Biofidelity Assessment of the 6-Year-Old ATDs in Side Impact

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ABSTRACT

The objective of this study was to assess and compare the current lateral impact biofidelity of the shoulder, thorax, abdomen, and pelvis of the Q6, Q6s, and HIII 6-year-old anthropometric test dummies (ATDs) through lateral impact testing.

A series of lateral impact pendulum tests, vertical drop tests, and Wayne State University (WSU) sled tests, based on the procedures detailed in ISO/TR 9790 (ISO/TR 9790, 1999) and scaling based on known research of 50th -percentile male testing to the 6-year-old using Irwin et al. (2002). The data collected from the three different ATDs was filtered using SAE J211 (SAE J211-1, 2003), aligned using the methodology described in Donnelly and Moorhouse (2012), and compared for each body region tested (shoulder, thorax, abdomen, and pelvis). In addition, the biofidelity performance for the three ATDs in lateral impact was assessed against the scaled biofidelity targets published in Irwin et al. (2002), as well as the abdominal biofidelity target assessment published in van Rantingen et al. (1997).

Preliminary results showed that the Q6s performed more closely to the outlined biofidelity targets than the Q6 or the HIII 6-year-old at all tested body regions. Even though the Q6s showed improved lateral impact performance, it did not meet all biofidelity targets. Future research is to be performed to evaluate the validity of the current 6-year-old lateral impact biofidelity targets based on the lateral impact testing biofidelity assessment of surrogates of appropriate size and weight.

INTRODUCTION

In the United States during 2012, an average of 3 occupants 14 and younger were killed and 462 injured every day in motor vehicle crashes (National Highway Traffic Safety Administration [NHTSA] 2012). Due to the high injury and fatality rates observed in the pediatric population, research in child side impact protection has become of interest in the recent past (Arbogast, 2001).

In 2003, Orechowski et al. analyzed data for restrained children ages 0 to 14 years old who were admitted to a Level I pediatric trauma center due to crash injuries from 1991 to 2002 through the National Highway Traffic Safety Administration (NHTSA) sponsored Crash Injury Research and Engineering Network (CIREN). Based on this study, they concluded that side impact crashes compared to frontal crashes produce 2.5 times greater risk of an AIS 2+ head injury, 3.7 times greater risk of AIS 2+ cervical spine injury, and 4.0 times greater risk of AIS 2+ thoracic injury to children 0 to 14 years of age (Orechowski, 2003).

Howard et al., through their trauma-based collision study in 2004, determined that near-side child occupants were the most severely injured with principal injuries occurring at the head, brain, and neck, typically accompanied by thoracic, abdominal, pelvic girdle, and limb injuries. The primary mechanism of injury was determined to be contact with the vehicle interior, which could occur with or without significant intrusion (Howard, 2004).

In 2008, Viano et al. analyzed field accident data for 0- to 7-year-old 2nd row restrained and unrestrained occupants in the FARS and NASS-CDS database covering years 1991 to 2005 for fatality risk based on seating position and PDOF. It was determined that 30.9% of serious to fatal child 2nd row injuries (MAIS 3+F) were caused by side impact (Viano, 2008).

The results above indicated the need for assessment and development of child side impact dummies. The purpose of the current study is to provide the existing design and biofidelity performance of the 6-year-old anthropometric test dummies (HIII, Q6, and Q6s) shoulder, thorax, abdomen, and pelvis in side impact.

METHODS

A series of lateral impact pendulum tests, vertical drop tests, and WSU 6.8 m/s rigid sled tests, was performed using the 6-year-old ATDs; the protocols for which were based on the procedures detailed in ISO/TR 9790 (ISO/TR9790, 1999) and scaling based on known research of 50th -percentile male testing to the 6-year-old using Irwin et al. (2002). The three ATDs tested were instrumented based on SAE J211-1 standard guidelines (SAE J211-1, 2003), with tri-axial accelerometer mount blocks at head CG, T1 spine, T12 spine, rib (at rib 3-4 location), and lumbar spine locations. The lateral impact direction of the tri-axial accelerometer mount blocks were equipped with Endevco 7264-2000TZ (2000 g) piezoresistive accelerometers and the longitudinal and vertical directions of the tri-axial accelerometer mount blocks were equipped with Measurement Specialties 64C-0200-360T (200 g) piezoresistive accelerometers. T1, T12, and lumbar spine tri-axial accelerometer mount blocks were attached to the posterior side of the dummies' spine box for consistent accelerometer readings among the ATDs at these locations. An IRTRACC linear transducer (Humanetics, Plymouth, MI) was installed laterally in each of the dummies' rib cage, corresponding to a left side impact at the rib3-4 location, to record rib deflection relative to the spine. Six channel load cell force and moment sensors (Humanetics) were installed and data was documented at the upper neck, lower neck, and pelvis in the Q6 and Q6s ATD and at the upper neck in the HIII ATD. All sensors were connected to a TDAS data acquisition system, and data was collected at a sampling rate of 10,000 Hz. The impact events were captured at 2,000 frames per second by a high-speed video camera. The data collected from the three different ATDs was filtered using the SAE J211 standard (SAE J211-1, 2003), aligned using the methodology described in Donnelly and Moorhouse (2012), and compared for each body region tested (shoulder, thorax, abdomen, and pelvis). In addition, the biofidelity performance for the three ATDs in lateral impact was assessed against the scaled biofidelity targets published in Irwin et al. (2002) and abdominal biofidelity target suggested in van Rantingen et al. (1997). Three replicate runs were performed for each of the tests.

Pendulum Tests

A flat-faced, rigid, aluminum pendulum probe was fabricated for use in the shoulder, thorax, and abdomen lateral impact pendulum tests with a 3.5-inch diameter impacting surface and a 0.5-inch edge radius. The pendulum impacting face diameter was based on the 3.5 inch pendulum probe used in Q6 lateral calibration testing (Q6 User Manual, 2012). Pendulum impact force data was collected through a uniaxial accelerometer mounted on the rear of the pendulum mass. Total pendulum mass was 2.9 kg, which is based on the target pendulum weight specified in Irwin et al. (2002).

A flat-faced, rigid, aluminum pendulum probe for use in the pelvis lateral impact pendulum tests was fabricated with a 3.0-inch diameter impacting surface and a 0.5-inch edge radius. The pendulum impacting face diameter was based on similar scaling of the 50^{th} -percentile male dummy pelvis probe to the Q3s probe used in Carlson et al. (2007) to scale from the 50^{th} -percentile male dummy pelvis probe to the 6-year-old. Pelvis pendulum impact force data was collected through a uniaxial accelerometer mounted on the rear of the pendulum mass. Total pelvis pendulum mass was 3.89 kg, which is based on the target pelvis pendulum weight specified in Irwin et al. (2002).

In all pendulum tests, the ATDs were seated on two sheets of 0.125-inch thick mechanical grade Teflon, and the ATDs were impacted on their left side. An optical sensor speed trap was used in all pendulum tests to verify pendulum speed just prior to impact.

Vertical Drop Tests

A vertical drop fixture which allowed the ATD to drop freely was fabricated using a flat metal frame structure, chains, and a two-stage “quick release” device which utilized a stage 1 - manual “quick release” and stage 2 - hybrid electromagnets (Kanetec USA Corp., Bensenville, IL). Two separate rigid loading surfaces and a wooden armrest loading surface were fabricated as specified in ISO 9790 Abdomen Impact Response Requirement 1 (ISO/TR9790, 1999) for interception of the dummy torso, pelvis, and abdomen, respectively. Ten 1,000-pound load cells (Transducer Techniques, Temecula, CA) were used to acquire dummy impact force loads (four mounted under each torso and pelvis load plate and 2 mounted under the wooden armrest). The ATD was positioned based on ISO 9790 specifications (ISO/TR9790, 1999). Drop distances from the ATD to the impact surface were 1-meter and 0.5-meters, respectively. The wooden armrest was removed for the 0.5-meter drop test per ISO 9790 test requirements. Figure 1 illustrates the vertical drop test fixture and pre-test setup.

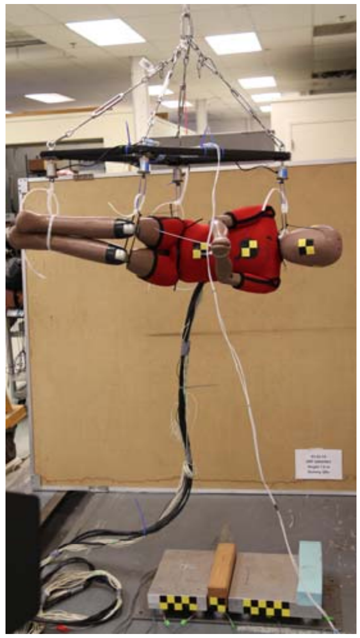

Figure 1: Vertical Drop Fixture Pre-test Setup – 1-Meter Drop Test.

