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Side Impact Assessment and Comparison of Appropriate Size and Age Equivalent Porcine Surrogates to Scaled Human Side Impact Response Biofidelity Corridors

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ABSTRACT – Analysis and validation of current scaling relationships and existing response corridors using animal surrogate test data is valuable, and may lead to the development of new or improved scaling relationships. For this reason, lateral pendulum impact testing of appropriate size cadaveric porcine surrogates of human 3-year-old, 6-year-old, 10-year-old, and 50th percentile male age equivalence, were performed at the thorax and abdomen body regions to compare swine test data to already established human lateral impact response corridors scaled from the 50th percentile human adult male to the pediatric level to establish viability of current scaling laws. Appropriate Porcine Surrogate Equivalents PSE for the human 3-year-old, 6-year-old, 10-year-old, and 50th percentile male, based on whole body mass, were established. A series of lateral impact thorax and abdomen pendulum testing was performed based on previously established scaled lateral impact assessment test protocols. The PSE thorax and abdominal impact response data were assessed against previously established scaled human thorax lateral impact response corridors and scaled abdominal oblique impact response corridors for the 3-year-old, 6-year-old, 10-year-old, and 50th percentile human male based on lateral pendulum impact testing. The overall findings of the current study confirm that lateral impact force response of the thorax and abdomen of appropriate weight porcine surrogates established for human-equivalent-age 3-year-old, 6-year-old, 10-year-old, and 50th adult male are consistent with the previously established human scaled lateral impact response corridors). Porcine surrogate biomechanics testing can prove to be a powerful research means to further characterize and understand injury and response in lateral impact.

KEYWORDS – Lateral Impact, Thorax, Abdomen, Scaling, Biofidelity, Response Corridor, Side Impact, Pediatric, ATD

INTRODUCTION

Due to a paucity of pediatric post-mortem human subjects (PMHS) for use in testing over history, researchers have had to consider other avenues to help establish response corridors for child crash test dummy design and development. Response corridor development is central to establishing anthropometric test device (ATD) response similar to that of humans. Normalization of data can be described as the method by which measured impact responses from individual specimen tests with variable characteristics are brought into a standard. Scaling, particularly in impact biomechanics, can be used as a process to convert normalized response data from one standard group to another; for example, mid-size male lateral impact response corridor data to the pediatric population (Petitjean et. al, 2015).

Normalization and scaling of response data has been an indirect technique used for many years to establish pediatric response biofidelity corridors for crash test dummy design and development, both through scaling of adult PMHS data and animal surrogate test data to the pediatric level. Eppinger (1976), in evaluating PMHS thoracic impact data from several different sources, used a basic linear normalization approach (labeled a “scaling approach” by the authors) which assumed linear relationships between the central constraints of length, mass, and time as well as equal density and modulus of elasticity between the mass and its reference (dummy).

Mertz (1984) derived an impulse-momentum normalization technique for specific body regions based on segment characteristics and type of impact test. This approach used mass and stiffness ratios along with assumptions of lumped mass and spring models. Mertz et al. (1989) established scaling criteria for the 5th percentile female and 95th percentile male Hybrid III ATDs from the 50th percentile male Hybrid III ATD, whose biofidelity was based on dynamic responses relative to PMHS and limited volunteer data (Foster et al., 1977). Geometric and mass scale factors were used to scale the Hybrid III 50th percentile male design drawings and biomechanical impact response requirements to the corresponding target design size for preservation of scaled biofidelity response in each ATD design (Mertz et al., 1989). Irwin and Mertz (1997) used the scaling techniques from Mertz (1984, 1989) to develop biomechanical frontal impact response corridors for the HIII 3-year-old and 6-year-old child dummies and the Child Restraint Air Bag Interaction (CRABI) child dummies representing the 6-month, 12-month, and 18-month child. In 2002, these similar scaling techniques were used to develop guidelines for assessing the biofidelity of dummies of all ages and sizes in side impact (Irwin et al., 2002).

Swine have been used as a surrogate for human adults in a number of past studies (Gogler et al., 1977, Viano et al., 1989B, Viano et al., 1989C, Miller, 1989, Rouhana et al., 1989). Prasad and Daniel (1984) used piglets as surrogates to children to develop preliminary head, neck, and torso injury tolerance data for the child surrogates and compare it to a 3-year-old child test dummy. A subjective anatomical comparison between the piglet and human's major organs were made with respect to injury potential. It was determined that the piglet's thoracic-abdominal organ masses were similar to those of a 3-year-old child; however, initial sternal deflection would increase intra-thoracic volume in the piglet, whereas it would decrease intra-thoracic volume in the child based on the difference in their rib cage design. The piglet was also found to have a larger abdomen and a longer, more rigid ribcage, which would in effect better guard the liver and spleen from injury compared to a child. For each piglet test, a similar test was run using a 3-year-old child dummy in an attempt to associate dummy response with animal injury.

Mertz and Weber (1982) compared physical development between the piglet and the human 3-year-old child based on an equivalent human 3-year-old's weight and size. It was determined that the pig's thoracic and abdominal breadths comparably favored the human 3-year-old. In addition, state of physical development of a 15 kg pig was estimated to be quite comparable to a 3-year-old child based on comparison of human versus pig puberty ages. The equivalent child age for the pig, based on a formula provided in the paper, was equal to the ratio of the human puberty age to the pig puberty age multiplied by the pig test age. Puberty ages for the human and pig were not provided in the paper and the basis for the provided formula is unclear.

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Kent et al. (2006) performed an anatomically focused necropsy study of 25 swine, aged from birth to maturity, in order to develop a properly sized and aged porcine surrogate model for the human 6-year-old. Once a proper pig model was determined, this surrogate was tested to determine abdominal response characteristic of the swine through seatbelt loading. Although this comparison was made direct to the 6-year-old in the Kent et al. (2006) study, no attempt was made to establish biomechanical response data for any other age equivalent porcine model to human relationship. Kent et al. (2009) and Lamp et al. (2010) compared 6-year-old PMHS thoracic and abdominal belt loading to the Kent et al. (2006) previously developed 6-year-old porcine model to determine the efficacy of the porcine surrogate model in predicting human response.

There is no research known to the authors that establishes scaling of animal surrogate thorax and abdomen lateral impact response data to the human adult and pediatric thorax and abdomen. In addition, no validation of the currently used scaling laws for the biofidelity response of the adult male down to the 3-year-old ATD in lateral impact in known by these authors.

In order to provide additional response corridor research data for pediatric ATD biofidelity enhancement, validation of the current scaling laws and a scaling relationship using animal surrogate test data to apply to the pediatric level is very valuable. For this reason, lateral pendulum impact testing of appropriate size cadaveric porcine surrogates to human 3-year-old, 6-year-old, 10-year-old, and 50th percentile male equivalents were performed in order to compare the actual swine test data to already established human response corridors scaled from the 50th percentile human male to the pediatric level. The selected ages were chosen for the current study based on already established ATDs and human pendulum lateral impact response corridors at these age levels.

