Analysis of Kinetic Metrics in Submarining vs Non-Submarining Conditions for a 6YO Pediatric Human Body Model in Frontal Impacts

Bethany Williams¹,², Jalaj Maheshwari²
¹Louisiana Tech University, Ruston, LA, USA
²Center for Injury Research and Prevention, Children’s Hospital of Philadelphia, Philadelphia, PA, USA

Introduction

Field data has shown that belt-positioning boosters help reduce the risk of injury to children in a crash (Arbogast et al. 2009; Benedetti et al. 2017; Pitt et al. 2021). Booster seats achieve this by providing a more appropriate belt fit around a child that cannot be achieved with a seatbelt alone (Reed et al. 2013). However, with the different designs of booster seats available in the market, this seatbelt fit may vary (Reed et al. 2009; Baker et al. 2021) – the shoulder belt may be placed further outboard or inboard of the ideal mid-clavicle position, or the lap belt may be placed further up on the abdomen or down on the thighs. Furthermore, variation in the child’s posture can change the position of the seatbelt around the child. Prior studies have assessed how these belt positions and postures may affect a child occupant’s kinematics and kinetics in a crash (Bohman et al. 2018; Maheshwari et al. 2020a, b). However, certain unfavorable kinematics, which could be a result of inappropriate belt fit due to booster design or the occupant’s seating posture, are difficult to estimate due to limitations in the tools available. One of these dangerous unfavorable kinematics is submarining.

In a crash, submarining occurs when the lap belt slides over the occupant’s pelvis and loads the abdominal soft tissue, causing serious injury. Submarining has been a prevalent issue in crashes affecting people of all ages due to many factors namely improper seating and varying occupant size (Thorbole, 2015). This phenomenon is often seen in children in improper or no child restraint systems (CRS). Prior studies have tried to evaluate submarining-like characteristics for a 6-year-old child anthropomorphic test device (ATD) in a crash by associating it to easily attainable kinematic metrics such as a combination of pelvis rotation and femur displacement (Beck et al. 2012), or torso angle and knee-head excursion (Klinich et al. 2010). Thresholds for these metrics were identified which would classify the kinematic behavior as ‘non-submarining’ or ‘submarining’. However, an assessment of these kinematic metrics using the PIPER 6YO pediatric human body model found that these metrics were not consistent in evaluating submarining for the child model (Slusher et al. 2022). The study reported that tracking the lap belt trajectory over the crash duration with respect to the anterior superior iliac spine (ASIS) was the only true assessment of submarining. Other studies using the Q6 ATD have evaluated ASIS loads and moments in
addition to video analysis to assess favorable or unfavorable kinematics, and hence submarining (Visvikis et al. 2018).

All booster seats sold in the market need to pass regulations outlined as per the safety standards in that market, such as the Federal Motor Vehicle Safety Standards (FMVSS) No. 213 in the United States and UN ECE R129 in Europe. These standards evaluate child ATD performance in crash tests by comparing them to injury thresholds identified for various body regions. However, passing regulatory thresholds may not mean the CRS is entirely safe i.e., a booster seat may pass regulatory thresholds, but could result in detrimental kinematics at the same time. Furthermore, pediatric ATDs are less sophisticated than adult ATDs and do not accurately reflect the unique pediatric anatomy, particularly in the pelvis (Hu et al., 2012). In general, most ATDs lack the proper spine flexibility to fully portray the kinematics of the occupant (Hu et al., 2012). In the case of submarining, it is important to translate the findings from human body models, where submarining can be definitively determined using the lap belt trajectory over the ASIS, to ATDs which are ultimately used in standard sled and vehicle crash testing. This study builds on the prior submarining work (Slusher et al. 2022) and aims to analyze kinetic metrics (which can be easily recorded from ATDs in crash tests) in submarining and non-submarining conditions for a 6YO pediatric human occupant in frontal crashes.

