Kinematics Comparison between the Hybrid III 6 Year-old with Standard Pelvis and Modified Pelvis with Gel Abdomen in Booster Sled Tests

Jessica S. Jermakian, Marcy A. Edwards

Abstract The Hybrid III 6 year-old anthropomorphic test device has limited pelvis and abdomen biofidelity, limiting its ability to discriminate good and poor restraint performance in dynamic events. The objective of this study is to determine whether the Hybrid III 6 year-old with modified pelvis and gel abdomen provides better discrimination of restraint performance than the standard 6 year-old in a series of sled tests with highback, backless, and no booster conditions. Sixteen paired sled tests were conducted in a vehicle buck subjected to a 56 km/h crash pulse simulating a frontal impact. Injury and kinematic measures were calculated and the population means were compared between the standard and modified 6 year-old using paired sample t-tests. Overall kinematics of the standard and modified 6 year-old were similar for measures such as head acceleration, chest acceleration and compression, and head excursion. The modified 6 year-old had 257% larger abdominal penetrations, 19% smaller anterior superior iliac spine loads, 5% larger knee excursions, 70% larger knee – head excursions, and 25% smaller torso rotations, all potential indicators of the propensity to submarine. However, these submarining indicators did not necessarily correspond to those test conditions more likely to result in submarining in real-world data, such as initial belt placement on the abdomen.

Keywords booster seat, child restraint systems, Hybrid III, sled testing

I. INTRODUCTION

Belt-positioning booster seats are for children who have outgrown forward-facing harness-equipped child restraints but are still too small for vehicle seats and safety belts to fit them properly. Booster seats have proven effective at reducing the risk of injury, with studies of crash data showing injury reductions ranging from 14% to 45% for children ages 4 to 8 years [1-2]. Boosters are primarily designed to reduce the likelihood of seat belt-induced injuries, sometimes referred to as seat belt syndrome, such as cervical and lumbar spine injuries and intra-abdominal injuries caused by improperly fitted seat belts (see [3] for a review), and there is evidence they are effective in achieving that goal. Children ages 4 to 8 who are restrained with seat belts alone were 3.5 times more likely to sustain an abdominal injury than children using booster seats [4]. Abdominal injuries sustained by booster-seated children are similar to injuries sustained by properly restrained adults in moderate to severe frontal crashes rather than typical seat belt syndrome injuries [5].

Despite the risk of abdominal injuries in children from improperly fitted belts, the child anthropomorphic test devices (ATDs) used in regulatory testing have limited anthropometric biofidelity in the pelvis and lack a biofidelic abdomen and injury assessment, limiting the ATDs' ability to discriminate good and poor restraint performance in dynamic events. Specifically, the dimensions of the Hybrid III 6 year-old (HIII 6Y0) pelvis differ significantly from that of 6-year-old children, who have less prominent and lower anterior superior iliac spine (ASIS) locations than the ATD [6-7]. Biofidelic geometry is critical to assessing belt interaction with the pelvis. In addition, the seated pelvis limits pelvic rotation relative to the spine and thigh, restricting the ATD's ability to slouch [7].

Efforts to improve the HIII 6YO pelvis and abdomen biofidelity have been underway for more than a decade, resulting in a pelvis with improved geometry and stiffness characteristics, and a gel abdomen with more biofidelic force-deflection characteristics. These changes have collectively been termed the DAPRR, for Dummy Abdomen Pelvis Round Robin [8]. A few studies have evaluated the new pelvis and gel abdomen. [7] and [9] conducted a series of sled tests with an early version of the pelvis and found the HIII 6YO retrofitted with the prototype pelvis was more sensitive to lap belt geometry than the standard pelvis. However, when the modified pelvis was

J. S. Jermakian, DSc (+1-703-247-1582, jjermakian@iihs.org) is a Senior Research Engineer and M. Edwards is a Research Engineer at the Insurance Institute for Highway Safety in Ruckersville, VA, USA.

combined with the gel abdomen, the combination resulted in less sensitivity to belt geometry because the abdomen distended during the crash event, keeping the lap belt in position on the pelvis [9]. The modified 6YO with the gel abdomen did, however, show sensitivity to ATD positioning procedures, with a higher propensity toward submarining behaviour when positioned in a more realistic posture. The National Highway Traffic Safety Administration (NHTSA) conducted an evaluation of a later version of the 6YO with modified pelvis and gel abdomen. The sled test series varied seat pan angle, restraint type, and crash pulse and found the modified 6YO was more sensitive than the standard 6YO to restraint type [8].

The previous tests of the modified 6YO used varied belt geometries and seat pan angles to better mimic the vehicle environment but were still conducted in an FMVSS 213-style bench seat and belt setup, which has limited fidelity with the vehicle environment [10-12]. The objective of this study is to determine whether the HIII 6YO with modified pelvis and gel abdomen provides better discrimination of restraint performance between highback, backless, and no booster restraint conditions than the standard HIII 6YO in a series of sled tests on a vehicle buck.

II. METHODS

A series of sled tests was conducted to compare the kinematic performance of the standard HIII 6YOand the modified 6YO. Details of the test series are described below.

Sled Tests

A series of 16 sled tests (Table I) was conducted on a HyperG reverse acceleration sled (DSD, Austria). For each test, the ATD was positioned in the right rear outboard seat position of a 2010 Chevrolet Malibu vehicle buck and subjected to a 56 km/h crash pulse (Fig. A1 in the Appendix) simulating a frontal impact. The pulse was based on the FMVSS 213 regulation pulse and scaled up to 56 km/h. The front passenger seat was removed to allow unencumbered occupant excursion. The buck was equipped with the standard vehicle safety belt assembly, which was replaced after each test.

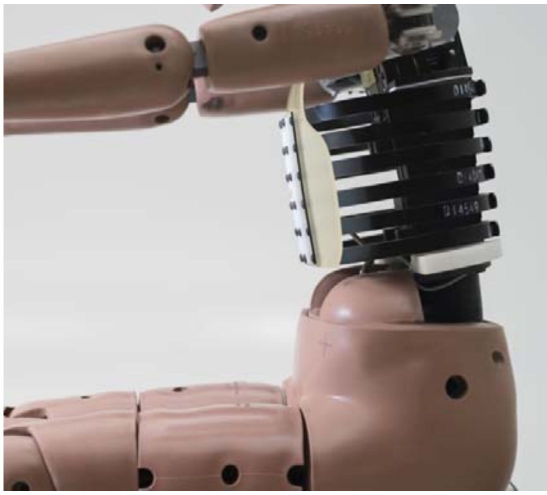
TABLE I
SLED TEST MATRIX

<table>
<tr><th>Booster</th><th>Lap belt fit</th><th>Booster type</th><th>Dummy</th></tr>
<tr><td>Evenflo Amp (2 tests)</td><td rowspan="4">Good</td><td rowspan="2">Backless</td><td rowspan="7">HIII 6YO standard</td></tr>
<tr><td>Cosco Ambassador</td></tr>
<tr><td>Evenflo Chase</td><td rowspan="4">Highback</td></tr>
<tr><td>Recaro Performance</td></tr>
<tr><td>Safety 1st Vantage</td><td rowspan="3">Poor</td></tr>
<tr><td>Cosco Highback</td></tr>
<tr><td>None</td><td>None</td></tr>
<tr><td>Evenflo Amp (2 tests)</td><td rowspan="4">Good</td><td rowspan="2">Backless</td><td rowspan="7">HIII 6YO with modified pelvis and gel abdomen</td></tr>
<tr><td>Cosco Ambassador</td></tr>
<tr><td>Evenflo Chase</td><td rowspan="4">Highback</td></tr>
<tr><td>Recaro Performance</td></tr>
<tr><td>Safety 1st Vantage</td><td rowspan="3">Poor</td></tr>
<tr><td>Cosco Highback</td></tr>
<tr><td>None</td><td>None</td></tr>
</table>

