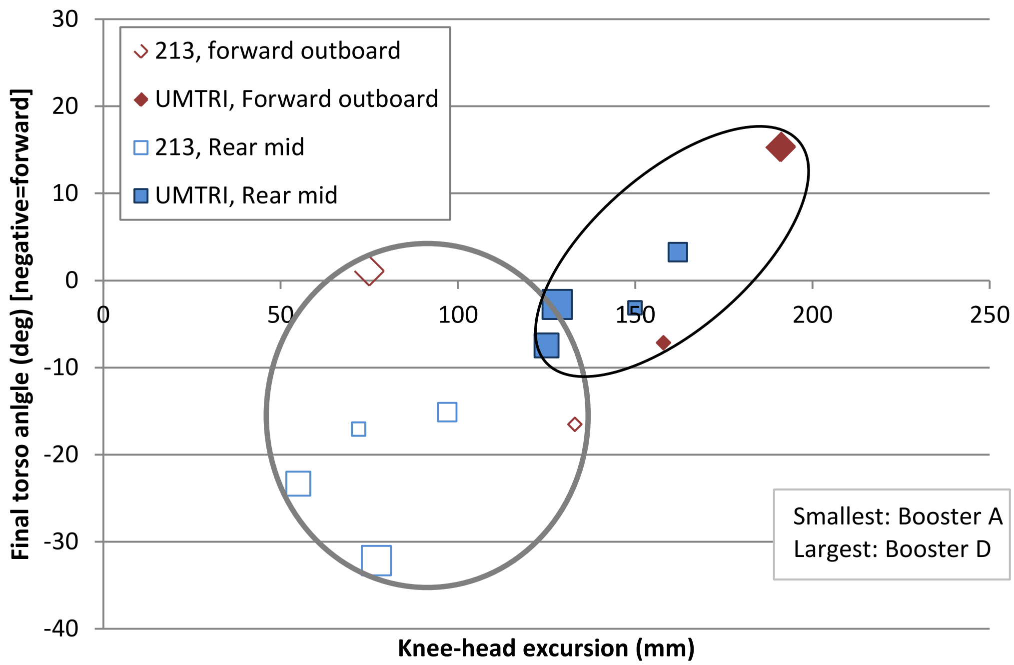
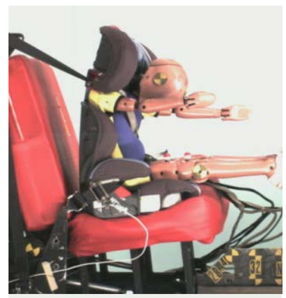
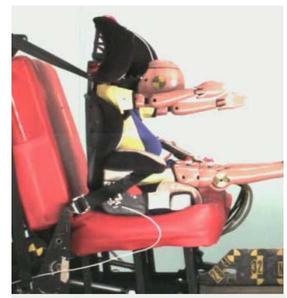
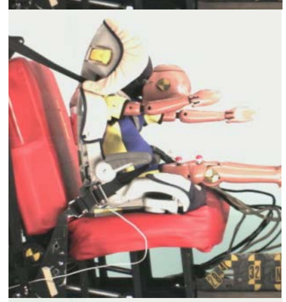
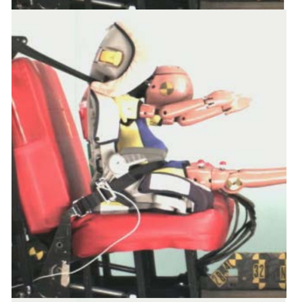
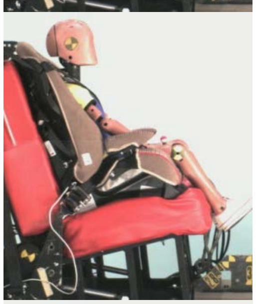
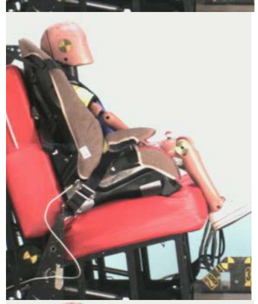
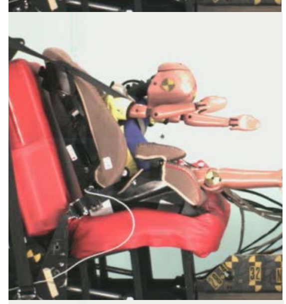
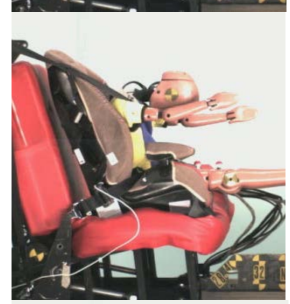
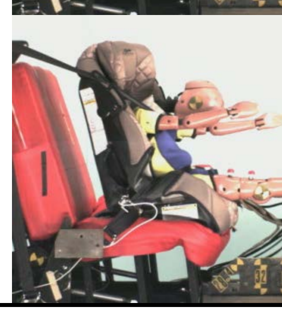
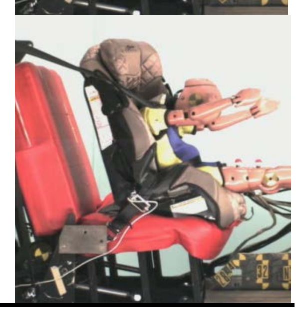


Figure 17. Final torso angle (deg) vs. knee-head excursion (mm) for tests using UMTRI (filled, black oval) and FMVSS No. 213 (open, gray oval) seating procedures under matched booster/geometry conditions with the modified ATD.