METHODS

Porcine Surrogate Size Determination

Appropriate size domestic female Hampshire/Yorkshire Cross domestic swine (*sus scrofa domesticus)* surrogates, equivalent to the whole body mass targets of a human 3-year-old, 6-year-old, 10-year-old and 50th percentile male (Table 1) were procured from Michigan State University[1] for the current study. Human whole body mass target data for the human 3-year-old, 6-year-old, and 10-year-old were obtained from Kent et al. (2006), and the whole body mass for the human 50th percentile male was obtained from the Hybrid III 50th percentile male ATD (HIII 50th Male User Manual, 2012). Average masses of the 3-year-old, 6-year-old, 10-year-old, and 50th percentile male porcine surrogate equivalents (PSE) were 3.90%, -1.43%, 6.75%, and 6.13%, respectively, above the specific human mass target.

Table 1: Specific Age-Based Human Whole Body Mass Targets

Subject	3-Year-Old Human	6-Year-Old Human	10-Year-Old Human	50th Percentile Male Human
Whole Body Mass (kg)	14.1	21	33.1	77.7

It should be noted that the methodology proposed by Kent et al. (2006), based on a necropsy and regression analysis involving specific anthropometry and organ masses was attempted. However, there was significant underestimation of determined PSE mass compared to the human target masses for all age targets other than the 6-year-old equivalent. Understanding that the Kent et al. (2006) study was focused on the 6-year-old, it appears more work needs to be done to validate and extrapolate from the Kent et al. (2006) model. It is acknowledged that swine growth can vary significantly with age and breed depending on how much they are fed over a given time span. Therefore, the human whole-body masses provided in Table 1 were the sole target parameter used to determine appropriate PSE for the current study.

Relevant measurements for the PSE are provided in Table 2, below. For clarity, each subject is identified by age, type of test performed (T=thorax, A=abdomen), and test sequence number. Swine from thorax impacts were used for measuring upper and lower torso mass. Gross dissection was performed on these swine post testing. Upper torso mass measurements included the head and thorax and the lower torso mass included the abdominal contents, pelvis, and hind legs.

Table 2: Relevant Measurements from Individual PSE

SUBJECT	3-T1	3-T2	3-T3	3-A1	3-A2	3-A3
Ear tag number	14-2	1-1	11-3	11-4	11-2	13-2
DOB	7/6/2016	7/4/2016	7/7/2016	7/7/2016	7/7/2016	7/5/2016
DOD	8/25/2016	8/26/2016	8/26/2016	8/24/2016	8/25/2016	8/25/2016
Age when studied (days)	50	53	50	48	49	51
Age when studied (weeks)	7.1	7.6	7.1	6.9	7.0	7.3
Whole-body mass (kg)	13.9	13.1	13.1	14.1	13.7	13.4
Top of head to tail base ("sitting" height) (cm)	74.9	74.9	73.66	74.3	78.7	76.84
Upper Torso Mass (kg)	7.4	7.4	7.2			
Lower Torso Mass (kg)	6.5	5.7	5.9			
Thorax Breadth (cm)	12.3	12.6	14	12.5	14	12.4
Thorax Depth (cm)	17.1	16.5	17.5	16.5	16.5	16.8
Thorax Circumference (cm)	52.1	49.5	50.8	50.8	52.1	50.8
Abdomen Breadth (cm)	11	12	12	10.5	13.4	11.5
Abdomen Depth (cm)	17.2	17.8	17	17	17	16.3
Abdomen Circumference (cm)	52.1	48.3	49.5	53.3	53.3	52.1

SUBJECT	6-T1	6-T2	6-T3	6-A1	6-A2	6-A3
Ear tag number	77-1	94-4	84-1	78-1	75-4	88-1
DOB	6/1/2016	6/2/2016	6/2/2016	5/31/2016	6/2/2016	5/29/2016
DOD	8/9/2016	8/9/2016	8/9/2016	8/18/2016	8/24/2016	8/25/2016
Age when studied (days)	69	68	68	79	83	88
Age when studied (weeks)	9.9	9.7	9.7	11.3	11.9	12.6
Whole-body mass (kg)	20.6	21.4	21.8	19.8	22	22.2
Top of head to tail base ("sitting" height) (cm)	81.3	83.2	83.8	83.8	83.8	85.1
Upper Torso Mass (kg)	10.6	11	11.4			
Lower Torso Mass (kg)	10	10.4	10.4			
Thorax Breadth (cm)	17	16.5	17	15	19.5	15.3
Thorax Depth (cm)	20	21.5	21	18.5	21	19.4
Thorax Circumference (cm)	61	61	63.5	55.9	64.8	59.7
Abdomen Breadth (cm)	16.5	14	16.5	15.5	18.1	17
Abdomen Depth (cm)	22.5	21.25	20.5	20	19.5	21.1
Abdomen Circumference (cm)	62.9	58.4	62.9	62.2	69.2	67.3

[1] Approval from the Wayne State University's Institutional Animal Care and Use Committee (IACUC) was obtained prior to procurement. The care and use of the swine were followed in accordance with the guidelines and procedures outlined in the IACUC approved protocol.

SUBJECT	10-T1	10-T2	10-T3	10-A1	10-A2	10-A3
Ear tag number	82-4	58-1	65-4	70-1	69-3	88-3
DOB	5/31/2016	5/10/2016	5/11/2016	5/15/2016	5/13/2016	5/29/2016
DOD	8/8/2016	8/9/2016	8/9/2016	8/8/2016	8/8/2016	8/8/2016
Age when studied (days)	69	91	90	85	87	71
Age when studied (weeks)	9.9	13.0	12.9	12.1	12.4	10.1
Whole-body mass (kg)	30.4	29.6	30.2	32.4	31.8	30.8
Top of head to tail base ("sitting" height) (cm)	95.3	95.3	94.6	94	99.1	99.1
Upper Torso Mass (kg)	15.4	15.4	15			
Lower Torso Mass (kg)	15	14.2	15.2			
Thorax Breadth (cm)	18	17.5	18		18.5	17
Thorax Depth (cm)	23.5	23	23.5		22.25	23
Thorax Circumference (cm)	70.5	67.9	68.6		67.9	67.3
Abdomen Breadth (cm)	17	16.5	17.5		16	15
Abdomen Depth (cm)	24.5	21.5	21		22.25	22.25
Abdomen Circumference (cm)	67.9	63.5	64.8		68.6	68.6

SUBJECT	50-T1	50-T2	50-T3	50-A1	50-A2	50-A3
Ear tag number	15-6	10-6	25-21	47-2	44-1	10-4
DOB	4/4/2016	4/7/2016	4/8/2016	4/12/2016	4/12/2016	4/7/2016
DOD	8/4/2016	8/4/2016	8/4/2016	8/5/2016	8/5/2016	8/5/2016
Age when studied (days)	122	119	118	115	115	120
Age when studied (weeks)	17.4	17.0	16.9	16.4	16.4	17.1
Whole-body mass (kg)	74.8	77	74.8	72.2	74.4	69.6
Top of head to tail base ("sitting" height) (cm)	121.9	127	124.5	124.5	121.9	124.5
Upper Torso Mass (kg)	38.4	37.8	38.8			
Lower Torso Mass (kg)	36.4	39.2	36			
Thorax Breadth (cm)					24	26
Thorax Depth (cm)					32	31
Thorax Circumference (cm)					97.2	91.4
Abdomen Breadth (cm)					22.5	19
Abdomen Depth (cm)					32	31
Abdomen Circumference (cm)					99.1	95.3

SUBJECT	50-T4-A4	50-T5-A5	50-T6-A6
Ear tag number	5-3	43-5	43-1
DOB	4/7/2016	4/10/2016	4/10/2016
DOD	8/9/2016	8/9/2016	8/9/2016
Age when studied (days)	124	121	121
Age when studied (weeks)	17.7	17.3	17.3
Whole-body mass (kg)	74.2	74	73.2
Top of head to tail base ("sitting" height) (cm)	124.5	127	124.5
Upper Torso Mass (kg)			
Lower Torso Mass (kg)			
Thorax Breadth (cm)	25.5	24.5	25
Thorax Depth (cm)	33	35	32.5
Thorax Circumference (cm)	97.8	98.4	96.5
Abdomen Breadth (cm)	20.5	21.5	21.5
Abdomen Depth (cm)	32.5	33.5	30.5
Abdomen Circumference (cm)	91.4	94	90.2

Similar measurements are provided in Table 3 for humans as the PSE equivalent age measurements for comparison.