Anthropomorphic Test Devices (ATDs)

Testing was conducted with two versions of the HIII 6YO ATD, the standard ATD and a modified version with a prototype pelvis and gel-filled abdomen. The retrofitted pelvis was developed to better represent the geometry and skeletal landmarks of 6YO children to make the ATD's interaction with the safety belt more biofidelic [7-9]. A gel-filled abdomen with more biofidelic geometry and biomechanically-based force deflection characteristics replaces the foam abdomen of the standard 6YO (Fig. 1) [13-14]. More detailed description of the development of the pelvis and gel abdomen can be found in NHTSA's report on its evaluation of the HIII prototype ATD with modified pelvis and gel abdomen [8].

Standard HIII 6YO



Modified HIII 6YO

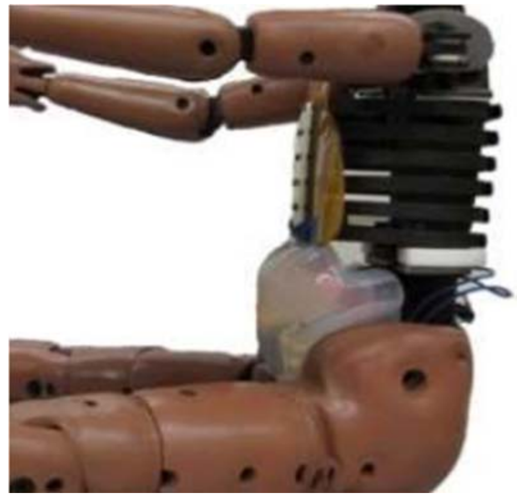


Fig. 1. The standard HIII 6YO has the original pelvis and foam abdomen, while the modified HIII 6YO has a more realistic pelvis geometry and a deformable gel abdomen. Photo credit (right): NHTSA in [8].

The standard HIII 6YO was outfitted with the regular chest jacket, and a silicone lap shield was used to prevent the lap belt from slipping into the gap between the pelvis and thigh. The modified 6YO was outfitted with a custom wetsuit, which alleviates the need for the silicone lap shield. For both ATDs, a pelvis positioning pad was attached to the rear surface of the pelvis to offset the pelvis from the seat back during positioning to better mimic how real children sit in vehicle seats [15]. Hip offset tools were fully inserted into the ATD's pelvis when possible due to booster geometry.

Each dummy was instrumented to measure head triaxial acceleration; upper neck X and Z loads and Y moment; chest triaxial acceleration, compression (the modified 6YO uses an IR-TRACC instead of a chest potentiometer), and angular rate; lumbar spine 6-channel loads; pelvis X and Z acceleration, and angular rate; and upper and lower ASIS loads (right and left). Belt loads at the D-ring and outboard lap were recorded, and lap belt centreline X and Z acceleration and angular rate were collected at the ATD midline.

Booster Seats and Dummy Positioning

Booster seats were chosen to represent highback and backless styles and a range of static lap belt fit. Lap belt fit for each booster seat was categorised as good or poor based on the Insurance Institute for Highway Safety (IIHS) booster evaluation protocol [16]. Sled tests were run with six different booster seats, one no booster condition, and one repeat test of a backless booster.

Booster and dummy positioning was performed in accordance with the IIHS booster evaluation protocol [16] and adapted for the vehicle buck. For each test, the booster, if applicable, was centred on the buck seat cushion, moved rearward until touching the seat back, then a force of 133 N (30 lb) was applied to the front of the booster, moving the booster rearward into the vehicle seat. The ATD was positioned in the centre of the booster and touching the seat back, then a 178 N (40 lb) force was applied rearward to the abdomen and chest. The ATD's knees were bent until the back of the lower legs were in minimal contact with the booster or vehicle seat. The lap and shoulder belt were routed in accordance with the booster manual, including the use of a belt clip for backless boosters. The lap belt was tensioned through repeated pulls of approximately 44 N (10 lb) until no additional movement of the lap belt was apparent. The shoulder belt was routed to the shortest or most natural position and tensioned. A 3D coordinate measuring device was used to record reference points on the booster and ATD to verify positioning.

Data Analysis

All channel data were filtered in accordance with SAE J211. HIC36, chest 3ms clip, chest compression, and head and knee excursion were calculated. The following kinematic measures were considered as potential indicators of the propensity to submarine: knee – head excursion [7][9], torso rotation [7][9], and abdominal penetration [8].

Abdomen penetration was calculated using pelvis and lap belt accelerometers and angular rate sensors following the method outlined in NHTSA's evaluation of the DAPRR prototype components [8]. First, the lap belt block accelerations were translated into the pelvis block coordinate system using the initial block orientations and the integral of the angular rate of each block. Once the lap belt acceleration was translated to the pelvis coordinate system, the relative acceleration between the pelvis and the lap belt was calculated. This relative acceleration was then integrated twice to determine the amount of relative travel between the pelvis block and the lap belt. This travel, when bounded by the time of maximum penetration, is the reported abdomen penetration value. To avoid reporting any integration errors that accumulates as the ATD rebounds, the amount of travel was only considered up to the time of maximum penetration of the seat belt into the abdomen. The time of maximum penetration was defined for each test by the time the relative velocity between the pelvis and the lap belt first returns to zero or, if this does not occur, using film analysis to determine the point at which rebound begins.

Initial head and knee positions were defined relative to the vehicle buck using a 3D coordinate measuring device. Relative displacement of the head and knee were determined using film analysis (TEMA version 3.4), then translated into absolute excursions from a simulated Z-point (the bench reference point used for excursion measurements in FMVSS 213 [17]) on the vehicle buck.

The population means were compared using paired sample t-tests (SAS version 9.4), and the significance level was set at 0.05. The paired t-test approach compares the standard 6YO test with the comparable modified 6YO test.