**Methods**

For this finite element (FE) study, a 2012 model year mid-size sedan FE model was used as the vehicle environment. The PIPER 6YO pediatric human body FE model (Beillas et al. 2016) was restrained in three different child restraint systems: low back booster (LBB), high back booster (HBB), and no CRS in the left outboard rear seat using a 3-point lap-shoulder belt with a retractor, shoulder belt pretensioner, and 4kN load-limiter. The CRS models were developed from digitization techniques (Belwadi et al., 2015), modeled as rigid polypropylene plastic, and previously used in frontal crashes (Maheshwari et al. 2020a, b; Slusher et al. 2022).

Five seating postures, as previously explored in full-frontal and small offset frontal impacts (Maheshwari et al. 2020a, b; Slusher et al. 2022), were simulated. These included a reference seating posture as per testing standards and four naturalistic seating postures: forward leaning, inboard leaning, outboard leaning, and pre-submarining. The no CRS condition was simulated with only two seating postures: reference and pre-submarining.

Currently, the PIPER pediatric human body model does not include load outputs from the ASIS. To evaluate the ASIS forces and moments, load cells were modeled in the PIPER 6YO’s pelvis. To do this, the left and right ASIS load cells from a Q6 ATD were superimposed on the PIPER’s pelvis. Cross-sections and local coordinate systems in the left and right ilium were defined as per the orientation of the Q6 ATD load cells. The entire environment, which included the vehicle,
booster seat and vehicle restraints, and the human body model, were then subjected to a full-frontal impact at 56 KPH (35 MPH). All conditions were simulated in LS-DYNA R12.0.0 (ANSYS, PA).

Data from the simulations was extracted using Python scripts. Metrics extracted included lap belt trajectory, abdominal pressure, lap and shoulder belt forces, ASIS forces and moments, and spine forces and moments at C6-C7, T6-T7, and T12-L1 levels of the spine. All data was processed and plotted in MATLAB (Mathworks, CA) and was filtered using SAE J211 conventions (SAE, 2007). Previous work analyzing lap belt trajectory has shown that only the no CRS pre-submarining posture exhibits submarining (Slusher et al., 2022). This simulation case was compared to all other simulated cases to identify variations in kinetic metrics for submarining and non-submarining cases.

**Results**

For this study, it is important to understand and relate all results back to abdominal pressure. The results for each metric analyzed have been evaluated as follows:

**Abdominal Pressure**

Submarining is defined as the lap belt sliding over the ASIS loading the abdomen, in which case, high abdominal pressure is to be expected. The data from the simulations showed that the no CRS pre-submarining case, where the occupant submarined, experienced the largest abdominal pressure. The maximum abdominal pressure values for each simulation are presented in Figure 2. Only the no CRS pre-submarining simulation experienced abdominal pressure of 113 kPa, which exceeded the abdominal pressure injury threshold used in previous literature (Visvikis et al. 2018).

![Figure 2: Maximum abdominal pressures experienced in each simulation.](image-url)
Figure 3 shows the abdominal pressure across the complete simulation. The submarining condition has one large peak that drops off suddenly as the lap belt slides across the abdomen. The non-submarining conditions have two distinct abdominal pressure peaks as the occupant moves throughout the crash. These trends can be seen in Figures 3a, 3b, and 3c in the no CRS reference seating posture and the HBB and LBB conditions.

![Abdominal pressures for the (a) no CRS, (b) LBB, and (c) HBB conditions](image)

**Figure 3: Abdominal pressures for the (a) no CRS, (b) LBB, and (c) HBB conditions**

**Lap and Shoulder Belt Forces**

For the no CRS presubmarining condition (Figure 4a), lap belt force increased as the occupant reached maximum excursion, rose sharply, and then fell steeply as the occupant slid under the belt. At this point, the lap belt stopped loading the abdomen and started loading the chest. For the non-submarining conditions, such as the reference LBB and HBB conditions (Figures 4b and 4c), lap belt force followed the abdominal pressure - increased as the occupant moved forward, and then
decreased. The no CRS pre-submarining simulation reached a maximum lap belt force of around 11 kN, nearly twice as large as any other condition. Shoulder belt forces showed no unique trends for submarining and non-submarining conditions because a load-limiter was used.