Table 3: Similar Human Measurements Comparable to PSE Equivalent Ages

Subject	3-year-old human (similar measurements)	6-year-old human (similar measurements)	10-year-old human (similar measurements)	50th percentile male human (similar measurements)
Whole-body mass (kg)	14.1	21	33.1	77.7
Supine seated height (cm)	58.1	64.5	73.3	94.2
Waist to superior sternum (cm)	23.1	25.4	29.7	40.9
Abdominal depth (umbilicus) (cm)	13.9	15.1	16.7	23.1
Abdominal breadth (deepest) (cm)	16.1	18.3	21.9	35.8
Chest depth (cm)	15.9	18.5	22	25
Chest breadth (cm)	16	19.7	23.9	33.2

Even though puberty ages for the human and pig were not provided in Mertz and Weber (1982) and the basis for the formula used is unclear, working backward from provided data from Mertz and Weber (1982), the human to pig puberty age ratio used was determined to be twenty-two. The average test age for the studied 3, 6, 10-year-old, and 50th percentile male PSE was 50 days, 76 days, 82 days, and 119 days, respectively. Using the Mertz and Weber (1982) formula, the equivalent child age calculated for the average swine test age for the 3, 6, 10-year-old, and 50th percentile male PSE in the current study was 3 years, 4.6 years, 4.9 years, and 7 years, respectively. There is clearly a discrepancy in using this formula to determine physical stage of development of the swine relative to the human. This was not explored in the current study but should be considered as an avenue for future research.

Porcine Surrogate Pendulum Lateral Impact Testing

A series of lateral impact thorax and abdomen pendulum testing of appropriate whole-body mass cadaveric PSE (3-year-old, 6-year-old, 10-year-old, and 50th percentile male) were performed based on the same scaled lateral impact assessment test protocol used in ISO/TR 9790 (1999) and van Rantingen (1997) and for the biofidelity assessment of the 6-year-old ATDs in Yaek et al. (2016). Since only impact response data comparable to testing performed and data used to develop the human impact response corridors was sought for this study, the porcine surrogates were euthanized just prior to physical testing, and therefore, the lungs were not inflated, pressurization of the vascular system was not performed, and specimen muscles were not tensed in the current study. After the PSE were euthanized, they were instrumented with tri-axial piezoresistive accelerometers attached to mount blocks, positioned to the posterior, external side of the PSE spine at the 1st thoracic vertebra (T1), the base of the thoracic vertebral spine (14th thoracic vertebra (T14), and the base of the lumbar vertebral spine location (6th lumbar vertebra (L6). The porcine surrogates were viewed under an OEC (Orthopedic Equipment Company) 9600 C-Arm fluoroscope (Salt Lake City, Utah) prior to affixing accelerometer mount blocks to the specified spinal regions to verify that this breed of pig indeed had 14 thoracic vertebrae and 6 lumbar vertebrae and that the mounts were secured to the proper vertebra. Once proper vertebral locations were verified, accelerometer mount blocks were secured to the 50th percentile male PSE vertebrae using appropriate size stainless steel, square drive, coarse threaded wood deck screws.

The tri-axial accelerometer mount blocks were equipped with Endevco 7264-2000TZ (2000 G) piezoresistive accelerometers for lateral accelerations, and with Measurement Specialties 64C-0200-360T (200 G) piezoresistive accelerometers for longitudinal and vertical accelerations.

For the thorax lateral pendulum impact tests, porcine surrogates were also instrumented to measure rib deflection. A trans-thoracic rod technique (Rouhana and Kroell, 1989) was used in which a 3.5-mm diameter carbon-fiber rod was pushed through an incision in the musculature and skin of the impacted side (left side) of the test swine specimen between ribs 6 and 7, maneuvered horizontally through its thoracic cavity at mid-thorax region, and pushed through an incision in the musculature and skin on the opposite, non-impacted side (right side). The positioning of the rod between ribs 6 and 7 was verified using the fluoroscope. A small aluminum mount bracket (Figure 1) was fabricated in order to secure the impacted end of the rod and affix it with small zip ties to the adjacent ribs (ribs 6 and 7).

The placement of the rod was chosen to allow the rod to lie in the horizontal plane (level), in the middle of the impacted thorax region, with the test specimen in a standing (upright) position. A photographic target was mounted to the non-impacted end of the rod. A fixed length secondary rod with attached photographic target was affixed to a similar bracket fastened to ribs 6 and 7 of the non-impacted side of the test in order to track the deflection of the impacted ribs relative to the non-impacted ribs. Once the carbon fiber rod was placed and secured, the incision on the impacted side of the test specimen was closed using super glue.

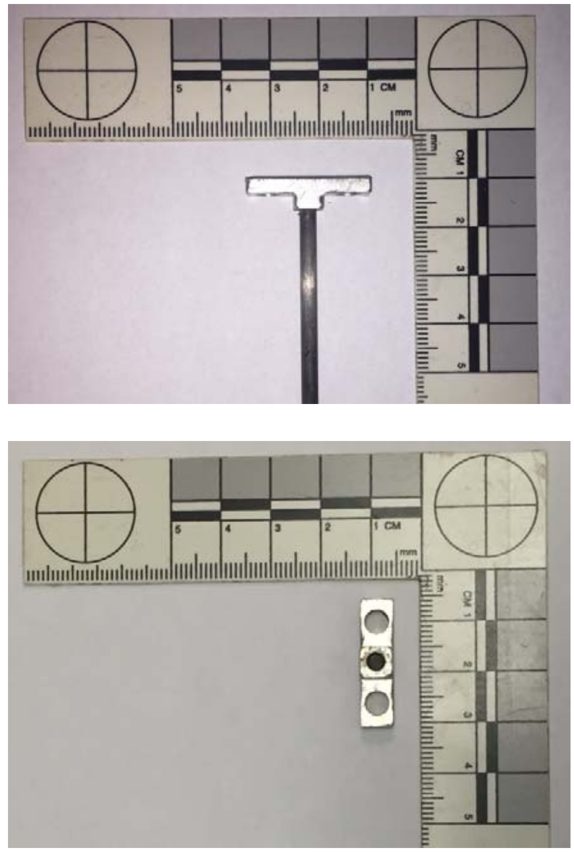


Figure 1: Fabricated aluminum mount bracket for rib deflection carbon fiber rod

Motion of the moveable target relative to the fixed target was tracked via a Redlake MotionXtra HG-100k high-speed camera positioned superiorly above the porcine surrogate at a frame rate of 2,500 frames per second to measure rib cage deflection as a function of time. Photographic targets were also placed at the T1 and T14 spine locations of the test specimens in order to track the impacted rib deflection relative to the spine.