WSU 6.8 m/s Rigid Sled Test

A bench and impact wall based on the WSU design documented in Cavanaugh et al. (1990a) were scaled from the 50th -percentile male anthropometry sled setup to a size appropriate for the 6-year-old. Five impact beams were used and locations scaled to target shoulder, thorax, abdomen and pelvis (iliac crest and greater trochanter region) impact during lateral impact. The bench and wall were fixed on the WSU HyGe sled. Two 1,000-pound load cells were installed on the back of the impacted side of each of the five impact beams to acquire lateral impact force data from each of the ATDs previously specified body regions during impact. The ATD was seated at a distance to achieve an impact speed of 6.8 m/s relative to the rigid wall.

Data Post Processing

Pendulum impact force, load cell data, and ATD lateral acceleration, force, and, moment data were analyzed for the current research. Sensor data were filtered according to the SAE J211-1 standard (SAE J211-1, 2003) except for the thorax and abdomen pendulum mass accelerometers which were filtered using the FIR 100 filters. Replicate runs for each of the tests were aligned using the methodology described in Donnelly and Moorhouse (2012). In order to assess the repeatability of the dummy test parameter responses in each of the tests performed, a single value peak response Percent Coefficient of Variation (%CV), as defined in Moorhouse et al. (2013), was calculated for each of the aligned test data sets for each of the dummies. Sensor data for each body region (shoulder, thorax, abdomen, and pelvis) were compared among the three ATDs. In addition, the biofidelity performance for the three ATDs in lateral impact was assessed against the scaled biofidelity targets published in Irwin et al. (2002), as well as the abdominal biofidelity target assessment published in van Rantingen et al. (1997).

RESULTS

Shoulder, thorax, abdomen, and pelvis data for the three dummies tested were compared to the response requirements described in the ISO/TR9790 standard (ISO/TR9790, 1999) as scaled to the 6-year-old in (Irwin, 2002). Pendulum impact abdominal data was compared for the three tested ATDs to the response corridor suggested in van Rantingen et al. (1997).

Shoulder Impact Tests

Figure 2 provides the results of the ISO 9790 Shoulder Pendulum Test Requirement 1. Mean peak force values for the HIII, Q6, and Q6s dummies are 4.10 kN, 1.71 kN, and 1.68 kN, respectively. The upper boundary corridor peak is 0.8 kN (Irwin, 2002).

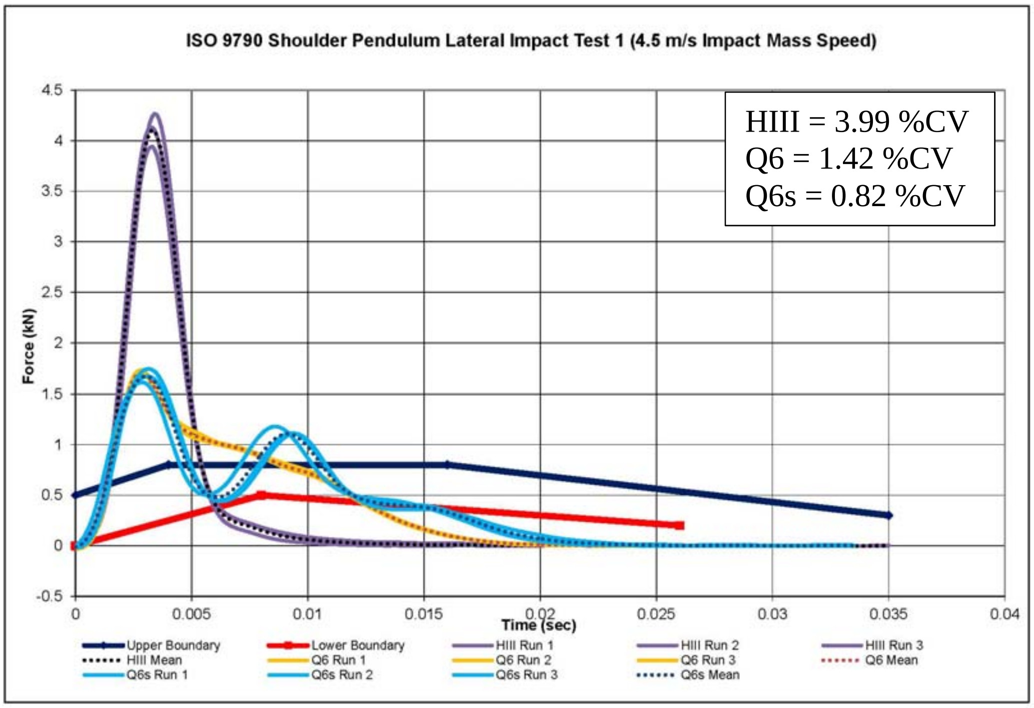

Figure 2: Shoulder Pendulum Lateral Impact Test 1 Response Requirements Comparison.

Figure 3 shows the results of the ISO 9790 WSU 6.8 m/s Rigid Sled Impact Response Test at the shoulder impact beam. Mean peak shoulder impact force values for the HIII, Q6, and Q6s dummies are 12.38 kN, 2.27 kN, and 3.21 kN, respectively.

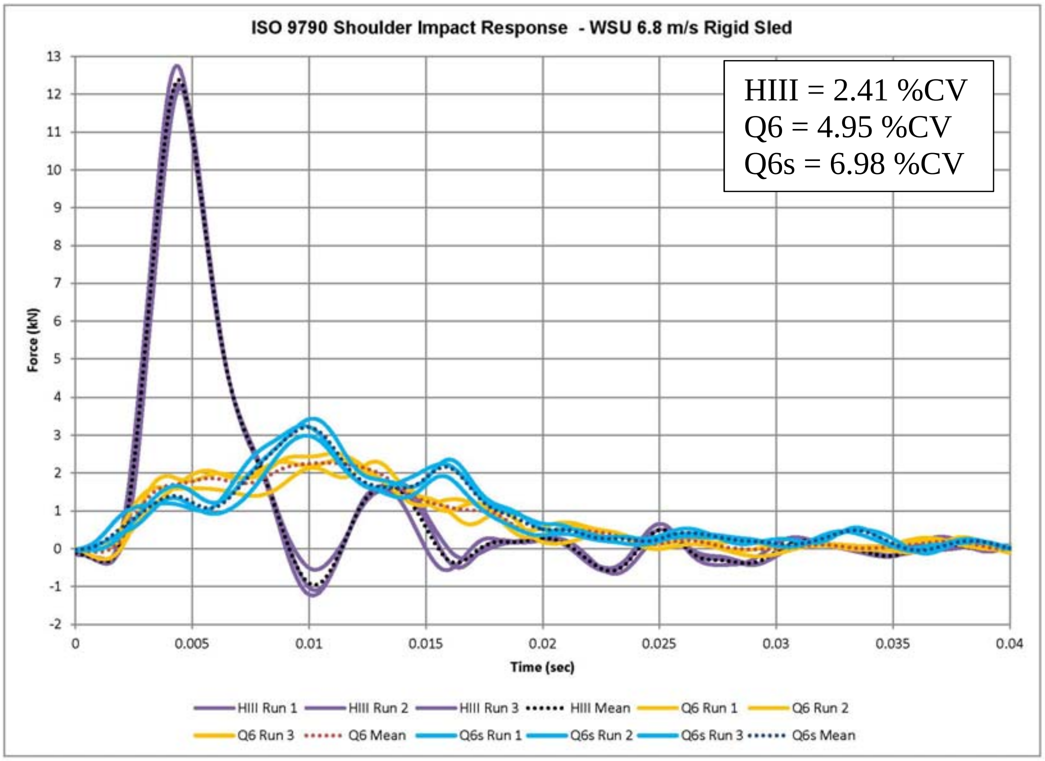

Figure 3: Shoulder WSU 6.8 m/s Rigid Sled Impact Response Comparison.

Thorax Impact Tests

Figure 4 provides the results for ISO 9790 Thorax Pendulum Impact Response Test Requirement 1 pendulum impact force data. Peak mean force values for the HIII, Q6, and Q6s dummies are 1.31 kN, 1.58 kN, and 1.08 kN, respectively. The upper boundary corridor peak is 1.1 kN (Irwin, 2002). Figure 5 provides the results for ISO 9790 Thorax Pendulum Impact Response Test Requirement 1 T1 acceleration data. Peak T1 acceleration values for the HIII, Q6, and Q6s dummies are 23.12 g, 20.58 g, and 26.95 g, respectively. The upper boundary corridor peak is 16 g (Irwin, 2002).