III. RESULTS

Sixteen sled tests were conducted with backless, highback, and no booster conditions with a range of lap belt fit varying from good to poor. From video inspection, neither ATD appeared to submarine in any of the tests; the lap belt remained on the pelvis throughout the event and did not migrate over the ASIS into the abdominal cavity. Data were compiled, and peak measures were compared between the standard HIII 6YO and modified HIII 6YO in each paired test. Average injury metrics and kinematic measures are summarised in Table II, with *p*-values indicating the probability of the difference in the measure between the paired tests. For all tests, HIC36 and chest 3 ms clip were higher than injury assessment reference values (IARV) outlined in FMVSS 213, but HIC36 was 11% lower on average in tests with the modified HIII 6YO. Overall kinematics of the standard and modified HIII 6YO were similar quantitatively for measures such as head acceleration, chest acceleration and compression, and head excursion. Knee excursions averaged 5% higher in tests with the modified 6YO, although still well below IARV.

Shoulder belt loads and pelvis accelerations were comparable in paired tests, but tests with the modified 6YO had, on average, 6% higher lap belt loads and 15% smaller ASIS loads compared with the standard 6YO.

All potential submarining indicators showed a larger propensity for submarining behaviour in the modified HIII 6YO, compared with the standard 6YO. Specifically, the modified 6YO had 257% higher abdomen penetrations, 70% larger knee-head excursions, and 24% smaller torso rotations.

TABLE II
AVERAGE INJURY METRICS AND KINEMATIC MEASURES FOR THE STANDARD HIII 6YO AND MODIFIED HIII 6YO AND P VALUES FOR PAIRED T-TESTS. P-VALUES MEETING THE 0.05 SIGNIFICANCE LEVEL ARE IN **BOLD**.

Metric	IARV*	Standard 6YO	Modified 6YO	*p*-value
HIC36	1000	1772	1577	***p*=0.020**
Peak head acceleration (g)		105	112	*p*=0.618
Chest 3 ms clip (g)	60	62	62	*p*=0.719
Chest compression (mm)	45	39	39	*p*=0.818
Head excursion (mm)	813	639	627	*p*=0.108
Knee excursion (mm)	915	702	734	***p*<0.001**
Shoulder belt load (N)		5794	5616	*p*=0.266
Lap belt load (N)		3804	4016	***p*=0.048**
ASIS loads sum (N)		3024	2558	***p*=0.012**
Pelvis acceleration (g)		12	15	*p*=0.290
Knee-head excursion (mm)		63	107	***p*<0.001**
Abdomen penetration (mm)		-14	-50	***p*=0.003**
Torso rotation (degrees)		58	44	***p*=0.003**

*Injury Assessment Reference Values (IARV) for HIC36, Chest 3 ms clip, head and knee excursion are from FMVSS 213 requirement. Chest compression IARV is from [18].

Fig. 2 plots head excursion against knee excursion for the sled test series. For a given test condition, head excursions were generally comparable between paired tests, but the modified 6YO (filled markers) shows consistently larger knee excursions than the standard 6YO (unfilled markers) for the same test conditions.

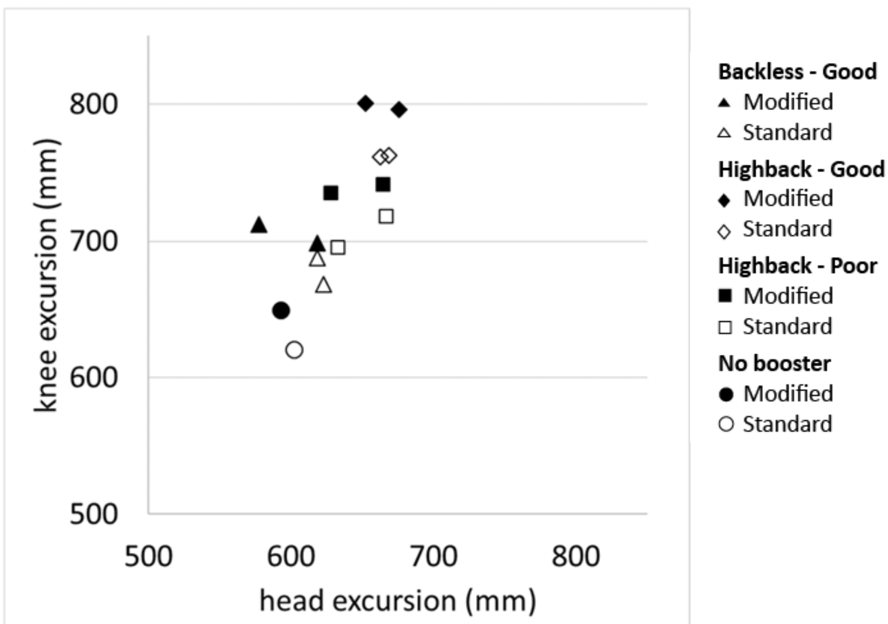


Fig. 2. Comparison of knee and head excursions between the standard and modified 6YO in paired test conditions of highback, backless, and no booster conditions with good and poor static lap belt fit

Fig. 3 shows a visual comparison between the standard HIII 6YO and modified 6YO at or near maximum head excursion for select paired tests. Qualitatively, the overall kinematics are similar between the standard and modified 6YO for paired tests.