A stable fixture was fabricated using 80/20 t-slot aluminum structural components in order to position the tested swine specimens in a standing, upright orientation at the time of impact. Three separate segments of chain were used in combination with carabineer clips and turn buckles to suspend the swine test specimens from the fixture at the proper level and orientation relative to the impact pendulum.

Mid-thorax region pendulum impacts of the tested porcine ribs were performed in a perpendicular impact orientation, and the chains were passed through the pig's thick adipose tissue via incisions made bilaterally along the spinal region. The superior-most chain was positioned at the test specimen's cervical spine region, passing anterior to the nuchal ligament to provide support in holding up pig specimen's head, neck, and shoulder region. The second chain was positioned superior to the T14 tri-axial mount block, passing through the thick adipose tissue posterior to the spinal column to support the torso of the pig specimen. The inferior-most chain was positioned inferior to the L6 tri-axial mount block, passing through the thick adipose tissue posterior to the spinal column to support the rear hindquarter of the pig specimen. An inclinometer was used to verify the pig specimen's spine was level to the ground prior to impact. Figure 1 (left) illustrates a pig test specimen in its pre-impact orientation from the stable fixture and in proper position relative to the impacting pendulum for the thorax pendulum impact testing.

The swine specimens in the abdominal impact test were positioned at an oblique 60-degree angle from anterior-posterior, in accordance with testing performed by van Rantingen et al. (1997) and scaled abdominal impact response corridors developed in that study based on oblique abdominal impact testing proposed in Viano (1989A). Chains were used to position the swine specimen through incisions in the adipose tissue located further anterior on the specimen's left side compared to its right side. Chains were positioned superiorly and inferiorly similar to the chain positions in the thoracic pendulum impact test setup. The swine specimen was positioned on the stable fixture such that the impacting face of the pendulum was positioned symmetrically caudal to the specimen's rib cage and cranial to its bony pelvis. An inclinometer was used to verify the test specimen was oriented to the 60-degree anterior-posterior position and its spine was level to the ground prior to impact. Figure 2 (right) illustrates a swine test specimen in its pre-impact orientation from the stable fixture and in proper position relative to the impacting pendulum for the abdominal impact testing.

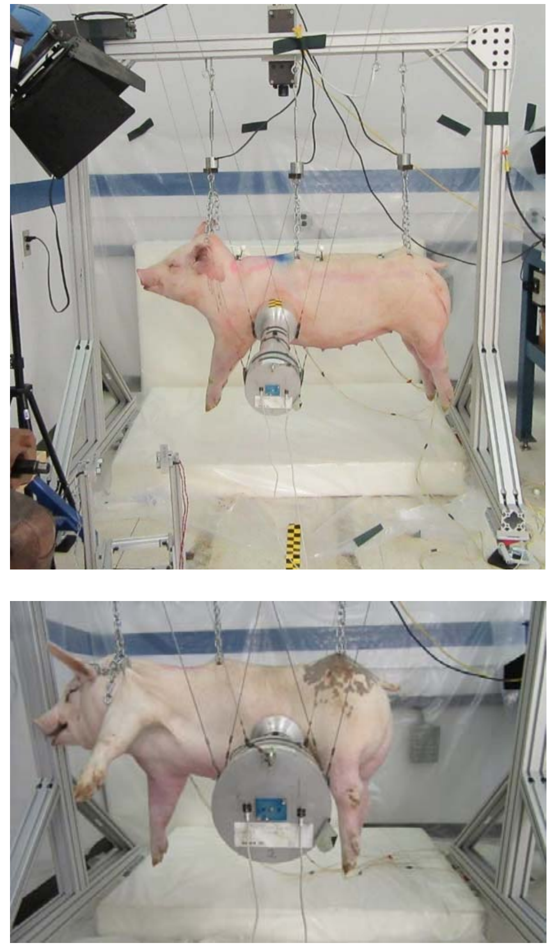


Figure 2: Thoracic Lateral Impact Test Setup (top) and Abdominal Lateral Impact Test Setup (bottom) with Swine Specimen in Proper Position Relative to Impacting Pendulum

Round, flat-faced, rigid aluminum pendulum masses with a 12.7-millimeter (0.5-inch) edge radius on the impacting surface were used in the testing. Impacting surface diameter and pendulum used for each age level tested are provided in Table 4.

Table 4: Pendulum Impacting Surface Diameters and Pendulums

	Pendulum Mass (kg)	Impacting Surface Diameter (mm) [in]
3-Year-Old PSE	1.7	70 [2.75]
6-Year-Old PSE	2.9	89 [3.5]
10-Year-Old PSE	6.5	121 [4.76]
50th Percentile Male PSE	23.4	152 [6.0]

Total pendulum mass used in the 10-year-old testing was slightly less (5.6%) than the 6.89 kilogram pendulum mass specified as the target pendulum mass in Irwin et al. (2002) for the 10-year-old. The impact face diameter for the 3, 6, and 10-year-old pendulum probes were based on scaling ratios relative to the 89-millimeter (3.5-inch) pendulum probe used in Q6 lateral calibration testing (Q6 User Manual, 2012) and the 50th percentile male impactor probe.

Pendulum impact force data was recorded through a uniaxial accelerometer mounted on the rear of the pendulum. A redundant uniaxial accelerometer was also mounted to the rear of the pendulum. Impact force was calculated by multiplying the pendulum by the recorded acceleration. The target impact speed for the thoracic impact tests was 4.3 m/s, and the target impact speed for the abdominal impact tests was 4.8 m/s. A test table describing the various testing is provided in Table 5, below.

Table 5: Pendulum Impact Testing Matrix

	Pendulum Tests	
3-Year-Old PSE	**ISO Thorax Test 1** 1.7 kg mass 4.3 m/s impact (3 Runs - 3 Pigs)	**van Rantingen Abdomen** 1.7 kg mass 4.8 m/s impact (3 Runs - 3 Pigs)
6-Year-Old PSE	**ISO Thorax Test 1** 2.9 kg mass 4.3 m/s impact (3 Runs - 3 Pigs)	**van Rantingen Abdomen** 2.9 kg mass 4.8 m/s impact (3 Runs - 3 Pigs)
10-Year-Old PSE	**ISO Thorax Test 1** 6.5 kg mass 4.3 m/s impact (3 Runs - 3 Pigs)	**van Rantingen Abdomen** 6.5 kg mass 4.8 m/s impact (3 Runs - 3 Pigs)
50th Percentile Male PSE	**ISO Thorax Test 1** 23.4 kg mass 4.3 m/s impact (3 Runs - 3 Pigs)	**van Rantingen Abdomen** 23.4 kg mass 4.8 m/s impact (3 Runs - 3 Pigs)

An optical sensor speed trap was used to verify pendulum speed just prior to impact. All sensors were connected to a TDAS data acquisition system, and data was collected at a sampling rate of 10,000 Hz. In addition to the superior mounted high-speed camera mentioned previously, the impact events were captured at a rate of 1,000 frames per second by a second, lateral view high-speed video camera (Kodak EKTAPRO HG Imager, Model 2000). Three replicate runs, each with a different specimen, were performed for each of the tests in Table 3.