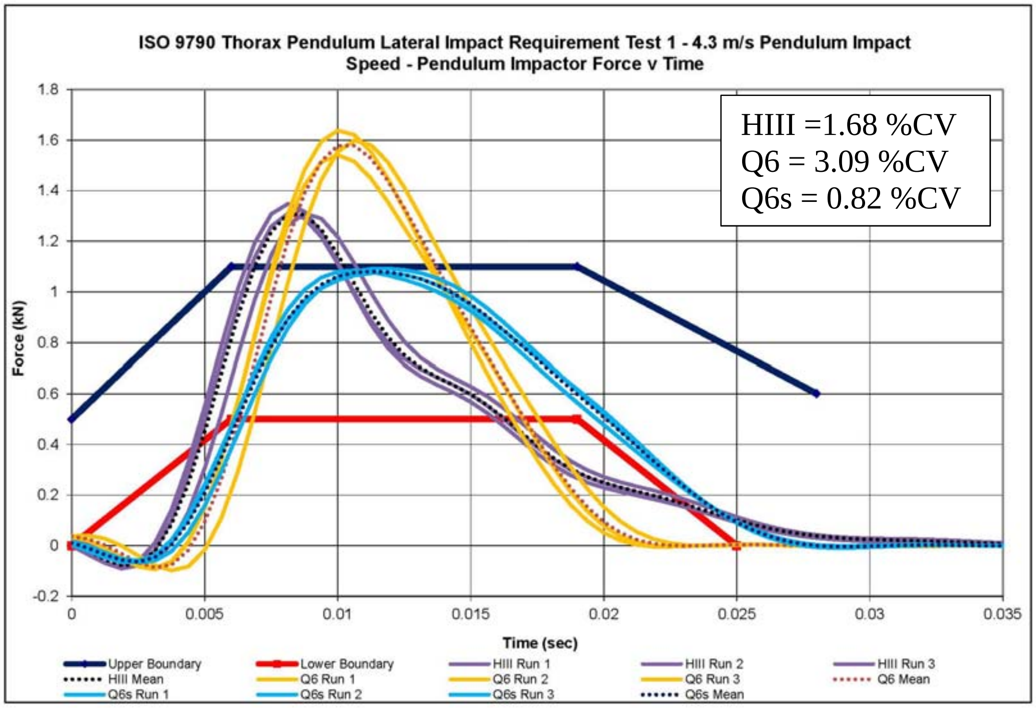

Figure 4: Thorax Pendulum Lateral Impact Test 1 Response Requirements Comparison Pendulum Impact Force.

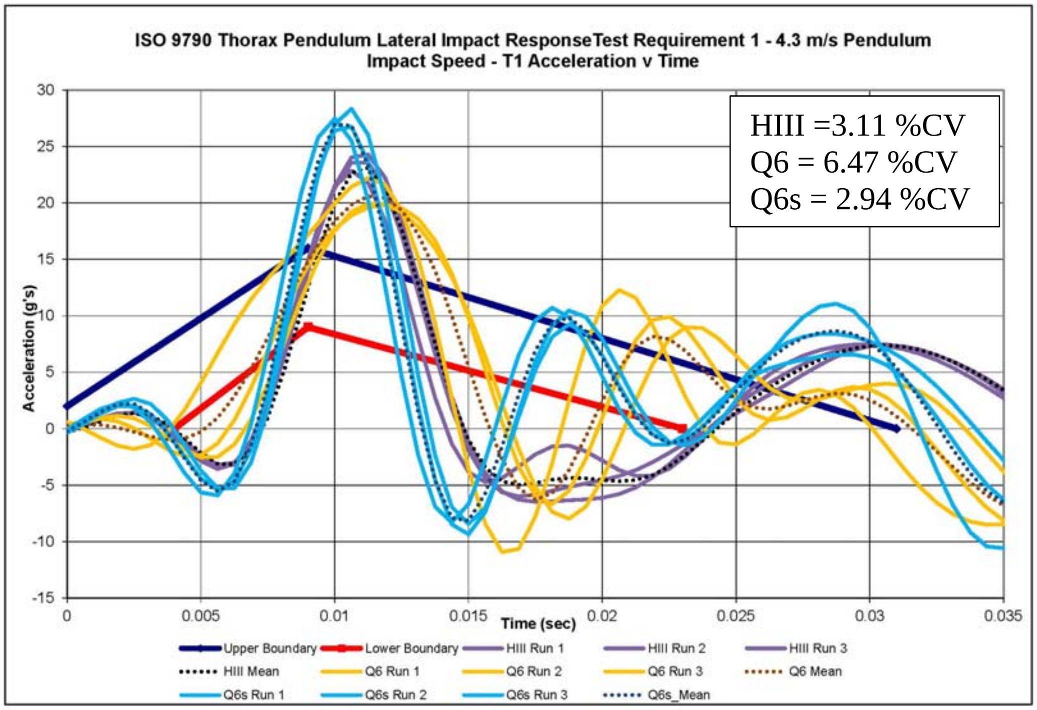

Figure 5: Thorax Pendulum Lateral Impact Test 1 Response Requirements Comparison T1 Acceleration.

Figure 6 provides the impact force results for ISO 9790 Thorax 1-Meter Drop onto a Rigid Surface Impact Response Test Requirement 3. Mean peak thorax impact force values for the HIII, Q6, and Q6s dummies are 6.80 kN, 3.44 kN, and 4.49 kN, respectively. The upper boundary corridor peak is 3.2 kN (Irwin, 2002).

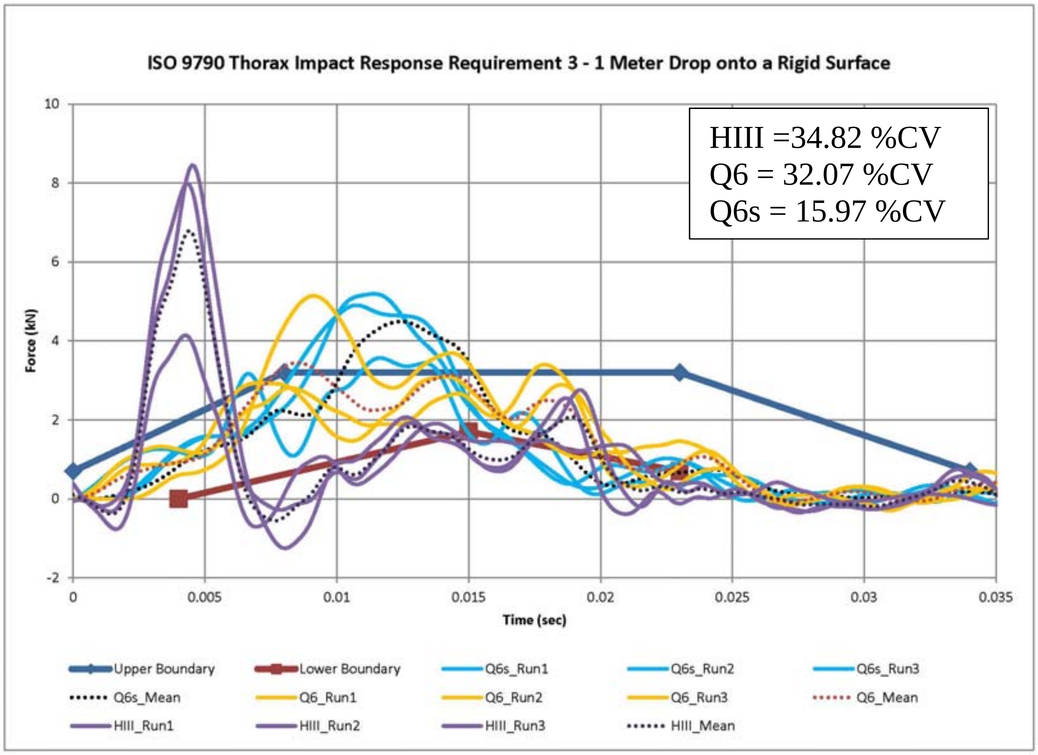

Figure 6: Thorax 1-Meter Drop onto a Rigid Surface Response Requirements Comparison.

Figure 7 provides the peak rib deflection results for ISO 9790 Thorax 1-Meter Drop onto a Rigid Surface Impact Response Test Requirement 3. Mean peak rib deflection for the HIII, Q6, and Q6s dummies are 7.46 mm, 13.47 mm, and 18.77 mm, respectively. The upper boundary peak is 29 mm (Irwin, 2002).