Standard HIII 6YO | Modified HIII 6YO

Backless booster with good static lap belt fit

Highback booster with good static lap belt fit

Highback booster with poor static lap belt fit

No booster condition with poor static lap belt fit

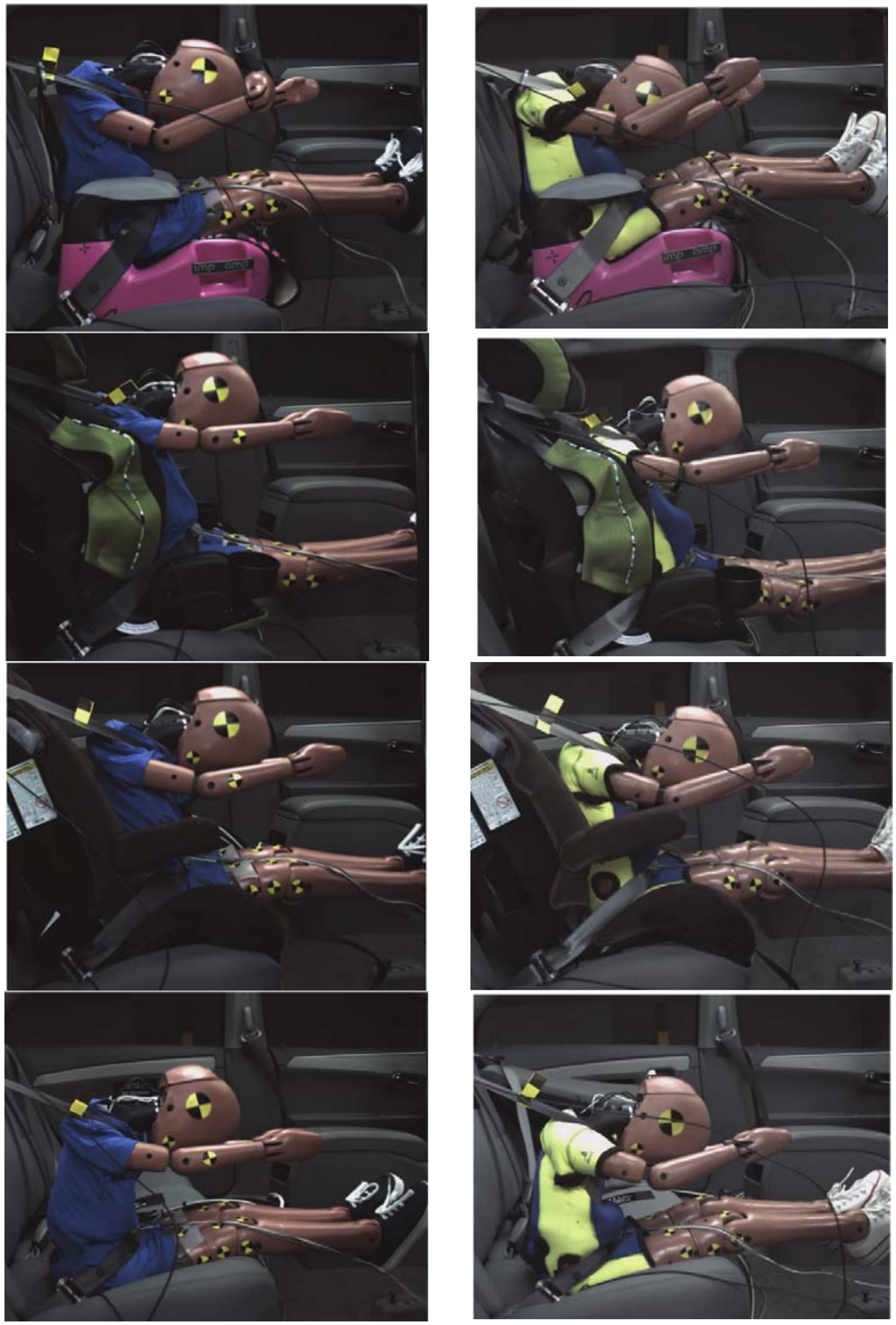


Fig. 3. Comparison between the standard HIII 6YO (left) and modified HIII 6YO (right) at or near maximum excursion for four test conditions including backless, highback and no booster conditions.

Predictors of the potential to submarine

The modified 6YO exhibited less forward torso rotation than the standard 6YO in paired tests. Fig. 4 shows torso rotation over time plotted on the same scale for the combinations of test conditions. The largest torso rotations in tests with the modified 6YO were in highback boosters with poor static belt fit, and the smallest rotations were in highback boosters with good belt fit. Torso rotations were similar in magnitude for the modified 6YO in the backless booster tests with good belt fit and no booster tests with poor belt fit. See Fig. A2 and A3 in the appendix for similar plots of lap belt loads and ASIS loads.

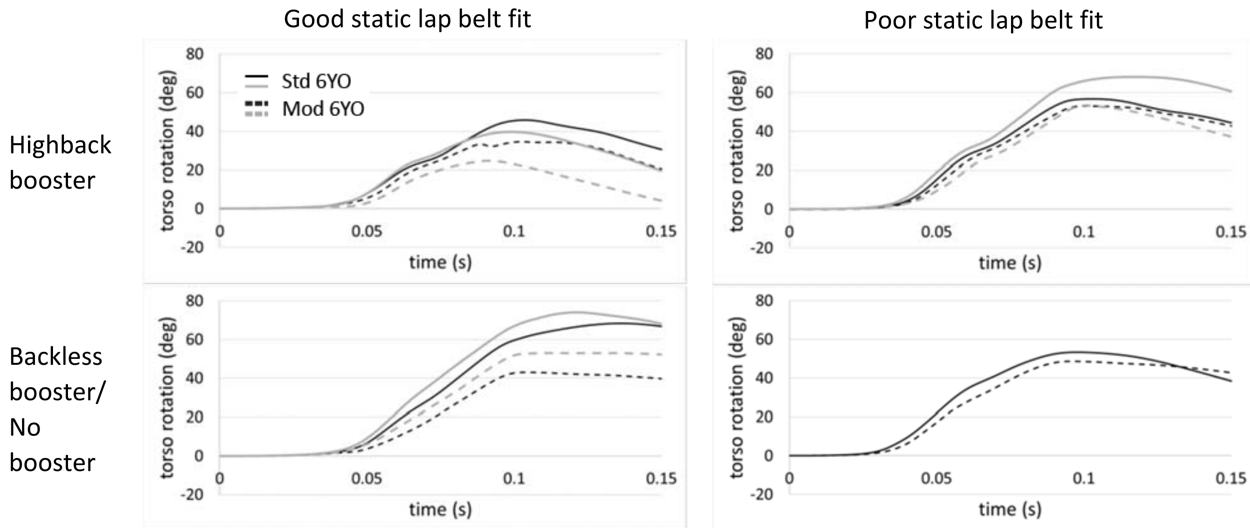


Fig. 4. Comparison of torso rotation (positive is forward rotation) for the standard 6YO (solid lines) and modified 6YO (dashed lines) in paired tests in highback, backless and no booster conditions.

Fig. 5 plots peak torso rotations with the difference between knee and head excursion. Knee-head excursions were consistently larger for the modified 6YO compared with the standard 6YO in comparable tests. There is some indication that larger knee-head excursions were correlated with smaller torso rotations for the modified 6YO (p=0.07), but a similar correlation for the standard 6YO was not found (p=0.27).

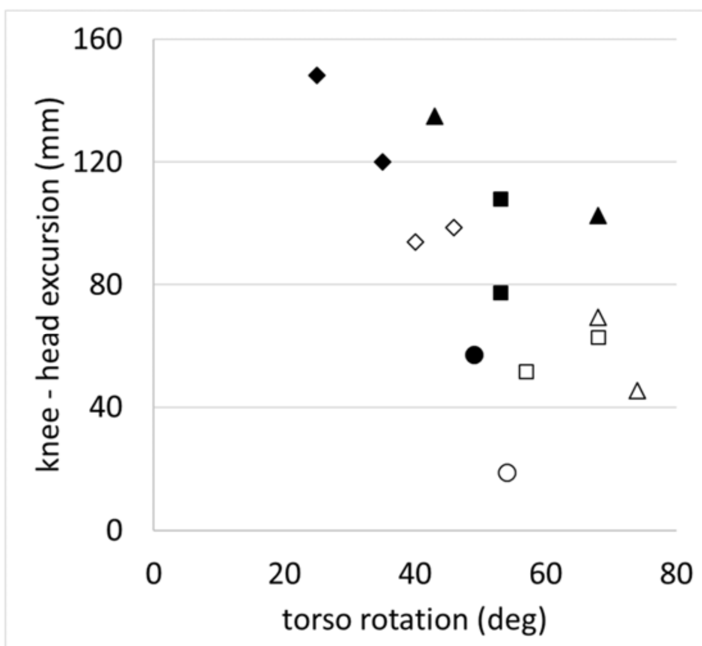


Fig. 5. Comparison of knee-head excursion and torso rotation between the standard and modified 6YO in paired test conditions of highback, backless, and no booster conditions with good and poor static lap belt fit

Abdomen penetrations are substantially larger in the modified 6YO with the gel abdomen than the standard 6YO with the foam abdomen (Fig. 6). Abdomen penetration was not correlated with torso rotation for the modified 6YO (p=0.10) or standard 6YO (p=0.16).