Table 8. Initial and final postures for four test conditions using FMVSS No. 213 seating procedure and UMTRI seating procedure

Condition	*T0*		*Peak*	
Time	FMVSS No. 213	UMTRI	FMVSS No. 213	UMTRI
A, RM				
B, RM				
C, RM				
D, FO				

3.4 ATD Outcomes with Variations in Shoulder Belt Geometry

Table 9 summarizes results of tests where the shoulder belt was positioned either inboard or outboard for the same ATD, seating procedure, booster, and lap belt conditions. All of these tests used the UMTRI seating procedure.

Table 9. Summary of results for tests examining shoulder belt geometry

Test ID	*ATD*	*Booster*	*Belt Geometry*	*Seating*	*HIC (36 ms)*	*Head R (g)*	*Chest 3 ms (g)*	*Pelvis R (g)*	*Head*	*Knee*	*Knee-head*	*Final Torso Angle*	*SBS*	*LBS*
NT1011	M3	A	FI	U	720*	65	52	58	588	770	182	7	29	-4
NT1009	M3	A	FO	U	703*	64	47	*	610	768	158	-7	31	-5
NT1012	M3	D	FI	U	1499*	101	55	82	675	845	170	7	47	-26
NT1010	M3	D	FO	U	1486*	99	54	69	660	851	191	15	56	-27
NT0909	*S*	*A*	*FI*	*U*	*736**	*80*	*53*	*59*	*604*	*766*	*162*	*2*	*35*	*21*
NT0912	*S*	*A*	*FO*	*U*	*661**	*86*	*48*	*55*	*618*	*754*	*136*	*-11*	*35*	*19*
NT0910	*S*	*D*	*FI*	*U*	*1808**	*102*	*55*	*58*	*662*	*845*	*183*	*8*	*43*	*-3*
NT0915	*S*	*D*	*FO*	*U*	*1529**	*198*	*50*	*59*	*650*	*861*	*211*	*-3*	*41*	*-4*
NT1005	M3	A	RI	U	820	65	48	55	547	671	124	-5	26	-10
NT1007	M3	A	RO	U	975	78	44	60	602	673	71	-27	33	-8
NT1013	M3	B	RI	U	932	69	47	55	555	729	174	5	8	-23
NT1015	M3	B	RO	U	1039*	77	47	55	586	720	134	-5	18	-25
NT1014	M3	C	RI	U	1308	97	55	56	607	715	108	-13	49	-23
NT1016	M3	C	RO	U	452*	177	56	91	627	705	78	-23	53	-26
NT1006	M3	D	RI	U	1562	89	53	58	644	749	105	-7	55	-29
NT1008	M3	D	RO	U	1098	71	51	56	616	749	133	-5	56	-27
NT0907	*S*	*A*	*RI*	*U*	*738*	*63*	*49*	*50*	*560*	*660*	*100*	*-13*	*27*	*22*
NT0905	*S*	*A*	*RO*	*U*	*793*	*69*	*44*	*54*	*592*	*658*	*66*	*-28*	*30*	*20*
NT0908	*S*	*D*	*RI*	*U*	*1573*	*84*	*45*	*48*	*622*	*752*	*130*	*-1*	*37*	*-4*
NT0906	*S*	*D*	*RO*	*U*	*1376*	*80*	*46*	*54*	*622*	*761*	*139*	*-2*	*46*	*7*

Italic: Standard ATD, normal: Modified ATD with gel abdomen
Blue-violet: Rear, outboard; Red-violet: rear, inboard; Red-orange: forward, inboard; Blue-green: forward, outboard
* Chin-to-chest contact affecting HIC

Table 10 shows the initial belt fit and peak excursion for the four boosters tested with a rear belt anchorage location and inboard and outboard shoulder belt anchorages. With the inboard condition on boosters C and D, the belt routing devices direct the belt away from the dummy. For each booster seat, the position of the shoulder belt prior to each test is nearly identical. However, in most test conditions, the outboard condition resulted in more forward rotation of the torso.