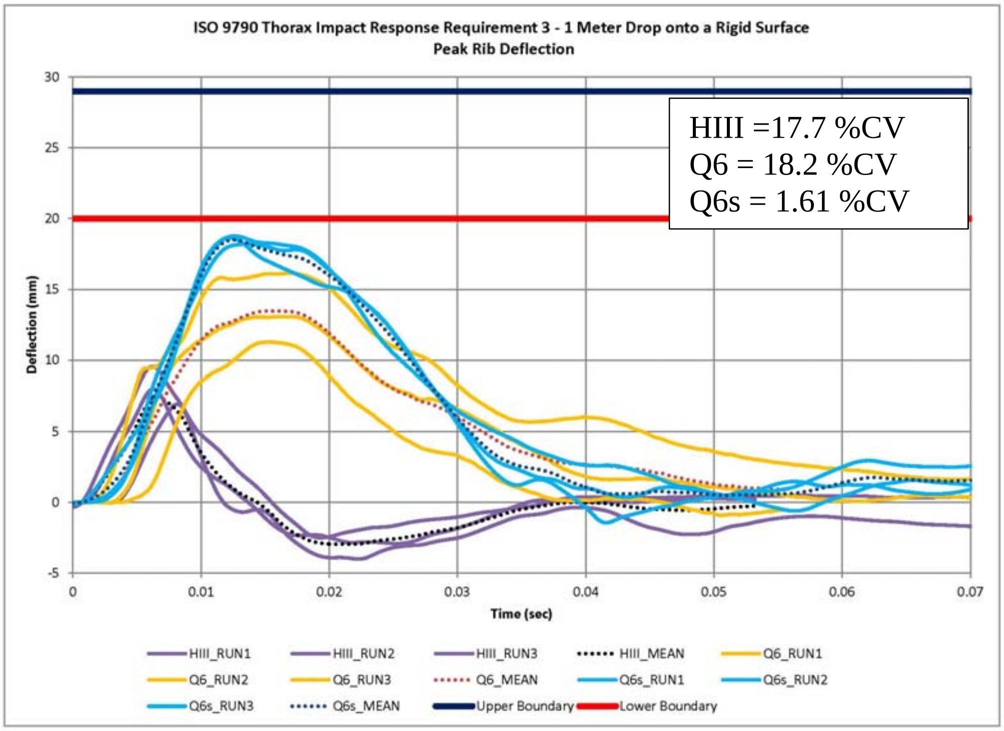

Figure 7: Thorax 1-Meter Drop onto a Rigid Surface Response Requirements Comparison – Peak Rib Deflection.

Figures 8, 9, 10, and 11 provide the various results from ISO 9790 Thorax WSU 6.8 m/s Rigid Sled Impact Response Test Requirement 5. Figure 8 shows the results of the ISO 9790 WSU 6.8 m/s Rigid Sled Impact Response Test at the thorax impact beam. Mean peak thorax impact force values for the HIII, Q6, and Q6s dummies are 2.96 kN, 1.70 kN, and 3.16 kN, respectively. The upper boundary corridor peak is 6 kN (Irwin, 2002). Figure 9 shows the results of the ISO 9790 WSU 6.8 m/s Rigid Sled Impact Response Test upper spine acceleration. Mean peak upper spine acceleration values for the HIII, Q6, and Q6s dummies are 430.7 g, 134.7 g, and 130.1 g, respectively. The upper boundary peak is 161 g (Irwin, 2002). Figure 10 shows the results of the ISO 9790 WSU 6.8 m/s Rigid Sled Impact Response Test lower spine acceleration. Mean peak lower spine acceleration values for the HIII, Q6, and Q6s dummies are 257.9 g, 113.7 g, and 102.7 g, respectively. The upper boundary peak is 142 g (Irwin, 2002). Figure 11 shows the results of the ISO 9790 WSU 6.8 m/s Rigid Sled Impact Response Test peak rib deflection. Peak rib deflection mean values for the HIII, Q6, and Q6s dummies are 9.28 mm, 25.27 mm, and 33.07 mm, respectively. The upper boundary peak is 132 mm (Irwin, 2002).

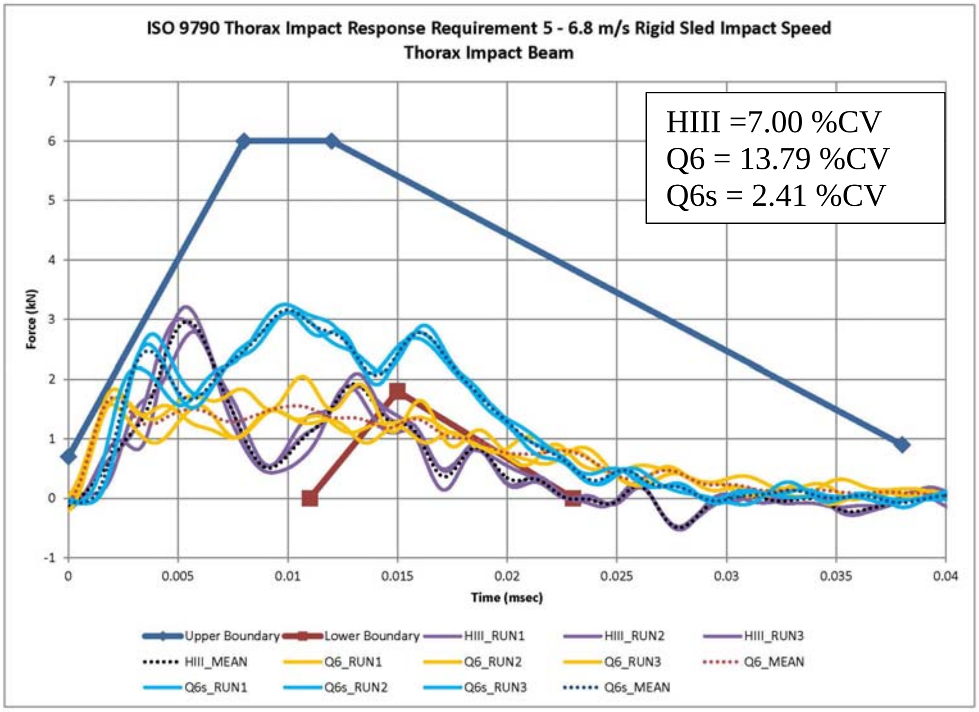

Figure 8: Thorax WSU 6.8 m/s Rigid Sled Impact Response Comparison.

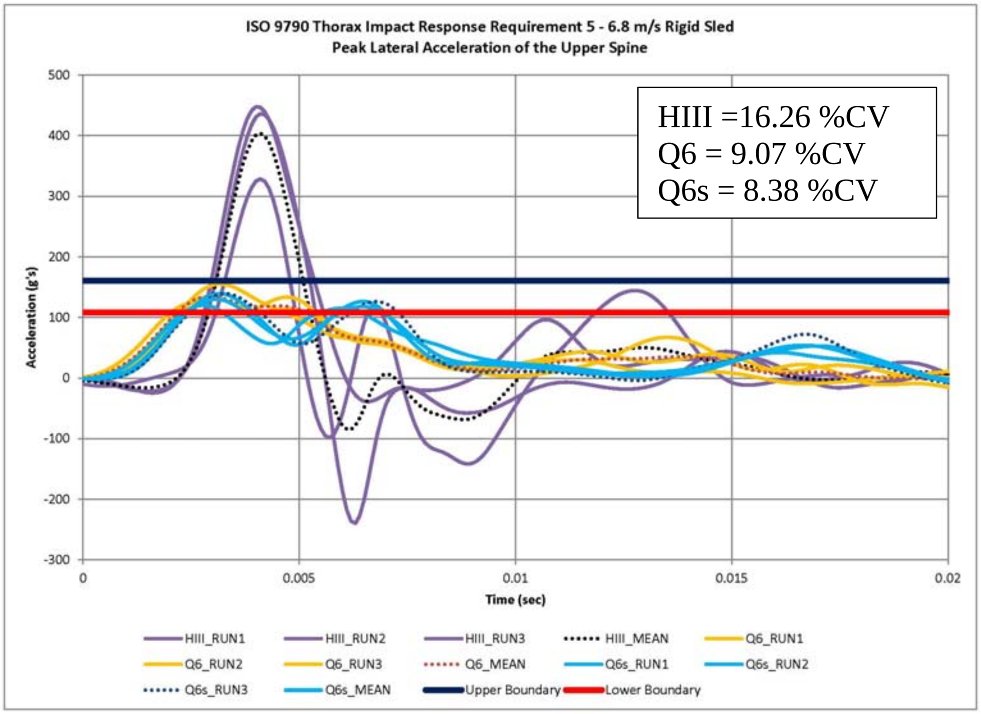

Figure 9: Thorax WSU 6.8 m/s Rigid Sled Impact Response Comparison Upper Spine Acceleration.