The data collected was filtered using the SAE J211 recommended practice (2003) and ISO/TR 9790 (1999) specifications. Thorax pendulum tests were filtered using 100Hz FIR filters. Since deflection data was not measured for the swine abdominal impacts, but measured using overall chest deflection in the thoracic pendulum impact tests, an effective stiffness normalization methodology was not feasible. The data, therefore, was normalized using the effective mass – characteristic length methodology described in Mertz (1984) and Irwin et al. (2002). The data was aligned using the methodology described in Donnelly and Moorhouse (2012), and compared for each body region tested (thorax and abdomen).

Human Response Corridor Target Comparison to Porcine Surrogate Data

The impact response data collected from the PSE thorax lateral impact pendulum tests were assessed against the scaled human impact response corridors from pendulum testing published in Irwin et al. (2002). The impact response data collected from the PSE abdominal oblique impact pendulum tests were assessed against the scaled human impact response corridors suggested in van Rantingen et al. (1997). Impact response corridor guidelines for the thorax and abdomen are provided in Tables 6 and 7, respectively.

Table 6: Human Thorax Impact Response Corridor Guidelines

Human Thorax Impact Response Corridors - 4.3 m/s Pendulum Impact (Irwin et al. (2002))									
		3-Year-Old Struck by a 1.7 kg Pendulum		6-Year-Old Struck by a 2.9 kg Pendulum		10-Year-Old Struck by a 6.5 kg Pendulum		Mid Male Struck by a 23.4 kg Pendulum	
		Time (sec)	Force (kN)	Time (sec)	Force (kN)	Time (sec)	Force (kN)	Time (sec)	Force (kN)
Upper Boundary Coordinates	A	0	0.3	0	0.5	0	0.8	0	1.7
	B	0.006	0.66	0.006	1.1	0.007	1.8	0.01	3.7
	C	0.019	0.66	0.019	1.1	0.022	1.8	0.03	3.7
	D	0.028	0.36	0.028	0.6	0.032	1	0.045	2
Lower Boundary Coordinates	E	0	0	0	0	0	0	0	0
	F	0.006	0.3	0.006	0.5	0.007	0.8	0.01	1.7
	G	0.019	0.3	0.019	0.5	0.022	0.8	0.03	1.7
	H	0.025	0	0.025	0	0.029	0	0.04	0
		Time (sec)	T1 Acceleration (G)	Time (sec)	T1 Acceleration (G)	Time (sec)	T1 Acceleration (G)	Time (sec)	T1 Acceleration (G)
Upper Boundary Coordinates	A	0	2	0	2	0	2	0	2
	B	0.009	14	0.009	16	0.011	18	0.015	15
	C	0.031	0	0.031	0	0.036	0	0.05	0
Lower Boundary Coordinates	D	0.004	0	0.004	0	0.004	0	0.006	0
	E	0.009	8	0.009	9	0.011	9	0.015	8
	F	0.023	0	0.023	0	0.027	0	0.037	0

Table 7: Human Abdomen Impact Response Corridor Guidelines

Human Abdomen Impact Response Corridors - 4.8 m/s Pendulum Impact (van Rantingen et al. (1997))									
		3-Year-Old Struck by a 1.7 kg Pendulum		6-Year-Old Struck by a 2.9 kg Pendulum		10-Year-Old Struck by a 6.5 kg Pendulum		Mid Male Struck by a 23.4 kg Pendulum	
		Time (sec)	Force (kN)	Time (sec)	Force (kN)	Time (sec)	Force (kN)	Time (sec)	Force (kN)
Upper Boundary Coordinates	A	0.000	0.0	0.000	0.0	0.000	0.0	0.00	0
	B	0.001	0.2	0.001	0.4	0.001	0.7	0.00	1.5
	C	0.010	0.5	0.011	0.8	0.013	1.4	0.02	3
	D	0.018	0.5	0.019	0.8	0.022	1.4	0.03	3
	E	0.034	0.2	0.036	0.3	0.042	0.6	0.06	1.3
Lower Boundary Coordinates	F	0.000	0.0	0.000	0.0	0.000	0.0	0.00	0
	G	0.015	0.2	0.016	0.4	0.019	0.7	0.03	1.5
	H	0.022	0.2	0.024	0.4	0.028	0.7	0.04	1.5
	I	0.034	0.1	0.036	0.1	0.042	0.2	0.06	0.5
		Deflection (mm)	Force (kN)	Deflection (mm)	Force (kN)	Deflection (mm)	Force (kN)	Deflection (mm)	Force (kN)
Upper Boundary Coordinates	A	0	0.0	0	0.0	0	0.0	0	0
	B	8	0.2	9	0.4	11	0.7	15	1.5
	C	48	0.5	50	0.8	60	1.4	85	3
	D	84	0.5	89	0.8	105	1.4	150	3
Lower Boundary Coordinates	E	0	0.0	0	0.0	0	0.0	0	0
	F	45	0.2	47	0.4	56	0.7	80	1.5
	G	56	0.2	59	0.4	70	0.7	100	1.5

RESULTS

Gross dissection of the thoracic and abdominal regions for PSE involved in the thoracic and abdominal impact tests, respectively, were performed to verify there were no broken ribs or internal tissue damage from the impacts. Ribs 6 and 7 on the impacted side of the 50th percentile male PSE used in Test 37 were the only ribs determined to have fractured during all testing performed. No abdominal region internal bleeding or contusions were identified in any of the testing.

Pendulum impact thorax response data for the PSE tested were compared to the response requirements described in the ISO/TR9790 Technical Report, as scaled to the 3-year-old, 6-year-old, 10-year-old human from the 50th percentile human male in Irwin et al. (2002) and pendulum thorax impact force and T1 level Y axis accelerations with respect to time are provided in Figures 3 through 6 (left and right, respectively).

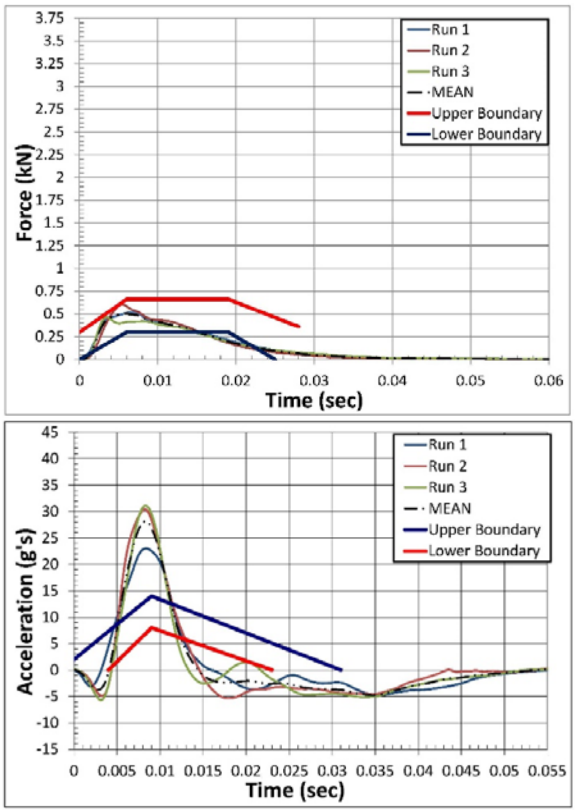
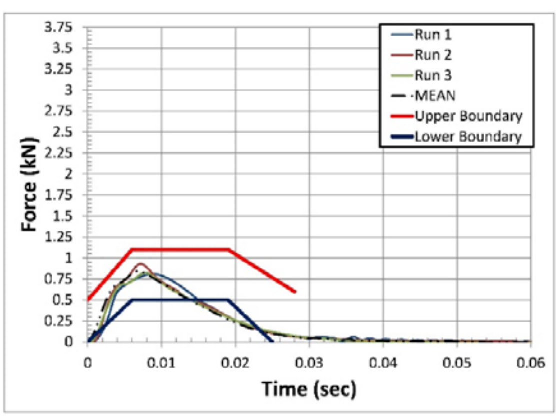