Table 10. Shoulder belt fit at time zero and peak excursion for each booster seat with inboard and outboard shoulder belt locations

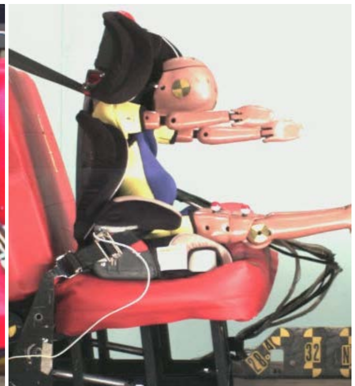
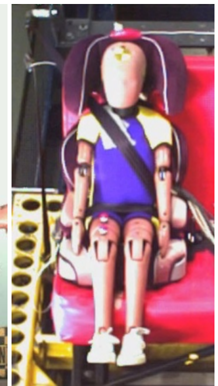
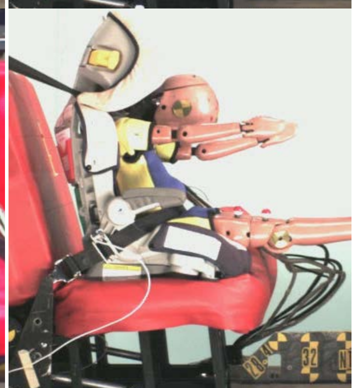
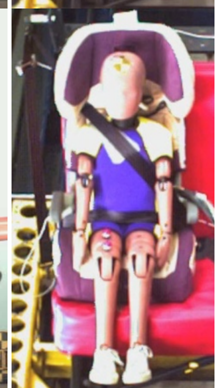
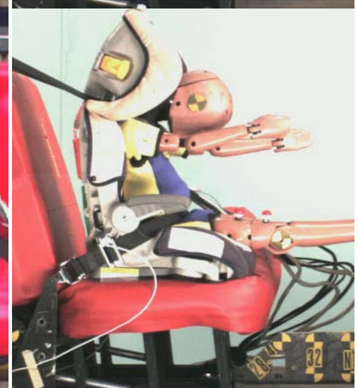
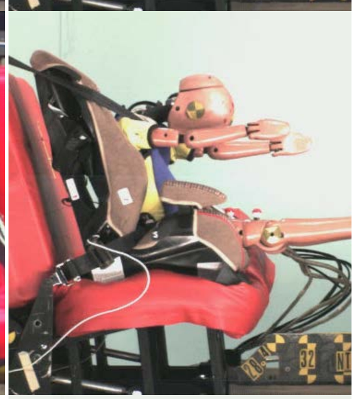
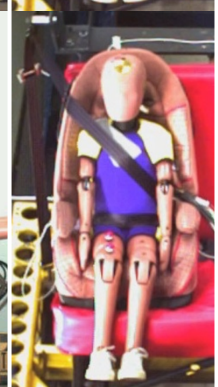
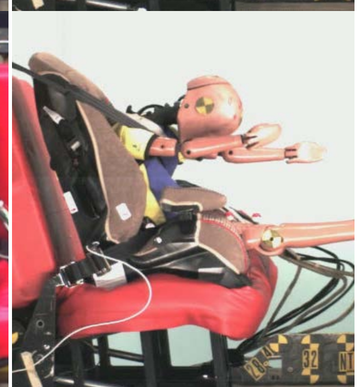
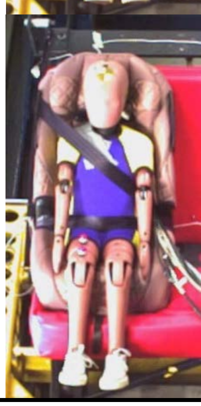
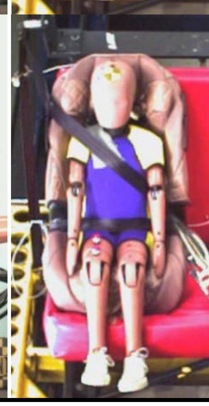
Booster	*Inboard*		*Outboard*	
	T0	Peak	T0	Peak
A				
B				
C				
D				

Figure 18 shows averaged values for outcome measures with inboard and outboard shoulder belt locations. Head and knee excursions are similar, as are the difference between knee and head excursions. The average SBS is 40 mm for the outboard condition and 36 mm for the inboard conditions, even though the distance between the shoulder belt anchorages is approximately 128 mm. The similarity between average shoulder belt scores shows how the shoulder belt routing features on the booster seats minimize variations in shoulder belt static position across a range of shoulder belt geometries. The average final torso angle is more upright for the outboard conditions compared to the inboard conditions. On average, Booster A shows a greater difference in final torso angle between inboard and outboard conditions compared to Booster D.