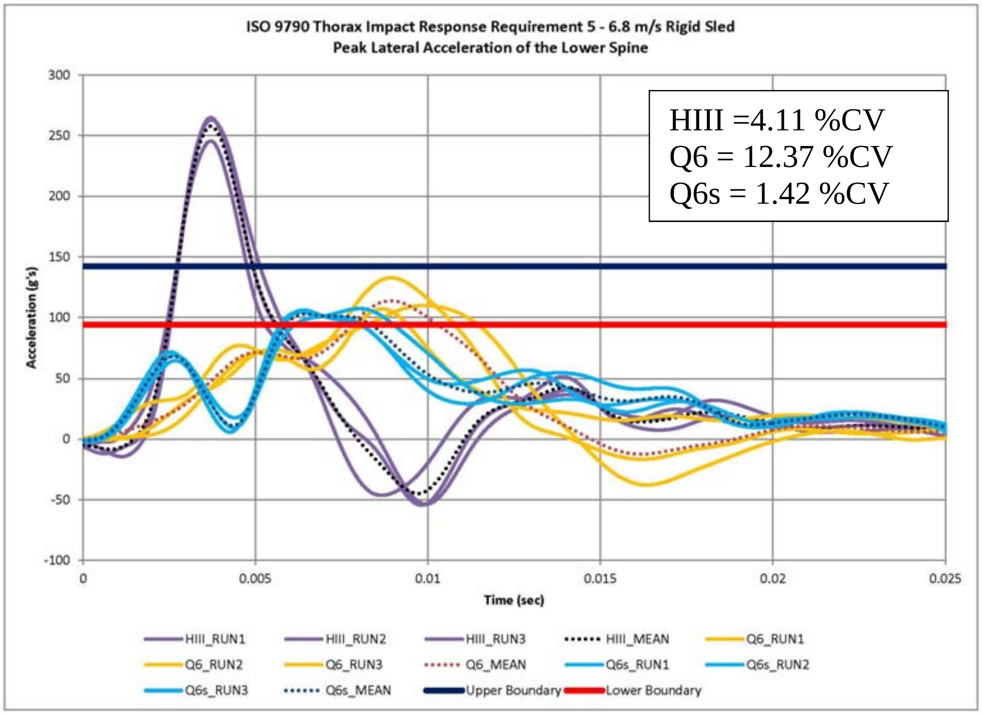

Figure 10: Thorax WSU 6.8 m/s Rigid Sled Impact Response Comparison Lower Spine Acceleration.

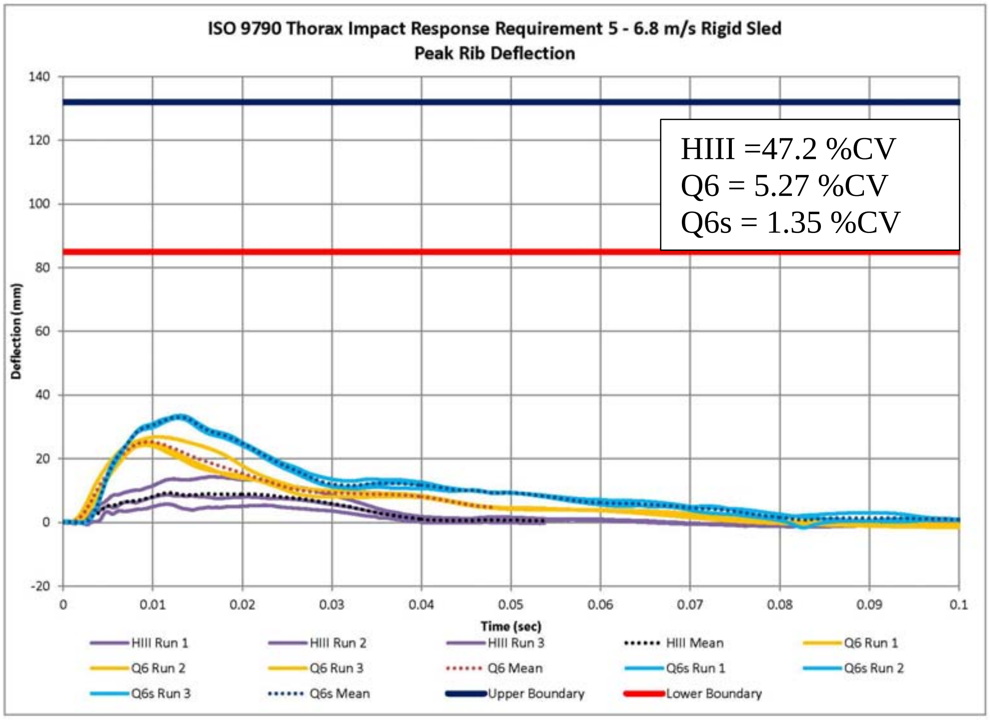

Figure 11: Thorax WSU 6.8 m/s Rigid Sled Impact Response Comparison Peak Rib Deflection.

Abdomen Impact Tests

Figure 12 shows the force versus time results from the abdomen pendulum tests evaluated based on 6 YO scaled response corridors suggested by van Rantingen et al. (1997). Mean peak abdomen impact force values for the HIII, Q6, and Q6s dummies are 1.08 kN, 1.44 kN, and 1.18 kN, respectively. The 6YO scaled upper boundary peak is 1.35 kN (van Rantingen, 1997).

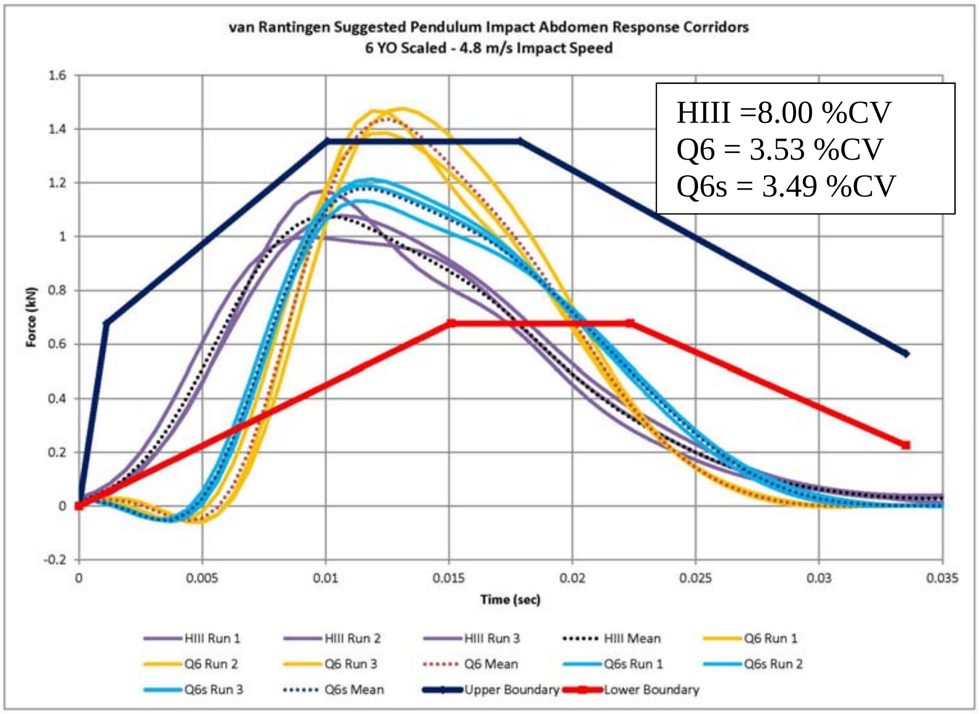

Figure 12: van Rantingen Suggested Pendulum Impact Response Corridors Scaled to 6-year-old.

Figure 13 provides the impact force results for ISO 9790 Abdomen 1-Meter Drop onto a Rigid Surface Impact Response Test Requirement 1. Mean peak abdomen impact force values for the HIII, Q6, and Q6s dummies are 5.31 kN, 4.10 kN, and 2.60 kN, respectively. The upper boundary corridor peak is 1.6 kN (Irwin, 2002).

Figure 14 illustrates the upper spine acceleration results for ISO 9790 Abdomen 1-Meter Drop onto a Rigid Surface Impact Response Test Requirement 1. Mean peak upper spine acceleration for the HIII, Q6, and Q6s dummies are 181.4 g, 70.1 g, and 49.7 g, respectively. The. upper boundary peak is 46 g (Irwin, 2002).