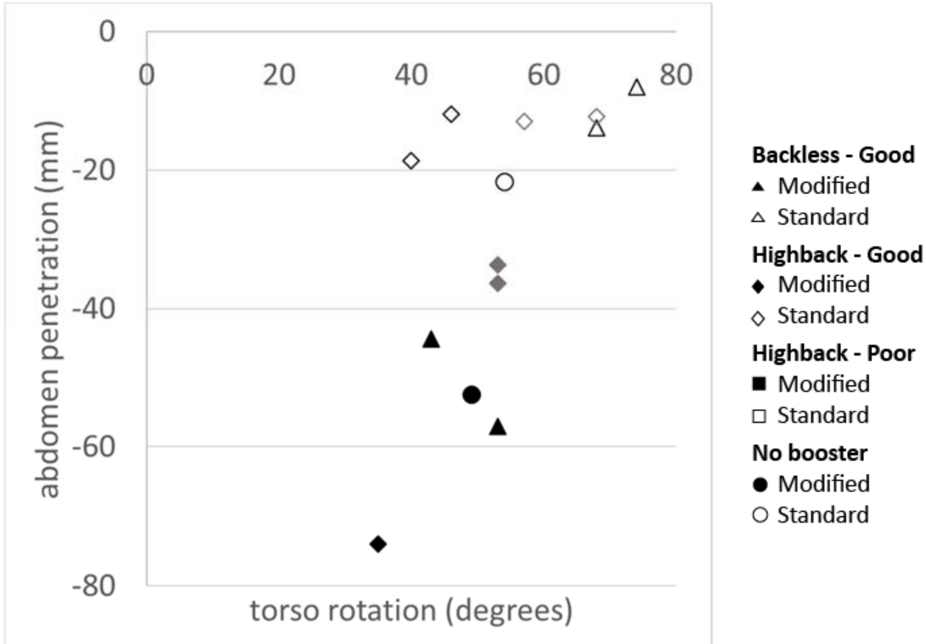


Fig. 6. Comparison of abdomen penetration and torso rotation between the standard and modified 6YO in paired test conditions of highback, backless, and no booster conditions with good and poor static lap belt fit

IV. DISCUSSION

The HIII 6YO with modified pelvis and gel abdomen had smaller torso rotations, larger knee-head excursions and other potential indicators of unfavourable kinematics associated with submarining when compared with the standard 6YO in paired tests. Other measures, such as head and chest acceleration, and chest compression were similar between the standard and modified 6YO. These results suggest the modified 6YO may be more sensitive to varying test conditions, such as booster type or lap belt initial position. However, examining the data in more detail suggests the submarining indicators do not necessarily correspond to test conditions expected to produce less favourable kinematics, such as no booster and poor lap belt fit conditions.

Previous studies have shown that the modified 6YO can discriminate between bench-related variables such as seat pan angle and lap belt angle [7-9]. This study sought to further that research by using the modified 6YO to evaluate more subtle differences, such as boosters with good and poor static lap belt fit. Despite many of the available boosters having poor static lap belt fit [19], field studies have shown boosters are very effective at reducing injury risk [1-2], particularly abdominal injuries [4-5]. Hence, these studies confirm that booster seats have injury-reduction benefits beyond guiding the lap and shoulder belt into good initial positions.

One benefit of booster seats is that they shorten the seat cushion length, which allows children to sit more comfortably and avoid slouching [19-22]. A child sitting upright avoids the pre-submarine belt position and torso recline that [23] outlined as key mechanisms contributing to abdominal injury in children, and increases the likelihood that the lap and shoulder belt will stay in good pre-crash positions [19-22]. The current test series used a seating procedure that accounts for more realistic child postures in booster seats [15-16] but does not account for postures associated with long cushion lengths, which likely result in slouched initial positions when seated directly on the vehicle seat [20-22]. The HIII 6YO pelvis is formed in a seated position, which limits its ability to achieve slouching initial postures and limits pelvis rotation relative to the thighs and torso. The modified pelvis has more biofidelic geometry and stiffness characteristics but remains in a seated position with the associated limitations. In contrast, the HIII 10YO has an adjustable lumbar spine with the ability to slouch, which allows for more complex belt-pelvis interactions [24]. Incorporating the ability to slouch into the 6YO and allowing more pelvis rotation may result in more biofidelic interaction with the lap belt.

Another benefit of boosters is that they steepen the lap belt angle and improve initial belt position [15][19][21]. Steeper lap belt angles reduce the likelihood of submarining in adults [25-27] and become even more important in securing the small and unformed pelvis of a child. Some of the improvement in belt angle comes from elevating the child, but an additional benefit comes from sitting in a more upright posture [15]. In addition, boosters minimise the effect of shallow lap belt angles and improve static belt fit [19][21]. There is limited data for the 6YO, but there is evidence that static belt fit is associated with improved dynamic performance in sled tests of the HIII 10YO [23].

Boosters have largely been a success story in the United States. Strong laws, public education about safety benefits, and changing social norms have resulted in more booster-age children being appropriately restrained [28-29]. Still, booster seats are big and bulky, which make them less practical during travel or carpool scenarios or in vehicles with narrow seat positions. New ultra-portable products have been introduced to meet this need, but they differ from traditional booster designs in potentially meaningful ways. For example, one design positions the seat belt without elevating the child, and other designs are constructed of inflatable materials. There is little real-world data to understand these new products, highlighting the need for an ATD that can adequately discriminate between good and poor designs. [12] studied a few nontraditional designs using the Q3 and HIII 6YO and found both ATDs lacking in their ability to identify submarining behaviour using traditional regulatory injury metrics. In the testing, there were clear cases of submarining and other unfavourable kinematics, but the traditional metrics all fell within IARVs. Other measures of potential to submarine, such as torso rotation, knee-head excursion, or abdomen penetration, were not evaluated in the test series.