Figure 4: Lap and shoulder belt forces for the (a) pre-submarining posture in no CRS, (b) reference posture on LBB, and (c) reference posture on HBB

ASIS Forces
The left and right ASIS resultant forces were substantially higher (Left ASIS: 64.95 N; Right ASIS: 170.08 N) for the no CRS presubmarining condition where the occupant submarined, compared to the non-submarining cases (Left ASIS: 16.95-52.14 N; Right ASIS: 22.17-71.70 N). Compared to the left ASIS force, the right ASIS resultant force was generally greater for all simulated conditions. Resultant ASIS forces are included in Figure 5.
Looking component-wise, the right x-ASIS force, which represents the compressive-tensile force on the ASIS, was greatest for the submarining condition. This peak was prominent, presenting itself just after the abdominal pressure reached its peak. The ASIS x-force for the no CRS pre-submarining condition is presented in Figure 6a. The no CRS pre-submarining condition reached a maximum right ASIS x-force of 105 N, the largest peak of any condition. The other simulations showed ASIS forces that stayed relatively constant around zero. This trend can be seen in the LBB reference seating posture in Figure 6b and in the HBB reference seating posture in Figure 6c. y-ASIS and z-ASIS forces had similar trends.
Figure 6: ASIS x-forces for the (a) pre-submarining posture in no CRS, (b) reference posture on LBB, and (c) reference posture on HBB

**Spine Forces**

The z-direction spine forces show the most distinct trends across the different levels of the spine. These represent the compressive-tensile forces on the occupant. In the no CRS pre-submarining condition (shown in Figure 7a), the thoracic and lumbar spine exhibit compression while the cervical spine undergoes only tension. These peak values all occur after the peak abdominal pressure with the thoracic and cervical forces experiencing much larger peaks. The T6-T7 region of the spine reaches a peak of 3 kN, over 3 times greater than peaks found in any other posture or condition. Conversely, the C6-C7 region of the spine reaches a peak compressive force of 2.1 kN in the negative z-direction, the largest peak value of all postures.

In the non-submarining conditions (Figures 7b and 7c), the thoracic and lumbar spine go into tension and compression as the neck and head move throughout the crash. The lower neck
undergoes slight tension and then compression. In general, the spine forces in the submarining condition have less fluctuation but are larger than the other conditions simulated.

All other data showed no trends and are therefore excluded.

**Discussion**

The data analyzed must be observed not only from the peak values but also across the whole time series of the crash. It is important to understand how the movement of the occupant affects the forces and moments experienced throughout the crash. It is observed from the simulation videos that as the occupant slides forward, the abdominal pressure increases then drops off suddenly as
the belt slides over the child occupant’s pelvis. The peak pressure value derived from this is consistent with data from prior literature that the occupant(s) with the highest abdominal pressure is experiencing submarining (Visvikis et al., 2018).

High lap belt forces seem to be a good indicator for submarining. Previous studies on adult post-mortem human subjects (PMHS) have also shown that higher lap belt loads are associated with the presence of submarining (Uriot et al., 2015). It would be suggested to observe the resultant pressure across different positions in the lap belt to help determine if the phenomenon is present in a crash. The data from these simulations show that the highest lap belt force was not experienced when the belt was loading the abdomen, but when it slid over the pelvis and started loading the ribs. Because the lap belt would not typically load the ribs during a crash, a large lap belt force experienced just after the abdominal pressure peak could be indicative of submarining.

Higher right ASIS forces compared to left ASIS forces could be attributed to the presence of the buckle on that side. The presence of the buckle causes both the shoulder and lap belts to engage with the occupant on the right side, thereby resulting in higher forces. Higher resultant and X-ASIS forces were uniquely found in the submarining case. This result is contrary to those reported in previous literature. Studies performed in ATDs have observed that the ASIS x-direction forces are actually much lower for the submarining cases than the non-submarining cases (Renner & Sharma, 2019). This inconsistency could be attributed to the biofidelity of the human body models and ATDs, and also the degree of submarining observed in our simulations.

The key trend present in the submarining condition in the spine is large peaks in the z-direction forces, specifically for the thoracic and lumbar spine. Prior literature from studies performed on ATDs has disagreed on whether lumbar spine forces increase or decrease with the presence of submarining (Rawska et al., 2019; Renner & Sharma, 2019). These differences are present due to the low biofidelity of ATD spines and varying test conditions.