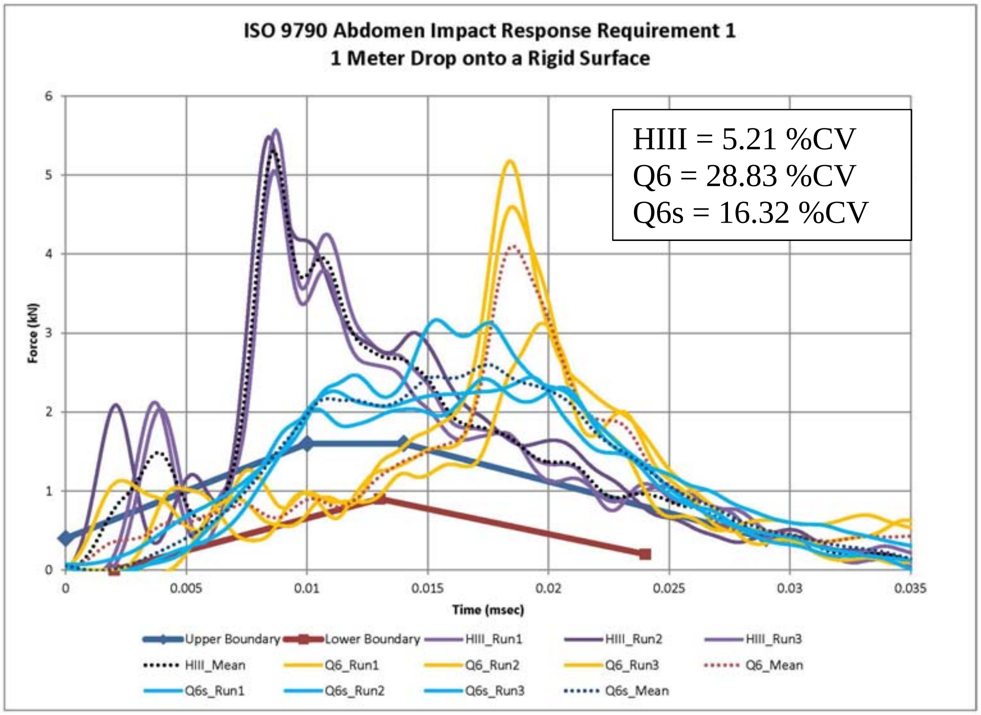

Figure 13: Abdomen 1-Meter Drop onto a Rigid Surface Response Requirements Comparison.

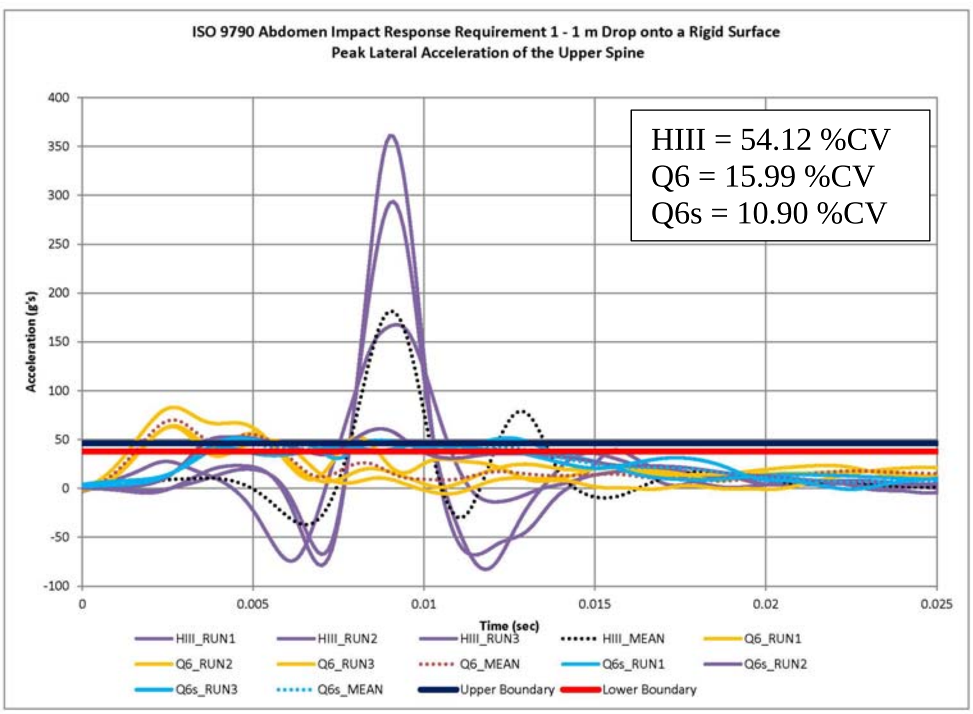

Figure 14: Abdomen 1-Meter Drop onto a Rigid Surface Response Requirements Comparison Upper Spine Acceleration.

Figure 15 illustrates the lower spine acceleration results for ISO 9790 Abdomen 1-Meter Drop onto a Rigid Surface Impact Response Test Requirement 1. Mean peak lower spine acceleration for the HIII, Q6, and Q6s dummies are 120.7 g, 30.2 g, and 48.4 g, respectively. The upper boundary peak is 165 g (Irwin, 2002).

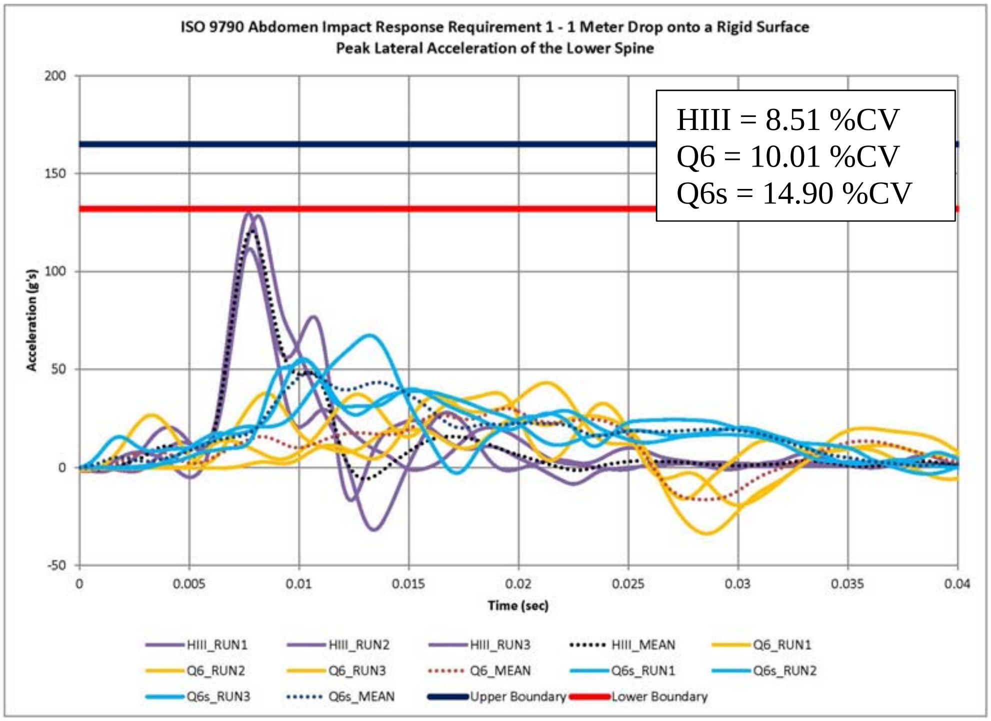

Figure 15: Abdomen 1-Meter Drop onto a Rigid Surface Response Requirements Comparison – Lower Spine Acceleration.

Figure 16 shows the results of the ISO 9790 WSU 6.8 m/s Rigid Sled Impact Response Test at the abdomen impact beam. Mean peak abdomen impact force values for the HIII, Q6, and Q6s dummies are 2.17 kN, 1.94 kN, and 0.84 kN, respectively. The upper boundary corridor peak is 1.2 kN (Irwin, 2002).

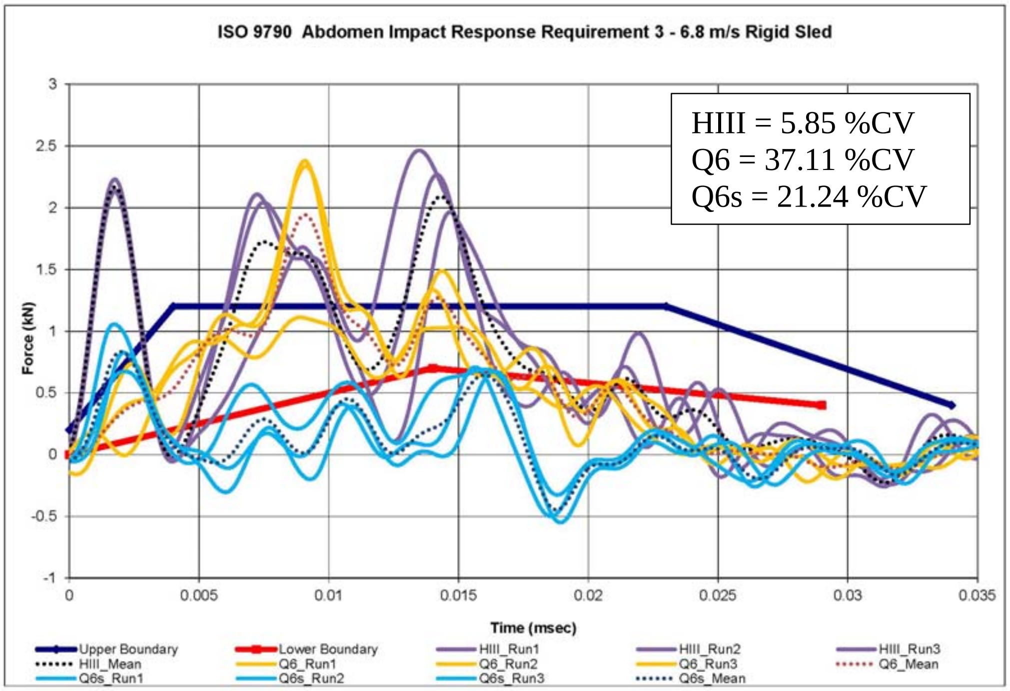

Figure 16: Abdomen WSU 6.8 m/s Rigid Sled Impact Response Comparison.