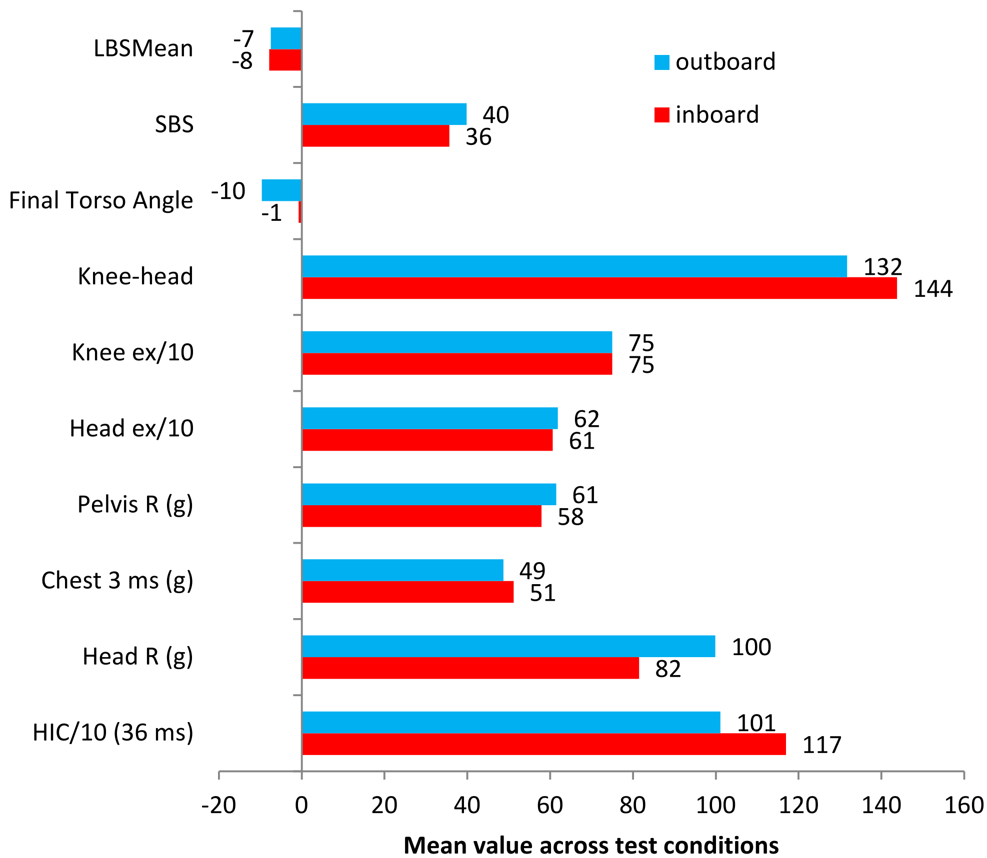


Figure 18. Mean values of outcome measures inboard and outboard shoulder belt locations.

Figure 19 plots the final torso angle vs. the knee-head excursion. As seen by the overlap in inboard conditions (red-orange triangles and red-violet diamonds, thick gravy oval) and the outboard conditions (blue-green squares and blue-violet circles, thin black oval), the effect on kinematics of moving the shoulder-belt inboard and outboard is small compared to other test variables. Results for the standard and modified ATDs were similar in most test conditions. For boosters A and C, the dummy showed a greater tendency to roll out of the belt (final torso angle greater than -20 degrees) in the outboard position compared to the inboard position, even though the initial static belt fit for each belt geometry is similar.

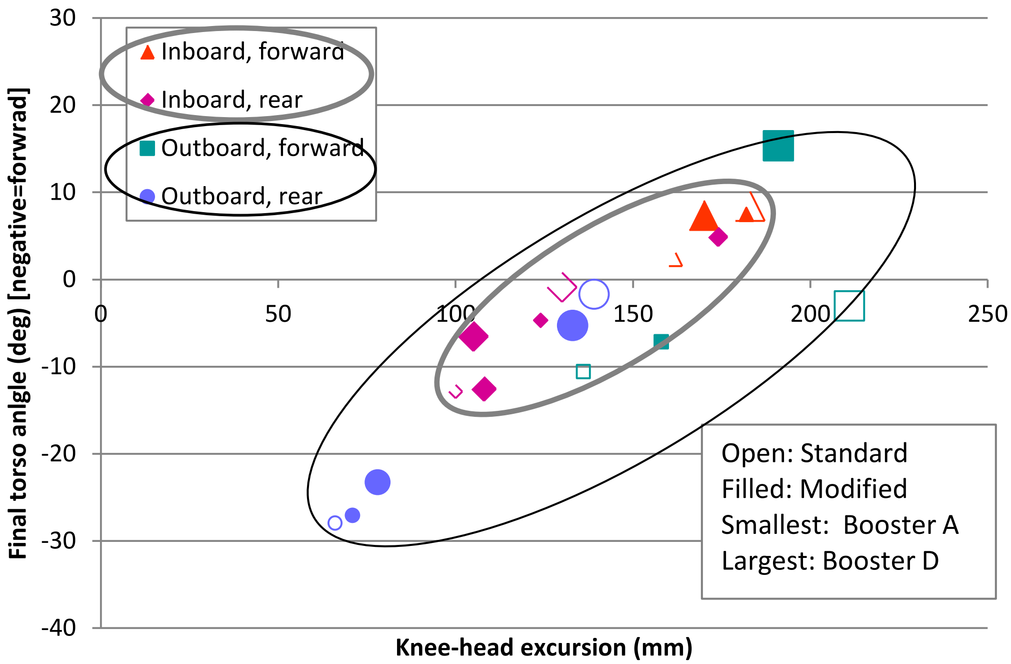


Figure 19. Final torso angle (deg) vs. knee-head excursion (mm) for under inboard and outboard shoulder belt anchorages.