In reviewing the simulations, it was found that the occupant’s lower extremities interacted with the front seat in the no CRS presubmarining condition. To assess if this had any effect on the kinematic and kinetic trends observed for submarining conditions, the front seat was removed and the conditions was simulated again. Removing the front seat had no effect on the trends observed for the different metrics.

A limitation of this study is the lack of comparison in trends across multiple submarining conditions due to only one simulation showing submarining. Multiple submarining and non-submarining conditions need to be simulated to identify consistent patterns and variations in kinematic and kinetic metrics to tie them to submarining. This study was focused on only one seating environment. Differences in the vehicle seat geometry, CRS design, and occupant
placement could result in differing kinematic and kinetic measures altering the presence of submarining across simulations.

**Conclusion**

These simulations provide useful data that could be translated into metrics for ATDs in physical crash tests as a way to more quantitatively determine the presence of submarining. Increased abdominal pressure, high lap belt force that rises as the belt moves upward past the abdomen, and large right ASIS compressive-tensile force are the best indicators that an occupant may be experiencing submarining according to the results of our study. Properly mapped lap belt trajectory in relation to the ASIS is still the gold standard for assessing submarining, which is difficult to assess for ATDs. Because only one simulation run showed submarining, it is essential that additional conditions of occupants in different positions that undergo submarining be simulated to verify the results found.
References


Appendix

*Lap and Shoulder Belt Forces*

Figure A-#: Lap and shoulder belt forces for the no-CRS reference seating posture.

Figure A-#: Lap and shoulder belt forces for the HBB forward leaning posture.

Figure A-#: Lap and shoulder belt forces for the HBB inboard leaning posture.
Figure A-1: Lap and shoulder belt forces for the HBB outboard leaning posture.

Figure A-2: Lap and shoulder belt forces for the HBB pre-submarining posture.

Figure A-3: Lap and shoulder belt forces for the LBB forward leaning posture.
Figure A-4: Lap and shoulder belt forces for the LBB inboard leaning posture.

Figure A-5: Lap and shoulder belt forces for the LBB outboard leaning posture.

Figure A-6: Lap and shoulder belt forces for the LBB pre-submarining posture.
**ASIS Forces**

Figure A-7: ASIS Y-forces for the no-CRS pre-submarining posture.

Figure A-8: ASIS Z-forces for the no-CRS pre-submarining posture.

Figure A-9: ASIS resultant forces for the no-CRS pre-submarining posture.
Figure A-10: ASIS X-forces for the no-CRS reference seating posture.

Figure A-11: ASIS Y-forces for the no-CRS reference seating posture.

Figure A-12: ASIS Z-forces for the no-CRS reference seating posture.
Figure A-13: ASIS resultant forces for the no-CRS reference seating posture.

Figure A-14: ASIS X-forces for the HBB forward leaning posture.

Figure A-15: ASIS Y-forces for the HBB forward leaning posture.
Figure A-16: ASIS Z-forces for the HBB forward leaning posture.

Figure A-17: ASIS resultant forces for the HBB forward leaning posture.

Figure A-18: ASIS X-forces for the HBB inboard leaning posture.
Figure A-19: ASIS Y-forces for the HBB inboard leaning posture.

Figure A-20: ASIS Z-forces for the HBB inboard leaning posture.

Figure A-21: ASIS resultant forces for the HBB inboard leaning posture.
Figure A-22: ASIS X-forces for the HBB outboard leaning posture.

Figure A-23: ASIS Y-forces for the HBB outboard leaning posture.

Figure A-24: ASIS Z-forces for the HBB outboard leaning posture.
Figure A-25: ASIS resultant forces for the HBB outboard leaning posture.

Figure A-26: ASIS X-forces for the HBB pre-submarining posture.

Figure A-27: ASIS Y-forces for the HBB pre-submarining posture.
Figure A-28: ASIS Z-forces for the HBB pre-submarining posture.

Figure A-29: ASIS resultant forces for the HBB pre-submarining posture.