Pelvis Impact Tests

Figure 17 provides the results of the ISO 9790 Pelvic Pendulum Impact Test Response Requirement 1. Mean peak force values at a 6 m/s pendulum impact speed for the HIII, Q6, and Q6s dummies are 4.59 kN, 4.46 kN, and 3.55 kN, respectively. The upper boundary peak at a pendulum impact speed of 6.0 m/s is 2.1 kN (Irwin, 2002).

Figure 18 provides the results of the ISO 9790 Pelvic WSU 6.8 m/s Rigid Sled Impact Response Requirement 10. Mean peak pelvic force values for the HIII, Q6, and Q6s dummies are 6.99 kN, 6.89 kN, and 6.70 kN, respectively. The upper boundary corridor peak is 2.4 kN (Irwin, 2002).

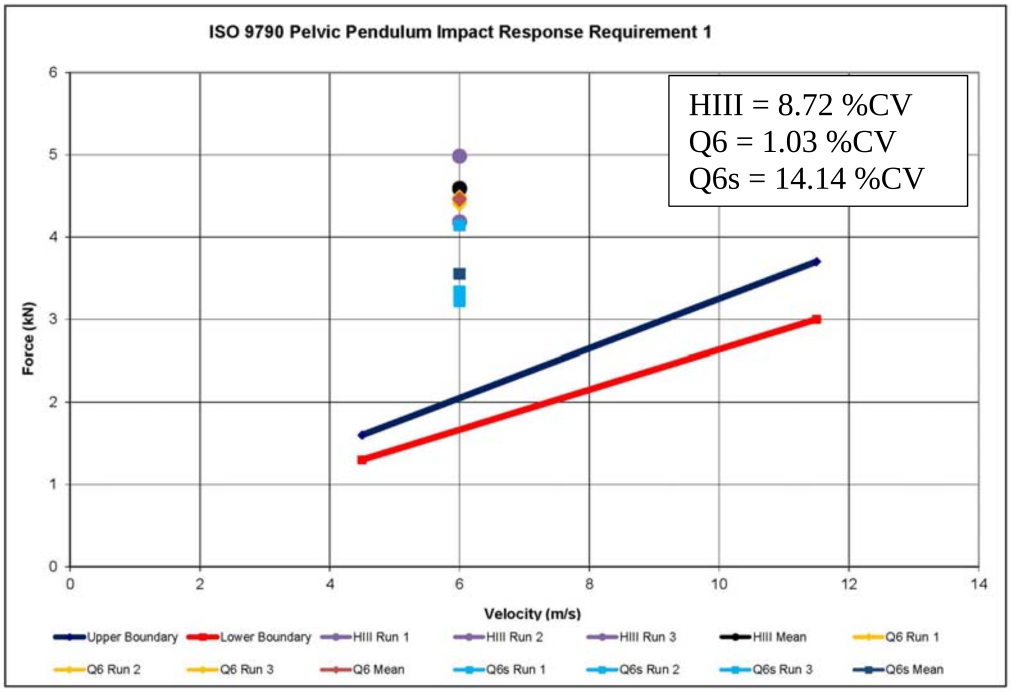

Figure 17: Pelvis Pendulum Lateral Impact Response Requirement 1 Comparison.

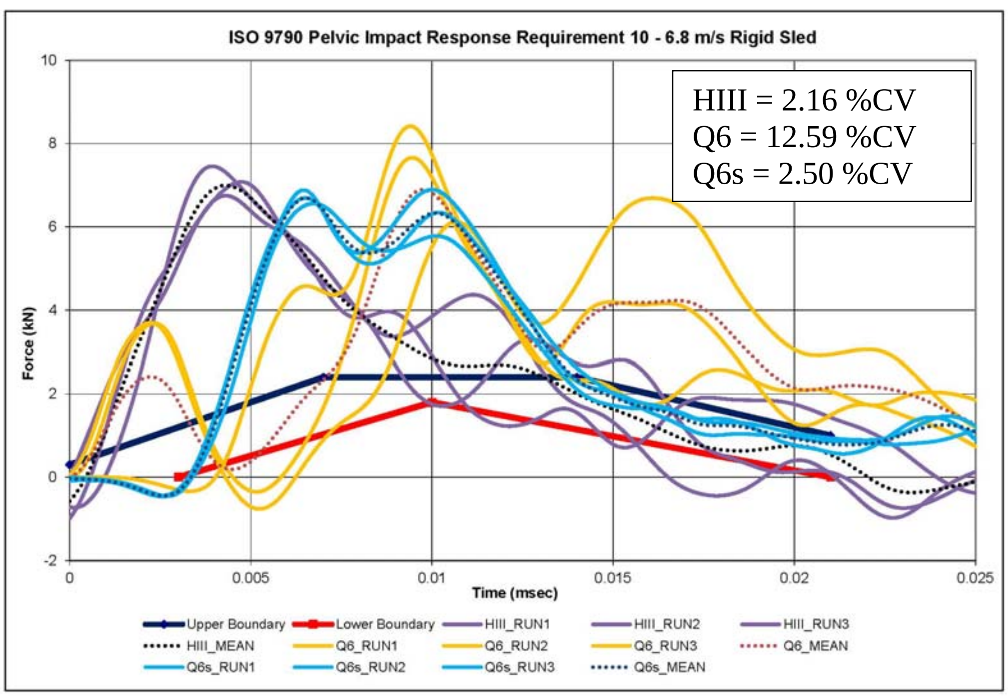

Figure 18: Pelvis WSU 6.8 m/s Rigid Sled Lateral Impact Response Requirement Comparison.

DISCUSSION

According to Humanetics Innovation Solutions (manufacturer of the HIII and Q series dummies), there are currently two 6-year-old dummies, the HIII and the more current Q6, both of which are designed primarily for frontal impact testing. The Q6s is a prototype side impact dummy. The biofidelic testing results presented in this paper were obtained in order to better understand how the mechanical response of each dummy compared to existing biofidelity response corridors scaled to the 6-year-old based on 50th-percentile male test data. This information is necessary in order to further develop the biofidelity of these ATDs for future child safety research and protection in side impacts.

Shoulder Design and Biofidelity

The shoulder is one of the first regions of the ATD that gets contacted in a lateral impact; therefore the biofidelity of shoulder is very important. Compared to the metal yoke joint of the HIII dummy, the shoulder joint of the Q6 dummies consists of a more human-like ball-and-socket joint in order to simulate the glenohumeral joint. In addition, a molded and compressible rubber component and other components attach the joint to the sternum and spine, allowing for load transfer. Figures 19 and 20 depict the design differences in the three 6-year-old ATD shoulders from a rear and front view, respectively.

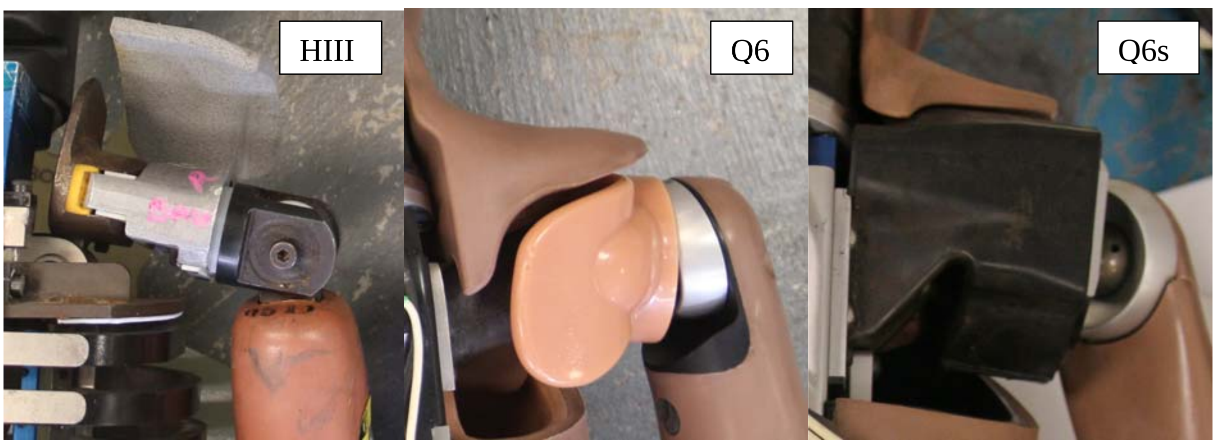

Figure 19: Visual Comparison of 6-year-old ATDs Shoulder Design – Rear View.