3.5 ATD Outcomes due to Variations in Lap Belt Anchorage Location

Results for ten conditions comparing forward and rearward lap belt anchorage locations are shown in Table 11. Figure 20 shows the mean values of key outcome measures for all of the rearward and forward test conditions.

Table 11. Summary of results for tests examining lap belt geometry

Test ID	*ATD*	*Booster*	*Belt Geom*	*Seating*	*HIC (36 ms)*	*Head R (g)*	*Chest 3 ms (g)*	*Pelvis R (g)*	*Head*	*Knee*	*Knee-head*	*Final Torso Angle*	*SBS*	*LBSMean*
NT1011	M3	A	FI	U	720*	65	52	58	588	770	182	*7*	29	-4
NT1005	M3	A	RI	U	820	65	48	55	547	671	124	*-5*	26	-10
NT0909	*S*	*A*	*FI*	*U*	*736**	*80*	*53*	*59*	*604*	*766*	*162*	*2*	35	21
NT0907	*S*	*A*	*RI*	*U*	*738*	*63*	*49*	*50*	*560*	*660*	*100*	*-13*	27	22
NT1012	M3	D	FI	U	1499*	101	55	82	675	845	170	*7*	47	-26
NT1006	M3	D	RI	U	1562	89	53	58	644	749	105	*-7*	55	-29
NT0910	*S*	*D*	*FI*	*U*	*1808**	*102*	*55*	*58*	*662*	*845*	*183*	*8*	43	-3
NT0908	*S*	*D*	*RI*	*U*	*1573*	*84*	*45*	*48*	*622*	*752*	*130*	*-1*	37	-4
NT1009	M3	A	FO	U	703*	64	47	*	610	768	158	*-7*	31	-5
NT1007	M3	A	RO	U	975	78	44	60	602	673	71	*-27*	33	-8
NT0912	*S*	*A*	*FO*	*U*	*661**	*86*	*48*	*55*	*618*	*754*	*136*	*-11*	35	19
NT0905	*S*	*A*	*RO*	*U*	*793*	*69*	*44*	*54*	*592*	*658*	*66*	*-28*	30	20
NT1017	M3	B	FO	U	1239*	99	41	112	625	854	229	*19*	25	-19
NT1015	M3	B	RO	U	1039*	77	47	55	586	720	134	*-5*	18	-25
NT1018	M3	C	FO	U	1788*	93	54	65	644	820	176	*8*	41	-26
NT1016	M3	C	RO	U	452*	177	56	91	627	705	78	*-23*	53	-26
NT1010	M3	D	FO	U	1486*	99	54	69	660	851	191	***15***	56	-27
NT1008	M3	D	RO	U	1098	71	51	56	616	749	133	***-5***	56	-27
NT0911	*S*	*D*	*FO*	*U*	*1529**	*198*	*50*	*59*	*650*	*861*	*211*	***-3***	41	-4
NT0906	*S*	*D*	*RO*	*U*	*1376*	*80*	*46*	*54*	*622*	*761*	*139*	***-2***	46	7

Italic: Standard ATD, normal: Modified ATD with gel abdomen
Purple: Rear, outboard; Green: rear, inboard; Orange: forward, inboard; Pink: forward, outboard
* Chin-to-chest contact affecting HIC

Although the lap and shoulder belt scores are nearly identical for the forward and rearward test conditions, the average kinematic measures vary considerably. The average knee-head excursion difference is 72 mm greater with the forward lap belt locations, and the final torso angle averages 5 degrees compared to -12 degrees, indicating that the forward lap belt positions have kinematics closer to submarining than the rearward lap belt geometries.