Figure A-30: ASIS Y-forces for the HBB reference seating posture.
Figure A-31: ASIS Z-forces for the HBB reference seating posture.

Figure A-32: ASIS resultant forces for the HBB reference seating posture.

Figure A-33: ASIS X-forces for the LBB forward leaning posture.
Figure A-34: ASIS Y-forces for the LBB forward leaning posture.

Figure A-35: ASIS Z-forces for the LBB forward leaning posture.

Figure A-36: ASIS resultant forces for the LBB forward leaning posture.
Figure A-37: ASIS X-forces for the LBB inboard leaning posture.

Figure A-38: ASIS Y-forces for the LBB inboard leaning posture.

Figure A-39: ASIS Z-forces for the LBB inboard leaning posture.
Figure A-40: ASIS resultant forces for the LBB inboard leaning posture.

Figure A-41: ASIS X-forces for the LBB outboard leaning posture.

Figure A-42: ASIS Y-forces for the LBB outboard leaning posture.
Figure A-43: ASIS Z-forces for the LBB outboard leaning posture.

Figure A-44: ASIS resultant forces for the LBB outboard leaning posture.

Figure A-45: ASIS X-forces for the LBB pre-submarining posture.
Figure A-46: ASIS Y-forces for the LBB pre-submarining posture.

Figure A-47: ASIS Z-forces for the LBB pre-submarining posture.

Figure A-48: ASIS resultant forces for the LBB pre-submarining posture.
Figure A-49: ASIS Y-forces for the LBB reference seating posture.

Figure A-50: ASIS Z-forces for the LBB reference seating posture.

Figure A-51: ASIS resultant forces for the LBB reference seating posture.
ASIS Moments

Figure A-52: ASIS X-moments for the no-CRS pre-submarining posture.

Figure A-53: ASIS Y-moments for the no-CRS pre-submarining posture.

Figure A-54: ASIS Z-moments for the no-CRS pre-submarining posture.
Figure A-55: ASIS resultant moments for the no-CRS pre-submarining posture.

Figure A-56: ASIS X-moments for the no-CRS reference seating posture.

Figure A-57: ASIS Y-moments for the no-CRS reference seating posture.
Figure A-58: ASIS Z-moments for the no-CRS reference seating posture.

Figure A-59: ASIS resultant moments for the no-CRS reference seating posture.

Figure A-60: ASIS X-moments for the HBB forward leaning posture.
Figure A-61: ASIS Y-moments for the HBB forward leaning posture.

Figure A-62: ASIS Z-moments for the HBB forward leaning posture.

Figure A-63: ASIS resultant moments for the HBB forward leaning posture.
Figure A-64: ASIS X-moments for the HBB inboard leaning posture.

Figure A-65: ASIS Y-moments for the HBB inboard leaning posture.

Figure A-66: ASIS Z-moments for the HBB inboard leaning posture.
Figure A-67: ASIS resultant moments for the HBB inboard leaning posture.

Figure A-68: ASIS X-moments for the HBB outboard leaning posture.

Figure A-69: ASIS Y-moments for the HBB outboard leaning posture.
Figure A-70: ASIS Z-moments for the HBB outboard leaning posture.

Figure A-71: ASIS resultant moments for the HBB outboard leaning posture.

Figure A-72: ASIS X-moments for the HBB pre-submarining posture.
Figure A-73: ASIS Y-moments for the HBB pre-submarining posture.

Figure A-74: ASIS Z-moments for the HBB pre-submarining posture.

Figure A-75: ASIS resultant moments for the HBB pre-submarining posture.
Figure A-76: ASIS X-moments for the HBB reference seating posture.

Figure A-77: ASIS Y-moments for the HBB reference seating posture.

Figure A-78: ASIS Z-moments for the HBB reference seating posture.
Figure A-79: ASIS resultant moments for the HBB reference seating posture.

Figure A-80: ASIS X-moments for the LBB forward leaning posture.

Figure A-81: ASIS Y-moments for the LBB forward leaning posture.
Figure A-82: ASIS Z-moments for the LBB forward leaning posture.

Figure A-83: ASIS resultant moments for the LBB forward leaning posture.