In addition to a more biofidelic ATD, additional measures beyond the injury metrics outlined in FMVSS 213 currently used in evaluating traditional boosters are needed to better discriminate between different booster designs, particularly new types of belt-positioning devices. In FMVSS 213, knee excursion is the primary indicator of excessive forward pelvic motion, indicating a potential for submarining. However, knee excursion is measured relative to a fixed point on the vehicle or bench fixture, which gives an advantage to devices that position the ATD closer to the seat back, such as backless boosters and even no booster conditions. Field data show highback boosters are as effective at reducing injuries as backless boosters [2], suggesting differences in knee excursion magnitudes are not adequately discriminating performance. [7] and [9] used occupant kinematics principles to identify knee-head excursion and torso rotation as indicators of the potential to submarine, while [8] used a mathematical computation of abdomen penetration.

Knee excursion as measured in FMVSS 213, kinematic knee-head excursion and torso rotation, and abdomen penetration were all explored in the current study. When comparing the submarining indicators in tests with the modified 6YO, there is a borderline correlation between torso rotation and knee-head excursion, but there is no correlation between torso rotation and abdomen penetration, which suggests that the measures are not capturing the same kinematic response. Tests with the modified 6YO had consistently lower torso rotations and knee-head excursions than the standard 6YO in paired tests but were not commensurate with variation in lap belt position or booster versus no booster conditions. Abdomen penetrations were much larger in the modified 6YO with the gel abdomen than the standard 6YO, which is by design — the gel abdomen was designed to have more biofidelic force-deflection characteristics than the standard foam abdomen [14][30]. In addition, the geometry of the gel abdomen is about 25 mm deeper (anterior-posterior thickness) than the standard abdomen and extends forward of the ASIS (see Fig. 1), and thus, some amount of abdomen penetration is expected before the belt interacts with the pelvis. However, because the gel abdomen lacks instrumentation, it is not possible to know the location of the penetration and whether the penetration occurred due to lap belt migration over the ASIS into the abdominal cavity. Instrumentation development is on-going [31], and improved sensing of penetration location may better correspond with injury potential.

While the efforts to improve HIII 6YO have continued in the United States, there have been similar efforts to improve child ATDs in Europe. The Q-series 6 year-old ATD (Q6) has been modified to include abdominal pressure sensors and hip liners to evaluate the benefits of different booster designs [32-33]. Studies of the modified Q6 suggest the Q6 shows a larger propensity toward submarining behaviour compared to the HIII 6YO but limited ability to discriminate between good and poor booster designs [12][34].

Several limitations should be considered when interpreting the findings. The modified 6YO had a neoprene suit rather than traditional clothes combined with a lap shield, and it is not known how much that affected results. Also, there is no instrumentation in the gel abdomen to assess penetration magnitude so a mathematical approach was taken, which involved double integration of multiple sensors and may be prone to error. In this series of tests, the gel abdomen showed clear distention during the crash event, but did not completely displace from the abdominal cavity as reported by [8-9]. The version of the modified 6YO tested had a webbing harness designed to keep the abdomen securely attached. This harness was not present in earlier tests and seemed to maintain the integrity of the abdominal contents while still allowing some distention, but it is unknown how representative the abdomen behaviour is of the abdomens of children in crashes.

A no-booster condition was included as a worst-case scenario, but ATD kinematics were favourable in that condition despite the lack of boost and an initial lap belt position on the abdomen. ATDs were positioned on the vehicle seat with no slouching, and the belt geometry and seat cushion characteristics might have been more favourable than other vehicles, reducing the likelihood of submarining despite poor initial lap belt placement. The vehicle buck (a 2010 Chevrolet Malibu) has steeper rear-seat lap belt angles when compared with average anchor locations in the field. The side view (XZ) lap belt angles are 59 and 55 degrees for outboard and inboard anchors, respectively, compared with an average of 53 (outboard) and 48 degrees (inboard) in the vehicle fleet [35]. A simulation study focused on optimizing rear seat belt geometry for varying child ATD sizes in frontal impacts showed that positioning lap belt anchors more forward to achieve steeper lap belt angles results in better pelvic restraint in the 6YO, but there is a tradeoff with increased knee excursion and reduced torso rotation [36]. The simulation study's optimized belt geometry for the 6YO results in lap belt angles of approximately 48 to 52 degrees for the outboard anchor and 57 to 60 degrees for the inboard anchor and the anchors are generally located closer to the h-point in all 3 dimensions than the anchors in the vehicle buck used in the current study. The vehicle buck seat cushion length is more than 100 mm longer than the optimized length of 350 mm. The vehicle buck represents one vehicle, and results are not generalisable to the broader vehicle fleet.

Despite these limitations, the current study provides data to suggest that while the modified 6YO showed a greater propensity toward submarining behaviour, the submarining indicators did not necessarily correspond to those test conditions more likely to result in submarining in real-world data, such as initial belt placement on the abdomen.

V. CONCLUSIONS

Previous studies have compared kinematics of the HII 6YO with standard and modified pelvis in sled tests using the bench used in US. federal regulations and found differences. This study is the first to compare the ATDs in a vehicle environment, and the results show the HIII 6YO with modified pelvis and gel abdomen exhibited smaller torso rotations, larger knee-head excursions and other potential indicators of unfavourable kinematics associated with submarining when compared with the standard 6YO in paired tests. However, the submarining indicators do not necessarily correspond to test conditions expected to produce less favourable kinematics, such as no booster and poor initial lap belt fit conditions.

VI. ACKNOWLEDGEMENT

This work was supported by the Insurance Institute for Highway Safety in the US. The authors would like to thank the National Highway Traffic Safety Administration in the US for loaning the Insurance Institute for Highway Safety the HIII 6YO with the modified pelvis and gel abdomen and associated instrumentation.

VII. REFERENCES

[1] Sivinski R. Booster seat effectiveness estimates based on CDS and state data. Report no. DOT-HS-811-338. 2010, U.S. Department of Transportation: Washington, DC, USA.

[2] Arbogast KB, Jermakian JS, Kallan MJ, Durbin DR. Effectiveness of belt positioning booster seats: an updated assessment. *Pediatrics,* 2009, 124:1281-86.

[3] Durbin DR, Arbogast KB, Moll EK. Seat belt syndrome in children: a case report and review of the literature. *Pediatric Emergency Care,* 2001, 17(6):474-7.

[4] Nance ML, Lutz N, Arbogast KB, Cornejo RA, Kallan MJ, Winston FK, Durbin DR. Optimal restraint reduces the risk of abdominal injury in children involved in motor vehicle crashes. *Ann Surg,* 2004, 239(1):127-31.

[5] Arbogast KB, Jermakian JS, Ghati Y. Abdominal injuries in belt-positioning booster seats. *Ann Adv Automot Med,* 2009, 53:209-19.

[6] Chamouard F, Tarrière C, Baudrit P. Protection of children on board vehicles. Influence of pelvis design and thigh and abdomen stiffness on the submarining risk for dummies installed on a booster. *Proceedings of the*

15th International Conference on the Enhanced Safety of Vehicles, Paper no. 96-S7-O-03, 1996, Melbourne, Australia.