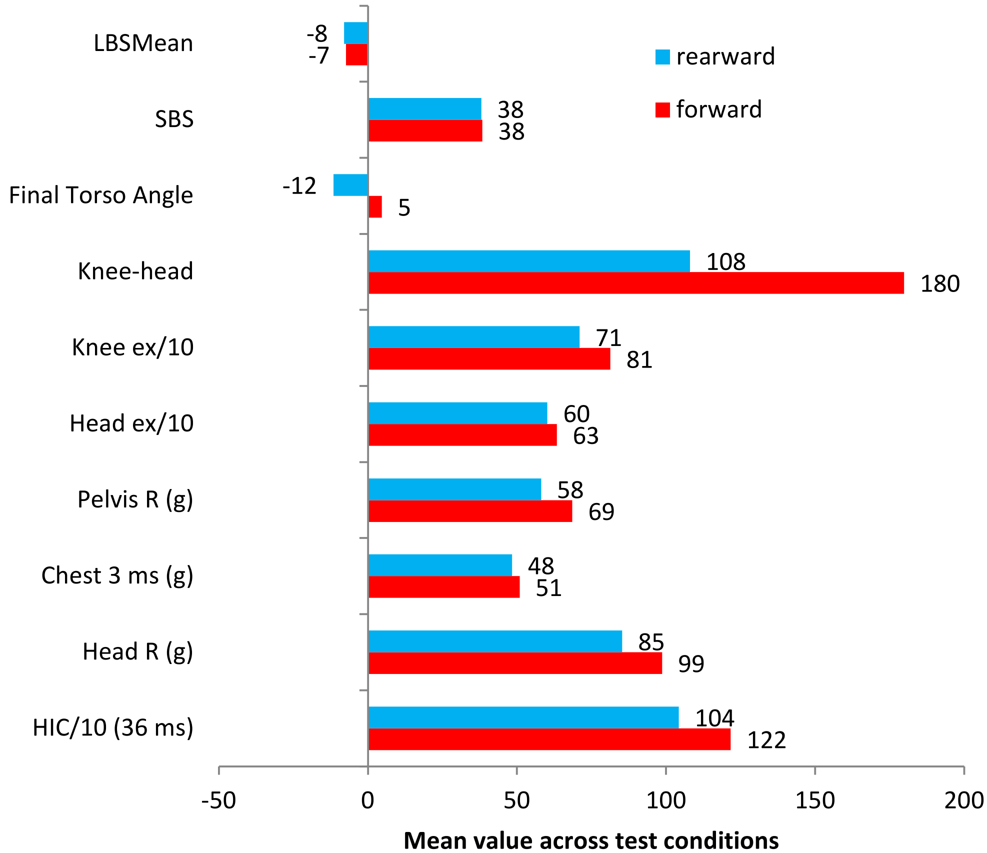
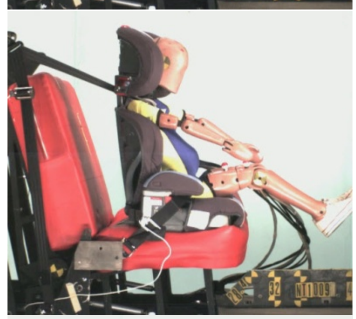
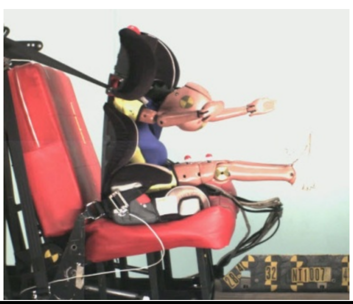
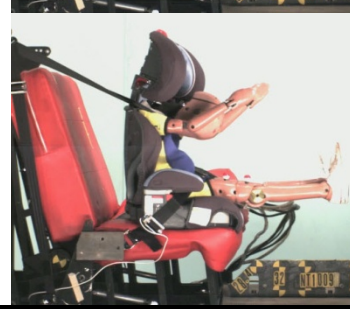


Figure 20. Mean values of outcome measures for forward and rearward lap belt locations.

Table 12 shows the sideview kinematics of tests NT1009, with forward lap belt geometry, and NT1007, with rearward lap belt geometry. Both tests use the modified 6YO, booster A, and outboard shoulder belt geometry. At 30 ms, the lap belt in the forward position has not yet engaged the dummy, while it is starting to load the pelvis in the rearward position. This is seen more clearly at 45 ms. With the forward geometry, the booster and dummy are still moving forward together and the lap belt has not fully engaged the pelvis, as seen by the back of the booster still being almost parallel to the bench seatback. With the rearward geometry, the lap belt is engaged and the booster and dummy are rotating forward. At 60 ms, the dummy's knees have translated forward farther with the forward geometry compared to the rearward geometry, and the torso angle is more upright with the rearward geometry compared to the forward geometry. At 90 ms, which is close to the time of peak head excursion, the forward geometry condition places the dummy and booster further forward on the bench seat, with the torso angle 20 degrees further rearward. Although this booster seat produces similar static lap belt scores with different belt geometries, the more forward position allows considerable forward translation of the dummy and booster before engaging the pelvis, which produces less desirable kinematics.

Table 12. Kinematic comparison of forward and rearward lap belt tests.