Figure A-84: ASIS X-moments for the LBB inboard leaning posture.
Figure A-85: ASIS Y-moments for the LBB inboard leaning posture.

Figure A-86: ASIS Z-moments for the LBB inboard leaning posture.

Figure A-87: ASIS resultant moments for the LBB inboard leaning posture.
Figure A-88: ASIS X-moments for the LBB outboard leaning posture.

Figure A-89: ASIS Y-moments for the LBB outboard leaning posture.

Figure A-90: ASIS Z-moments for the LBB outboard leaning posture.
Figure A-91: ASIS resultant moments for the LBB outboard leaning posture.

Figure A-92: ASIS X-moments for the LBB pre-submarining posture.

Figure A-93: ASIS Y-moments for the LBB pre-submarining posture.
Figure A-94: ASIS Z-moments for the LBB pre-submarining posture.

Figure A-95: ASIS resultant moments for the LBB pre-submarining posture.

Figure A-96: ASIS X-moments for the LBB reference seating posture.
Figure A-97: ASIS Y-moments for the LBB reference seating posture.

Figure A-98: ASIS Z-moments for the LBB reference seating posture.

Figure A-99: ASIS resultant moments for the LBB reference seating posture.
Spine Forces

Figure A-100: X-direction spine forces for the no CRS pre-submarining posture.

Figure A-101: Y-direction spine forces for the no CRS pre-submarining posture.

Figure A-102: Resultant spine forces for the no CRS pre-submarining posture.
Figure A-103: X-direction spine forces for the no CRS reference seating posture.

Figure A-104: Y-direction spine forces for the no CRS reference seating posture.

Figure A-105: Z-direction spine forces for the no CRS reference seating posture.
Figure A-106: Resultant spine forces for the no CRS reference seating posture.

Figure A-107: X-direction spine forces for the HBB forward leaning posture.

Figure A-108: Y-direction spine forces for the HBB forward leaning posture.
Figure A-109: Z-direction spine forces for the HBB forward leaning posture.

Figure A-110: Resultant spine forces for the HBB forward leaning posture.

Figure A-111: X-direction spine forces for the HBB inboard leaning posture.
Figure A-112: Y-direction spine forces for the HBB inboard leaning posture.

Figure A-113: Z-direction spine forces for the HBB inboard leaning posture.

Figure A-114: Resultant spine forces for the HBB inboard leaning posture.
Figure A-115: X-direction spine forces for the HBB outboard leaning posture.

Figure A-116: Y-direction spine forces for the HBB outboard leaning posture.

Figure A-117: Z-direction spine forces for the HBB outboard leaning posture.
Figure A-118: Resultant spine forces for the HBB outboard leaning posture.

Figure A-119: X-direction spine forces for the HBB pre-submarining posture.

Figure A-120: Y-direction spine forces for the HBB pre-submarining posture.
Figure A-121: Z-direction spine forces for the HBB pre-submarining posture.

Figure A-122: Resultant spine forces for the HBB pre-submarining posture.

Figure A-123: X-direction spine forces for the HBB reference seating posture.
Figure A-124: Y-direction spine forces for the HBB reference seating posture.

Figure A-125: Resultant spine forces for the HBB reference seating posture.

Figure A-126: X-direction spine forces for the LBB forward leaning posture.
Figure A-127: Y-direction spine forces for the LBB forward leaning posture.

Figure A-128: Z-direction spine forces for the LBB forward leaning posture.

Figure A-129: Resultant spine forces for the LBB forward leaning posture.
Figure A-130: X-direction spine forces for the LBB inboard leaning posture.

Figure A-131: Y-direction spine forces for the LBB inboard leaning posture.

Figure A-132: Z-direction spine forces for the LBB inboard leaning posture.
Figure A-133: Resultant spine forces for the LBB inboard leaning posture.

Figure A-134: X-direction spine forces for the LBB outboard leaning posture.

Figure A-135: Y-direction spine forces for the LBB outboard leaning posture.
Figure A-136: Z-direction spine forces for the LBB outboard leaning posture.

Figure A-137: Resultant spine forces for the LBB outboard leaning posture.