[7] Klinich KD, Reed MP, Manary MA, Orton NR. Development and testing of a more realistic pelvis for the Hybrid III 6-year-old ATD. *Traffic Inj Prev,* 2010, 11(6):606-12.

[8] Hagedorn A, Stammen J. Comparative evaluation of 6-year-old Hybrid III and DAPRR prototype ATD abdomen/pelvis components. Report no. DOT-HS-812-088. 2015, U.S. Department of Transportation: Washington, DC, USA.

[9] Klinich KD, Reed MP, Manary MA, Orton NR, Rupp JD. Optimizing protection for rear seat occupants: assessing booster performance with realistic belt geometry using the Hybrid III 6YO ATD. Report No. UMTRI-2011-40. 2011, University of Michigan Transportation Research Institute: Ann Arbor, MI, USA.

[10] Tylko S, Locey CM, Garcia-Espana JF, Arbogast KB, Maltese MR. Comparative performance of rear facing child restraint systems on the CMVSS 213 bench and vehicle seats. *Ann Adv Automot Med,* 2013, 57: 311–328.

[11] Maltese MR, Tylko S, Belwadi A, Locey C, Arbogast KB. Comparative performance of forward-facing child restraint systems on the C/FMVSS 213 bench and vehicle seats. *Traffic Inj Prev*, 2014, 15 Suppl 1:S103-10.

[12] Tylko S, Bussières A, Starr A. Evaluating child safety innovations: Have we got the right tools and the right test methodologies? *Proceedings of the 14th International Conference on the Protection of Children in Cars*, 2016, Munich, Germany.

[13] Rouhana SW, Elhagediab AM, Walbridge A, Hardy WN, Schneider LW. Development of a reusable, rate-sensitive abdomen for the Hybrid III family of dummies. *Stapp Car Crash J*, 2001, 45:33-60.

[14] Elhagediab A, Hardy W, Rouhana S, Kent R, Arbogast K, Higuchi K. Development of an instrumented rate-sensitive abdomen for the six year old Hybrid III dummy. *Congress Proceedings of the Japanese Society of Automotive Engineers*, 2007, Yokohama, Japan.

[15] Reed MP, Ebert-Hamilton SM, Manary MA, Klinich KD, Schneider LW. Improved positioning procedures for 6YO and 10YO ATDs based on child occupant postures. *Stapp Car Crash J,* 2006, 50:337-88.

[16] Insurance Institute for Highway Safety. *Booster seat belt fit evaluation protocol (version III)*; http://www.iihs.org/iihs/ratings/technical-information/booster-protocols. Ruckersville, VA, USA. Accessed March 23, 2017.

[17] Federal Motor Vehicle Safety Standard no. 213; *Child Restraint Systems*, 49 C.F.R. § 571.213. Washington, DC, USA. Accessed March 23, 2017.

[18] Ouyang J, Zhao W, Xu Y, Chen W, Zhong S. Thoracic impact testing of pediatric cadaveric subjects. *J Trauma,* 2006, 61(6):1492-500.

[19] Reed MP, Ebert SM, Sherwood CP, Klinich KD, Manary MA. Evaluation of the static belt fit provided by belt-positioning booster seats. *Accid Anal Prev,* 2009, 41(3):598-607.

[20] DeSantis Klinich K, Pritz H, Beebe M, Welty K. Survey of older children in automotive restraints, SAE Technical Paper 942222. 1994, Society of Automotive Engineers: Warrenton, PA, USA.

[21] Reed MP, Ebert-Hamilton SM, Klinich KD, Manary MA, Rupp JD. Effects of vehicle seat and belt geometry on belt fit for children with and without belt positioning booster seats. *Accid Anal Prev*, 2013, 50:512-22.

[22] Jakobsson L, Bohman K, Stockman I, Andersson M, Osvalder A-L. Older children's sitting postures when riding in the rear seat. *Proceeding of the IRCOBI Conference*, 2011, Krakow, Poland.

[23] Klinich KD, Reed MP, Ritchie N, Manary MA, Schneider LW, Rupp JD. Assessing child belt fit, Volume II: effect of restraint configuration, booster seat designs, seating procedure, and belt fit on the dynamic response of the Hybrid III 10YO ATD in sled tests. Report no. UMTRI-2008-49-2. 2008, University of Michigan Transportation Research Institute: Ann Arbor, MI, USA.

[24] Arbogast KB, Kent RW, Menon RA, Ghati Y, Durbin DR, Rouhana SW. Mechanisms of abdominal organ injury in seat belt-restrained children. *J Trauma*, 2007, 62(6):1473-80.

[25] Adomeit D, Heger A. Motion sequence criteria and design proposals for restraint devices in order to avoid unfavorable biomechanic conditions and submarining. SAE Technical Paper 751146. 1975, Society of Automotive Engineers: Warrenton, PA, USA.

[26]Gallup BM. Abdominal injuries to restrained front seat occupants in frontal collisions. *Proc Am Assoc Automo. Med Annu Conf*, 1982, 26: 131-145.

[27]Luet C, Trosseille X, Drazétic P, Potier P, Vallancien G. Kinematics and dynamics of the pelvis in the process of submarining using PMHS sled tests. *Stapp Car Crash J,* 2012, 56:411-42.

[28]Eichelberger AH, Chouinard AO, Jermakian JS. Effects of booster seat laws on injury risk among children in crashes. *Traffic Inj Prev*, 2012, 13(6):631-9.

[29]National Highway Traffic Safety Administration. The 2015 national survey of the use of booster seats. Report no. DOT HS-812-309. 2016, U.S. Department of Transportation: Washington, DC, USA.

[30]Kent R, Stacey S, Kindig M, Forman J, Woods W, Rouhana SW, Higuchi K, Tanji H, Lawrence SS, Arbogast KB. Biomechanical response of the pediatric abdomen, part 1: development of an experimental model and quantification of structural response to dynamic belt loading. *Stapp Car Crash J,* 2006, 50:1-26.

[31]Gregory TS, Howes MK, Rouhana SW, Hardy WN. Deflection measurement system for the Hybrid III six-year-old biofidelic abdomen. *Biomed Sci Instrum,* 2012, 48:149-56.

[32]Beillas P, Alonzo F, Chevalier MC, Lesire P, Leopold F, Trosseille X, Johannsen H. Abdominal twin pressure sensors for the assessment of abdominal injuries in Q dummies: in-dummy evaluation and performance in accident reconstructions. *Stapp Car Crash J,* 2012, 56:387-410.

[33]Renaudin F, Bruneteiere Y, Pitcher M, Carroll J, Burleigh M, Waagmeester K. Improvements in Q-series dummy submarining behavior in non-integral CRS. *Proceedings of the 13th International Conference on the Protection of Children in Cars,* 2016, Munich, Germany.