Figure 3: 3-Year-Old PSE Pendulum Thorax Impact Force v Time (Top) and 3-Year-Old PSE Pendulum Thorax Impact T1 Acceleration v Time (Bottom)



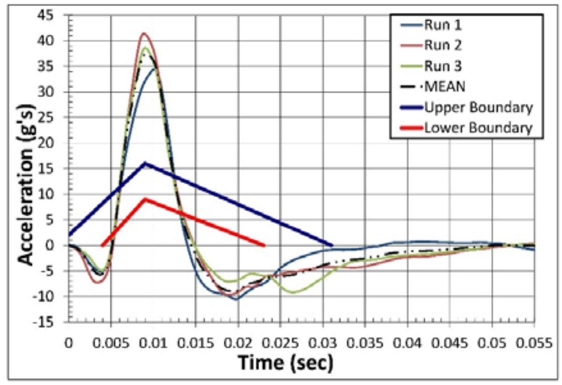


Figure 4: 6-Year-Old PSE Pendulum Thorax Impact Force v Time (Bottom Left) and 6-Year-Old PSE Pendulum Thorax Impact T1 Acceleration v Time (Above)

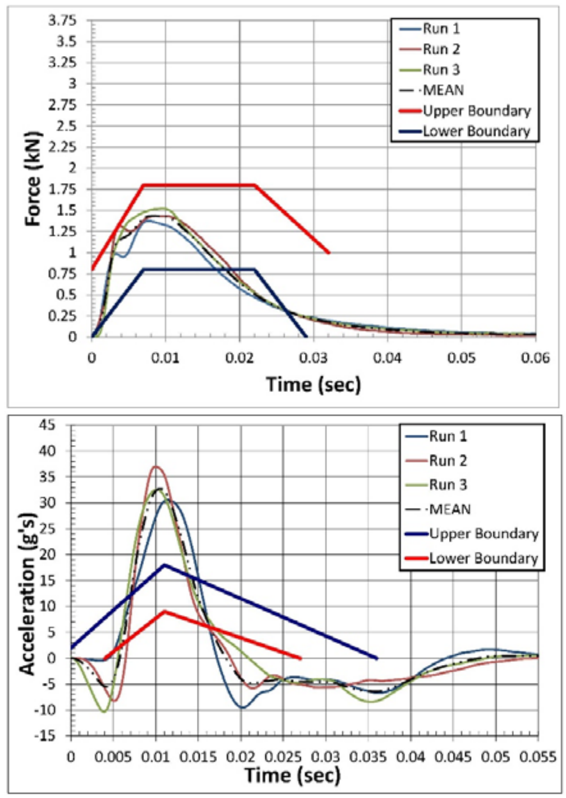


Figure 5: 10-Year-Old PSE Pendulum Thorax Impact Force v Time (Top) and 10-Year-Old PSE Pendulum Thorax Impact T1 Acceleration v Time (Bottom)

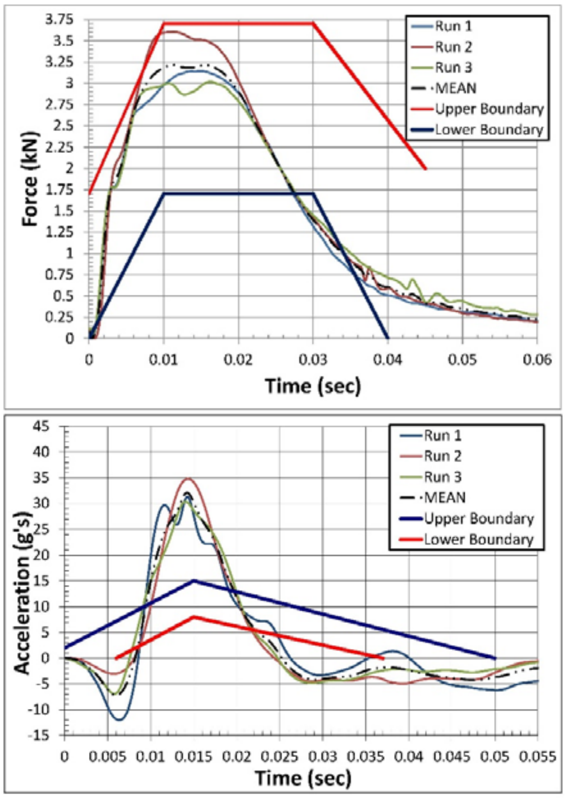
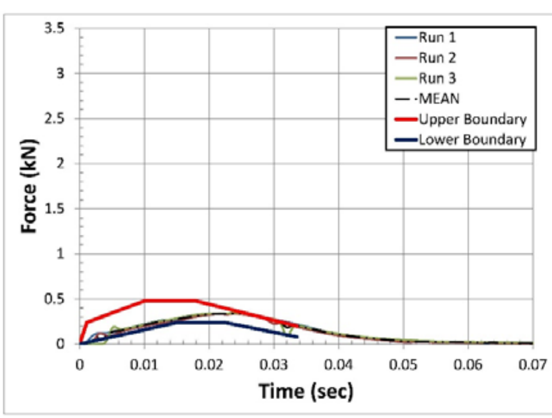


Figure 6: 50th Percentile Male PSE Pendulum Thorax Impact Force v Time (Top) and 50th Percentile Male PSE Pendulum Thorax Impact T1 Acceleration v Time (Bottom)

Pendulum impact abdominal response data for the PSE tested were compared to the abdominal response corridors suggested in van Ratingen et al. (1997), as scaled to the 3-year-old, 6-year-old, 10-year-old human from the 50th percentile human male and are provided in Figure 7 for reference.