Time	*NT1007 Rearward lap belt*	*NT1009 Forward lap belt*
0 ms		
30 ms		
45 ms		
60 ms		
90 ms		

The final torso angle vs. knee-head excursion for tests with forward and rearward lap belt locations are shown in Figure 21. In general, the forward locations (thick gray oval) produce less desirable kinematics than the rearward lap belt locations (thin black oval).

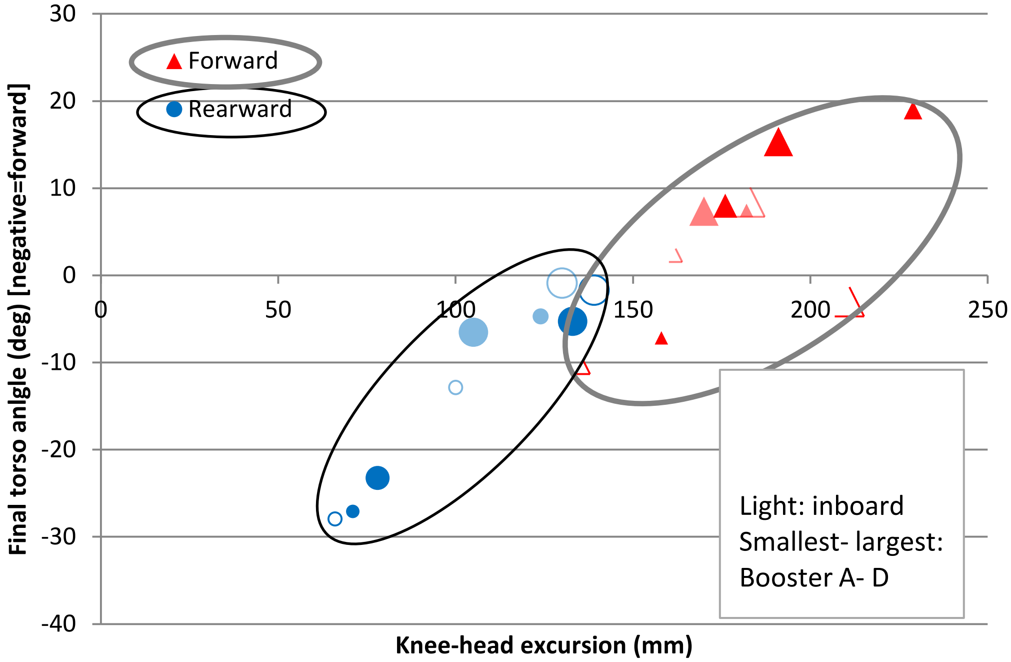


Figure 21. Final torso angle (deg) vs. knee-head excursion (mm) for forward and rearward lap belt anchorages.

4.0 Discussion

Modified ATD

The kinematic results using the standard and modified ATDs were surprisingly similar, particularly the head and knee excursions. The version of the modified abdomen tested during this program was not as sensitive to changes in lap belt position as the prototype version of the abdomen.

These results showed fewer differences between the standard and modified ATDs than were seen in testing with the prototype version of the modified ATD (Klinich et al. 2010). Differences between the prototype and current versions of the modified ATD include the following:

1) Production version of the pelvis, with slightly flatter contour to the pelvis flesh in front of the ASIS
2) Wetsuit style jacket custom-made for the ATD, which produced a tighter fit over the front of the ATD. The prototype testing of the standard ATD used a jacket designed for the Q6 ATD, which had more fabric along the length of the torso.
3) Stiffer gel abdomen that was slightly larger than that previously tested.
4) Gel abdomen attached to the ATD at its base, at its top to the base of the ribcage using clamped Velcro, and around the lumbar spine using a cable tie routed through loops glued to the sides of the abdomen. The abdomen was not attached to the ATD during prototype testing.

The gel abdomen used in this test was attached to the ATD in three locations, while the version used in prototype testing was not attached. As the belt moved off the pelvis during prototype testing, it shifted the abdomen upwards and out of the way. During the most recent test series, the attached abdomen may have resisted upward movement of the belt. In addition, the forward distension of the gel abdomen under inertial loading may have restricted upward movement of the belt.

Based on videos of belted adult cadaver tests, some forward distention of the abdomen is expected. However, the appropriate amount of forward motion of the abdomen for a pediatric dummy and the appropriate resistance to belt movement of the simulated abdomen have not been defined. In addition, some of forward abdomen motion seen in adult cadavers tests is due to anterior bending of the lumbar spine, which likely is minimal in the current design of the 6YO child dummy.

Substitution of softer foam abdomens for the gel abdomen produced results that were closer to that seen in prototype testing. This suggests that the custom jacket designed to fit better than the one used in prototype testing is likely not the cause of the different response. In addition, current testing used a production version of the modified pelvis rather than the prototype version. The slope of the flesh in front of the ASIS is slightly more upright than the prototype version. However, because the lap belt came off the pelvis when a softer foam abdomen was used, the slight differences in pelvis design between the production and prototype versions are not thought to have important effects on performance.