Figure A-138: X-direction spine forces for the LBB pre-submarining posture.
Figure A-139: Y-direction spine forces for the LBB pre-submarining posture.

Figure A-140: Z-direction spine forces for the LBB pre-submarining posture.

Figure A-141: Resultant spine forces for the LBB pre-submarining posture.
Figure A-142: X-direction spine forces for the LBB reference seating posture.

Figure A-143: Y-direction spine forces for the LBB reference seating posture.

Figure A-144: Resultant spine forces for the LBB reference seating posture.
Spine Moments

Figure A-145: X-direction spine moments for the no CRS reference seating posture.

Figure A-146: Y-direction spine moments for the no CRS reference seating posture.

Figure A-147: Z-direction spine moments for the no CRS reference seating posture.
Figure A-148: Resultant spine moments for the no CRS reference seating posture.

Figure A-149: X-direction spine moments for the no CRS pre-submarining posture.

Figure A-150: Y-direction spine moments for the no CRS pre-submarining posture.
Figure A-151: Z-direction spine moments for the no CRS pre-submarining posture.

Figure A-152: Resultant spine moments for the no CRS pre-submarining posture.

Figure A-153: X-direction spine moments for the HBB forward leaning posture.
Figure A-154: Y-direction spine moments for the HBB forward leaning posture.

Figure A-155: Z-direction spine moments for the HBB forward leaning posture.

Figure A-156: Resultant spine moments for the HBB forward leaning posture.
Figure A-157: X-direction spine moments for the HBB inboard leaning posture.

Figure A-158: Y-direction spine moments for the HBB inboard leaning posture.

Figure A-159: Z-direction spine moments for the HBB inboard leaning posture.
Figure A-160: Resultant spine moments for the HBB inboard leaning posture.

Figure A-161: X-direction spine moments for the HBB outboard leaning posture.

Figure A-162: Y-direction spine moments for the HBB outboard leaning posture.
Figure A-163: Z-direction spine moments for the HBB outboard leaning posture.

Figure A-164: Resultant spine moments for the HBB outboard leaning posture.

Figure A-165: X-direction spine moments for the HBB pre-submarining posture.
Figure A-166: Y-direction spine moments for the HBB pre-submarining posture.

Figure A-167: Z-direction spine moments for the HBB pre-submarining posture.

Figure A-168: Resultant spine moments for the HBB pre-submarining posture.
Figure A-169: X-direction spine moments for the HBB reference seating posture.

Figure A-170: Y-direction spine moments for the HBB reference seating posture.

Figure A-171: Z-direction spine moments for the HBB reference seating posture.
Figure A-172: Resultant spine moments for the HBB reference seating posture.

Figure A-173: X-direction spine moments for the LBB forward leaning posture.

Figure A-174: Y-direction spine moments for the LBB forward leaning posture.
Figure A-175: Z-direction spine moments for the LBB forward leaning posture.

Figure A-176: Resultant spine moments for the LBB forward leaning posture.

Figure A-177: X-direction spine moments for the LBB inboard leaning posture.
Figure A-178: Y-direction spine moments for the LBB inboard leaning posture.

Figure A-179: Z-direction spine moments for the LBB inboard leaning posture.

Figure A-180: Resultant spine moments for the LBB inboard leaning posture.
Figure A-181: X-direction spine moments for the LBB outboard leaning posture.

Figure A-182: Y-direction spine moments for the LBB outboard leaning posture.

Figure A-183: Z-direction spine moments for the LBB outboard leaning posture.
Figure A-184: Resultant spine moments for the LBB outboard leaning posture.

Figure A-185: X-direction spine moments for the LBB pre-submarining posture.

Figure A-186: Y-direction spine moments for the LBB pre-submarining posture.
Figure A-187: Z-direction spine moments for the LBB pre-submarining posture.

Figure A-188: Resultant spine moments for the LBB pre-submarining posture.

Figure A-189: X-direction spine moments for the LBB reference seating posture.
Figure A-190: Y-direction spine moments for the LBB reference seating posture.

Figure A-191: Z-direction spine moments for the LBB reference seating posture.

Figure A-192: Resultant spine moments for the LBB reference seating posture.