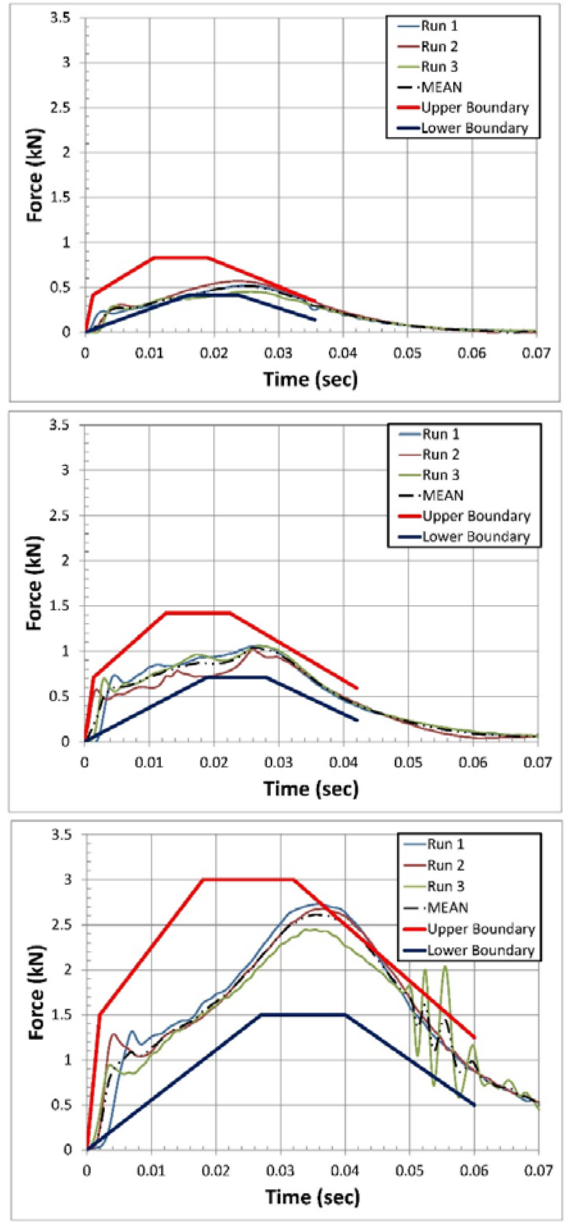
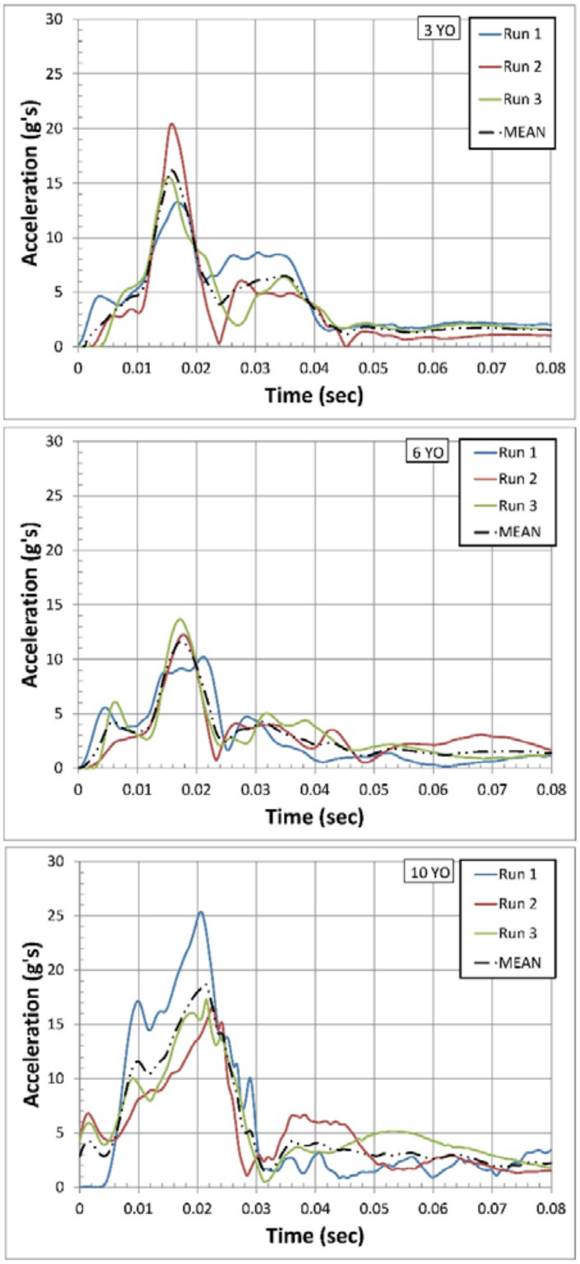


Figure 7: PSE Pendulum Abdominal Impact Force v Time Compared to van Rantingen scaled Human Abdominal Impact Response Corridor at all Studied Age Levels - 3-Year-Old (Bottom Left), 6-Year-Old (Top Right), 10-Year-Old (Middle Right), 50th Male (Bottom Right)

Although there are no human oblique abdominal pendulum impact testing equivalent impact response corridors for the swine resultant T14 or L6 acceleration versus time, this data has been provided for further research purposes. Figure 8 shows the comparison of the 3, 6, 10-year-old, and 50th male PSE tested pendulum impact resultant T14 acceleration versus time.



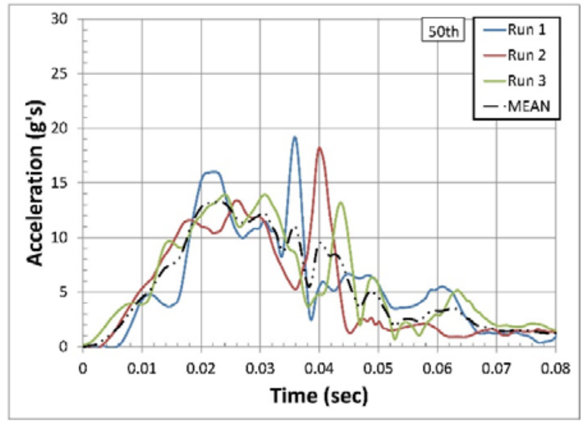
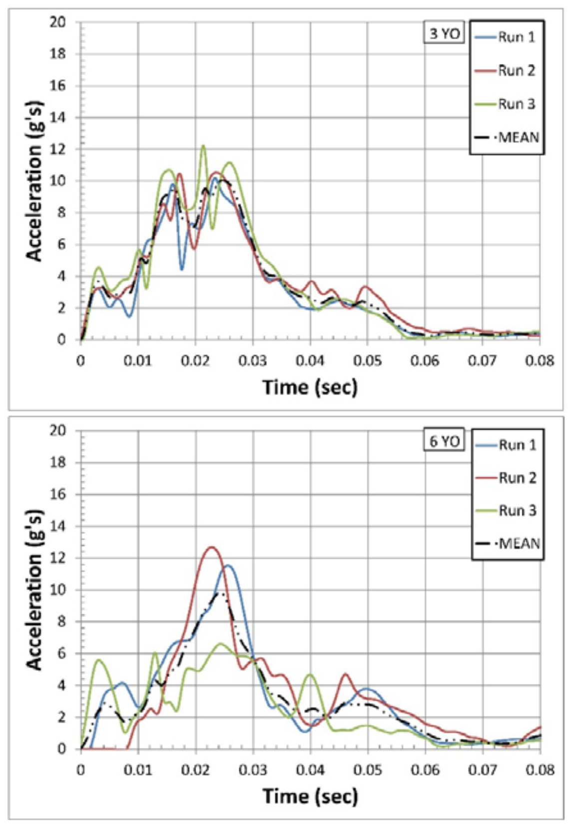


Figure 8: PSE Pendulum Abdominal Oblique Impact Resultant T14 Acceleration v Time at all Studied Age Levels - 3-Year-Old (Top Left), 6-Year-Old (Middle Left), 10-Year-Old (Bottom Left), 50th Male (Top Right)

Figure 9 shows the comparison of the 3, 6, 10-year-old, and 50th male PSE tested pendulum impact resultant L6 acceleration versus time.