Seating Procedure

Differences in ATD outcomes due to seating procedure were substantially greater than those seen between the standard and modified dummies. The lower lap belt tension (2-4 lb) in the UMTRI seating procedure compared to the 15 lb belt tension in the FMVSS No. 213 procedure is hypothesized to be responsible for most of the kinematic differences, because there were substantial changes in kinematics even in a few conditions where the difference in initial head-to-torso angle was less than two degrees. However, the slightly more reclined initial posture from the UMTRI seating position also contributes to the differences in kinematics in some conditions.

In this test series, the ATD usually shows less favorable kinematics when seated realistically. The NHTSA has recently proposed using a seating procedure for booster seat testing in FMVSS No. 213 that is similar to the UMTRI seating procedure used in this test series. Based on the results of this test series, it is expected that using this seating procedure will help child restraint manufacturers design booster seats that perform better for realistic child postures and lap belt tensions.

Belt Geometry

With regard to belt geometry, shifting the lap belt location from rearward to forward had considerably greater effect on dummy kinematics than shifting the shoulder belt from outboard to inboard. Having a forward lap belt location that produces a steeper angle allows the booster seat and dummy to translate forward a greater amount before fully engaging the pelvis. The rearward lap belt location engages the pelvis earlier, producing the desired forward rotation of the torso and head past vertical. Another contributing factor may be that the plywood base of the FMVSS No. 213 bench does not extend all the way to the front edge of the cushion, so the forward lap belt location allows the booster seat to move into the part of the cushion with less support.

These results suggest a possible tradeoff in belt design between performance for booster-seated children and providing good submarining protection for children and adults on the vehicle seat. A more-forward belt anchorage location (steeper lap belt angle) is believed to reduce the risk of submarining for adults and for children not using a booster. However, the current sled tests with boosters show better performance with rearward anchorages (flat lap belt angles). The booster mitigates the poor static belt fit that flat lap belt angles would otherwise produce, while the flat lap belt angle allows belt loads to build earlier in the event, producing better kinematics.

Lap belt scores tended to be fairly similar for forward and rearward belt geometries because of booster belt routing features, although the kinematics between the tests were different. While static lap belt fit scores can differentiate between the belt fit obtained with different boosters, it is not sufficient for characterizing dynamic performance because belt anchorage locations also matter.

Moving the shoulder belt from an outboard position (2.5” outboard of FMVSS No. 213 shoulder belt anchorage) to an inboard position (2.5” inboard of FMVSS No. 213 shoulder belt position) did not have a large affect on kinematics. Although the shoulder belt anchorage location shifted 75 mm, the shoulder belt scores for a given pair of inboard/outboard test conditions changed only 0-10 mm, because all of the booster seats used in this program had features to statically route the shoulder belt position. However, for boosters A and C, the dummy showed greater rollout tendencies (final torso angle greater than -20 degrees) for the outboard condition compared to the inboard condition. Most other conditions, but not all, also resulted in slightly greater final torso angles with the outboard condition.

5.0 Summary of Key Findings

- Minimal differences in kinematics were observed between the standard and modified 6YO ATDs.
- The modified gel abdomen proved to be durable through 25 tests after changes to the attachments were made.
- The current version of the modified 6YO was not as sensitive to changes in lap belt geometry as the prototype version for reasons that appear to be linked to the gel abdomen.
- The UMTRI seating procedure, which is designed to produce more realistic ATD postures and uses a realistic lap belt tension, produces ATD kinematics that have greater knee-head excursion differences and less forward torso rotation compared to using the standard FMVSS No. 213 seating procedure.
- Moving the shoulder belt anchorage from inboard 128 mm to outboard usually led to a greater final torso angle. However, these kinematic changes are smaller than those produced by different seating procedures or moving the lap belt. The moderate change in kinematics likely occurred because shoulder belt routing features of booster seats limited changes in static shoulder belt fit relative to the ATD to less than 10 mm between the inboard and outboard positions.
- Moving the lap belt geometry from rearward (shallow angle) to forward (steep angle) produced less desirable ATD kinematics with all booster seats tested. The forward position of the lap belt anchorage allows considerable forward translation of the booster and ATD before the belt engages the pelvis.
- The less desirable booster kinematics with a forward lap belt location is at odds with child dummy kinematics without a booster seat, where a more forward belt location usually produces better kinematics (Klinich et al. 2010).
- These preliminary results suggest that designing rear seat belt geometry to accommodate the children who sit with and without boosters may be challenging and involve optimization between these opposing trends.
- Past research suggested a change in torso angle less than 10 degrees and a knee-head excursion greater than 200 mm to be associated with submarining kinematics with both standard and modified ATDs (Klinich et al. 2010). The kinematics from the current test series generally support these suggestions for a submarining criteria.

6.0 References

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