[34]Visvikis C, Krebs C. The sensitivity of UN regulation no. 129 to differences in abdomen protection afforded by booster seats. *Proceedings of the 14th International Conference on the Protection of Children in Cars*, 2016, Munich, Germany.

[35]Reed MP, Ebert-Hamilton, S. Distribution of belt anchorage locations in the second row of passenger cars and light trucks. SAE Technical Paper 2013-01-1157. 2013, Society of Automotive Engineers: Warrenton, PA, USA.

[36]Hu J, Wu J, Reed MP, Klinich KD, Cao L. Rear seat restraint system optimization for older children in frontal crashes. *Traffic Inj Prev*, 2013, 14:614-622.

VIII. APPENDIX

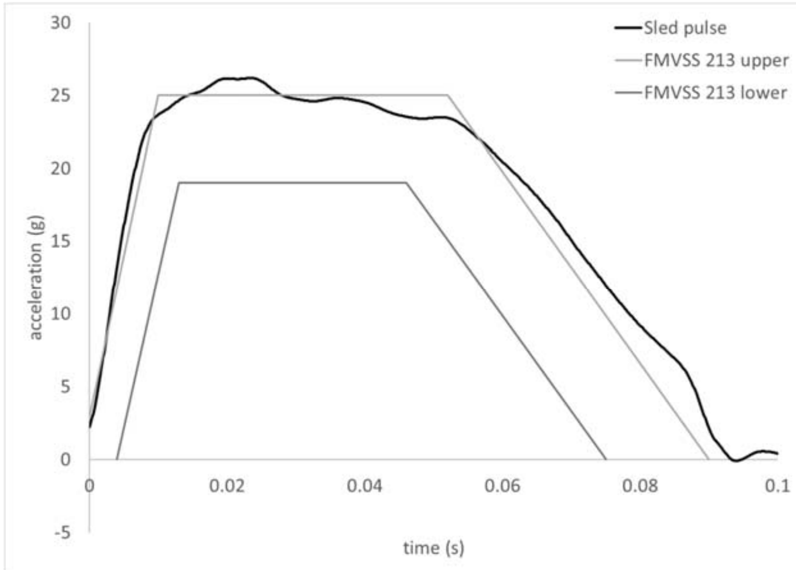


Fig. A1. Sled pulse based on the FMVSS 213 regulation pulse and scaled up to 56 km/h.

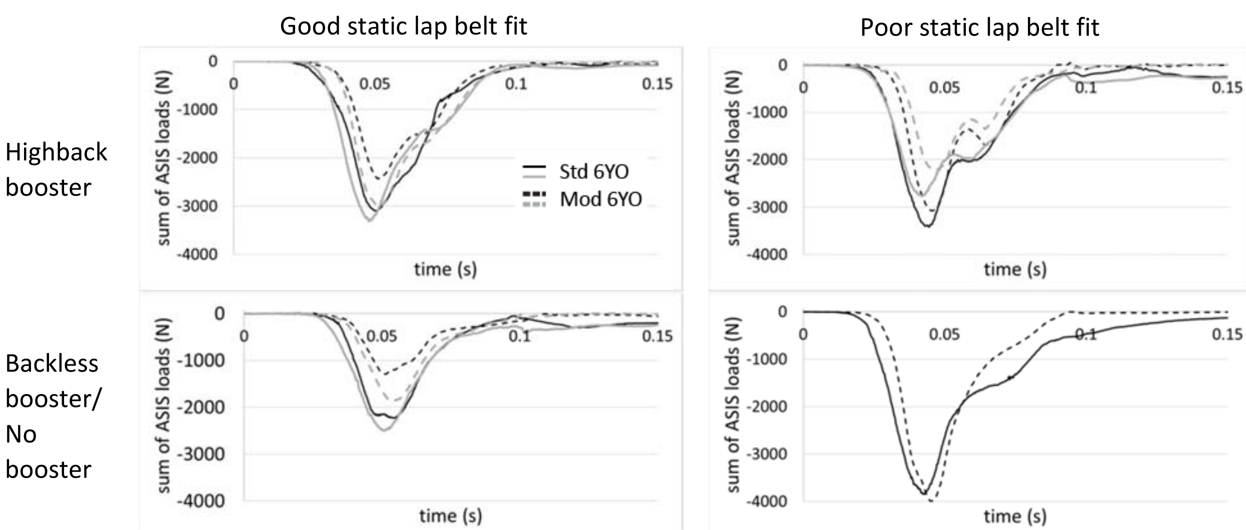


Fig. A2. Comparison of the sum of the ASIS loads for the standard 6YO (solid lines) and modified 6YO (dashed lines) in paired tests in highback, backless and no booster conditions.

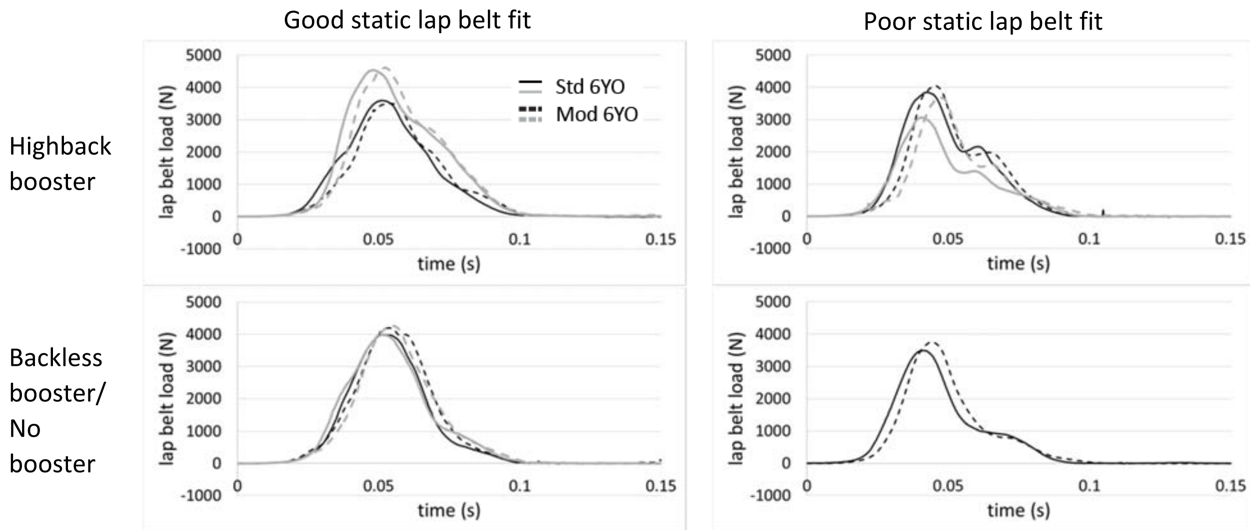


Fig. A3. Comparison of lap belt loads for the standard 6YO (solid lines) and modified 6YO (dashed lines) in paired tests in highback, backless and no booster conditions.