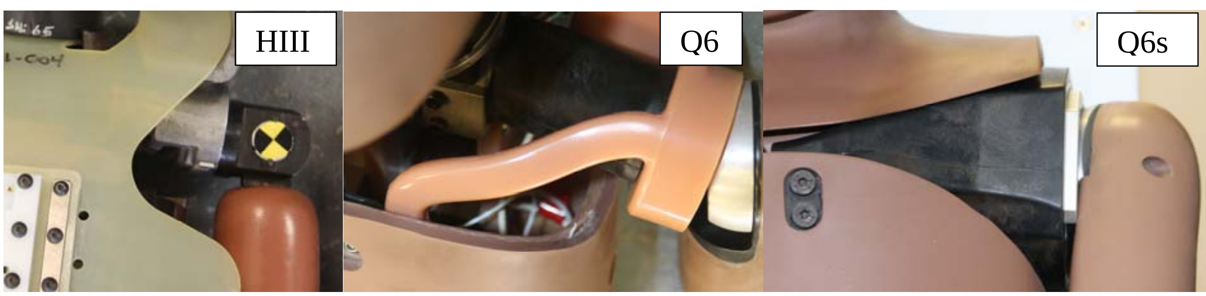

Figure 20: Visual Comparison of 6-year-old ATDs Shoulder Design – Front View.

The newer shoulder designs of the Q6 and Q6s dummies showed a significant reduction in peak load and stiffness over the HIII 6YO in both the pendulum (Figure 2) and WSU sled test (Figure 3). No significant difference was observed between the Q6 and Q6s shoulder designs. The improvement can be attributed to the lateral compliance of this newer shoulder design, which can deflect medially during impact as well as the rubber skin that covers the entire outer surface of the joint.

Thorax Design and Biofidelity

The thorax of the 6-year-old HIII ATD is comprised of an aluminum thoracic spine box with six individual spring steel ribs and polymer-based damping materials. The Q6 and Q6s dummies thorax consists of an aluminum thoracic spine box and a single, deformable, more child-like shaped synthetic composite or a PVC outer skin layer bonded to urethane rib cage, respectively. Figure 21 illustrates a comparison of the thorax design of three 6-year-old ATDs from a front view.

Figure 21: Visual Comparison of 6-year-old ATDs Thorax Design – Front View.

The updated shape, contour and thickness of the Q6s ribcage provides better lateral compliance as illustrated in the thorax test results of this study. The Q6s performed closer to the Irwin et al. corridors in the pendulum test (Figure 4), 1-Meter drop test (Figure 7), and WSU sled test (Figures 8 and 11). The newer single piece thorax designs of the Q6 and Q6s dummies showed a significant reduction in peak load and stiffness as well as increased load distribution in the dynamic drop and sled tests over the HIII 6YO (Figures 6, 7, and 9-11).

Abdomen Design and Biofidelity

The abdomen used in the 6-year-old HIII ATD for the current analysis is the Ford-designed abdomen, which is a silicone-filled compressible abdominal insert that sits in the space between the bottom of the rib cage and the pelvis structure. The Q6 and Q6s dummies both possess a foam covered by plastic skin abdomen that sits in the space between the rib cage and the pelvic structure. Figure 22 shows a comparison of the abdomen design of three 6-year-old ATDs from a front view.

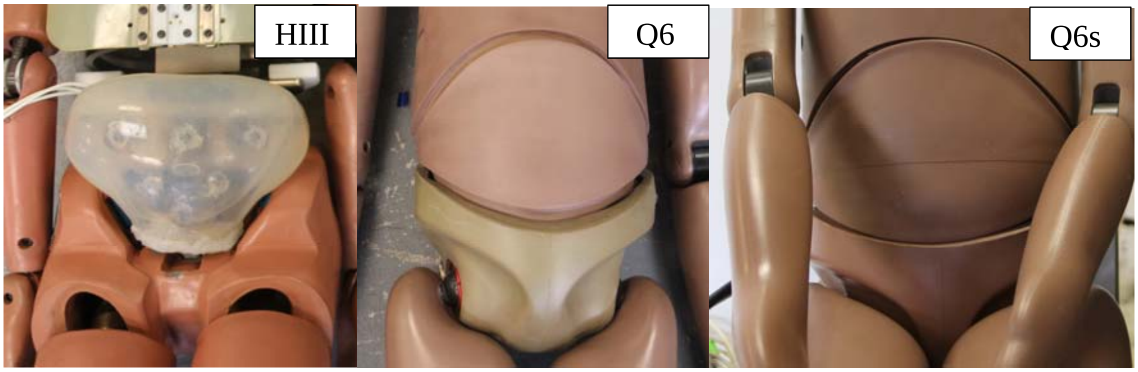

Figure 22: Visual Comparison of 6-year-old ATDs Abdomen and Pelvis Design – Front View.

The current study showed that the abdomen test results of the Q6 and Q6s follow the response corridor requirements more closely in the drop test and sled test than the HIII 6YO. This may be a function of the Q6 and Q6s abdomen and rib design, the fact that the Q6 upper arm is longer than the HIII and covers or shields this area to a certain extent during these impacts, or a combination of factors. The HIII 6YO, however, appeared to perform closer to the pendulum response corridor requirements than the other dummies. The arm is moved out of the way for the pendulum impact and therefore exposes more of the compliant abdomen itself on the HIII 6YO versus based on the nature of its abdomen and rib design.

Pelvis Design and Biofidelity

The pelvis is a source of first contact in side impact; therefore, pelvis design also plays a large role in the dummy's overall biofidelity. The pelvis of the 6-year-old HIII ATD consists of a seated design with an aluminum pelvis casting covered in a foam flesh and outer vinyl skin. The Q6 and Q6s ATDs' pelvis are comprised of a similar pelvis casting which sits inside a foam pelvic flesh. The Q6 and Q6s ATDs have ball-and-socket hip joint assemblies such that the ball attached to the upper legs can fit into the socket openings on the left and right sides of the pelvis casting. The hip joint socket of the Q6s ATD is constructed to allow for some inward deflection of the hip joint (Carlson, 2007). Figures 22 and 23 show a comparison of the pelvis design of three 6-year-old ATDs from a front view and oblique view, respectively.

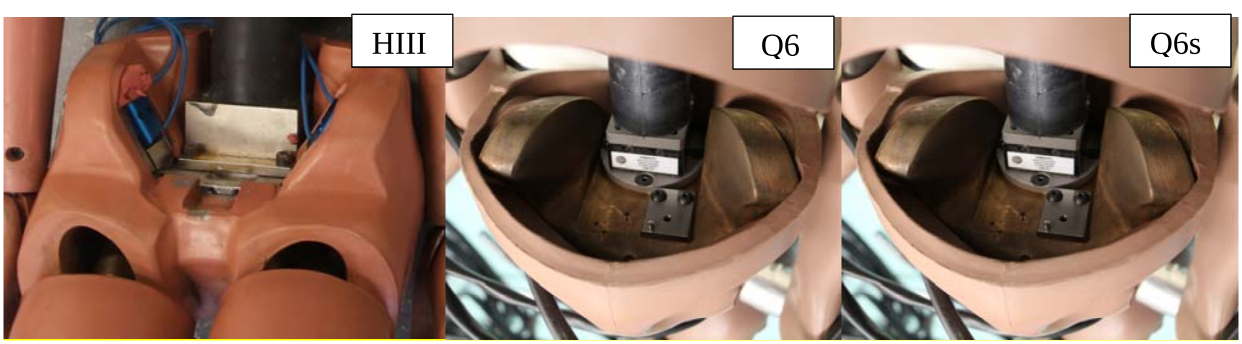

Figure 23: Visual Comparison of 6-year-old ATDs Pelvis Design – Oblique View.

A combination of the more compliant upper leg flesh, floating hip joints, and rubber buffer help the Q6s to reduce initial impact force and perform closer to the Irwin et al. corridors in the pendulum test (Figure 17) and WSU sled test (Figure 18).

CONCLUSIONS

Future testing will provide data to perform a more complete biofidelity analysis and provide data to evaluate the validity of the current 6-year-old lateral impact biofidelity targets based on the lateral impact testing biofidelity assessment of surrogates of appropriate size and weight. In addition, investigation of the oblique response characteristics of the dummy is required since many side impact vehicle crashes involve an oblique angle force component.

ACKNOWLEDGEMENTS

We would like to acknowledge and thank Ford Motor Company for its funding and support of the current research project, for TRL (Transport Research Laboratories) for use of its Q6 ATD, and Transport Canada for use of its Q6s prototype ATD.

DISCLAIMER

Funding for this study was provided by Ford Motor Company through its University Research Program. However, this paper has not been peer-reviewed, as stated on every page of the paper. The opinions presented in the paper are solely those of the authors and not of Ford Motor Company.

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