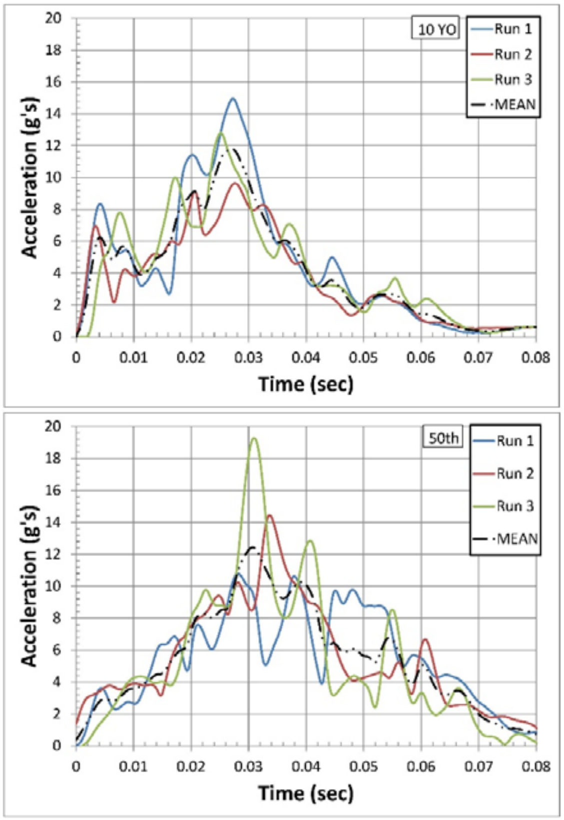


Figure 9: PSE Pendulum Abdominal Oblique Impact Resultant L6 Acceleration v Time at all Studied Age Levels - 3-Year-Old (Top Right – Previous Page), 6-Year-Old (Bottom Right – Previous Page), 10-Year-Old (Top Left), 50th Male (Bottom Left)

Again, although there are no impact response corridors for thoracic deflection, this data is also provided. Figure 10 shows the comparison of the 3, 6, 10-year-old, and 50th male PSE tested pendulum impact force versus lateral full chest deflection. This data exhibits an increase in force with age and an increase in full chest deflection up to approximately the 10-year-old age level based on the tested PSE. The current data shows similar full chest deflection at the 10-year-old PSE tested age level as the 50th male PSE age.

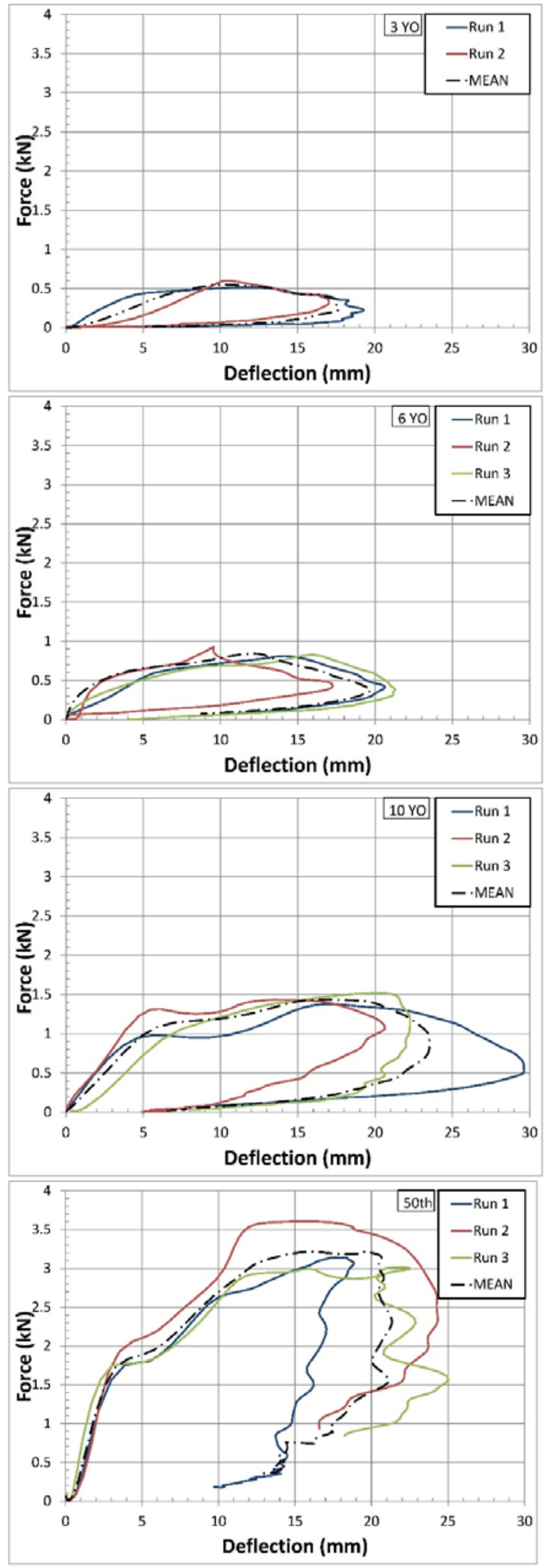
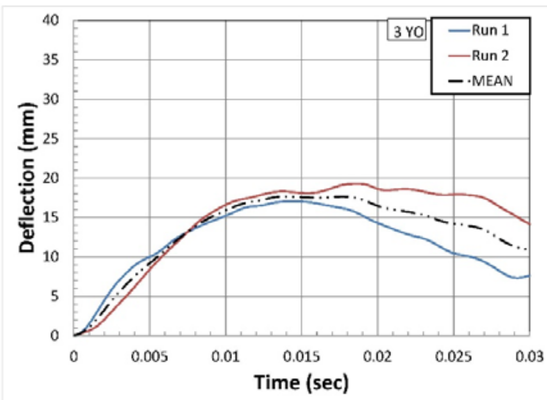
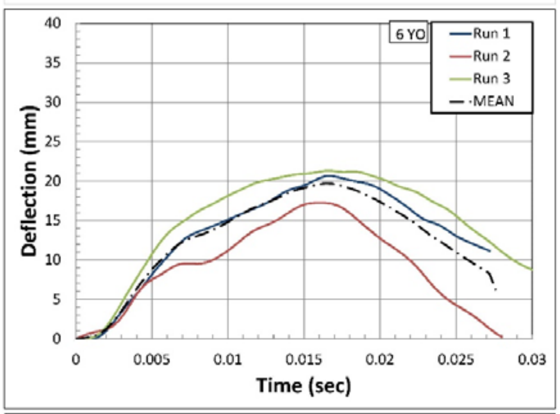


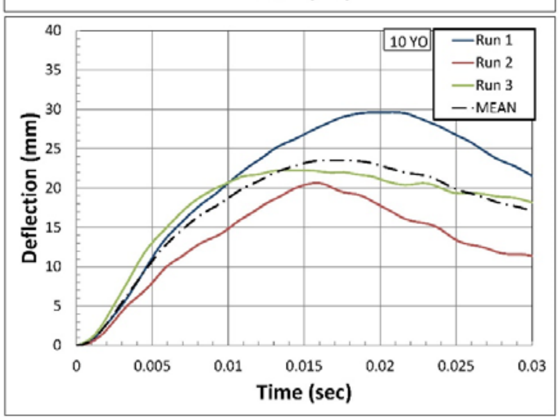
Figure 10: PSE Pendulum Impact Force v. Lateral Full Chest Deflection Data Comparison (3-year-old (Top

Right – Previous Page); 6-year-old (Second Right – Previous Page); 10-year-old (Third Right – Previous Page); 50th male (Bottom Right – Previous Page)

Figure 11 illustrates the comparison of the 3, 6, 10-year-old, and 50th male PSE tested lateral full chest deflection versus time. These graphs more readily show the increase in chest deflection with age up to the 10-year-old age level and a similar chest deflection at the 10-year-old level and 50th male PSE age level.







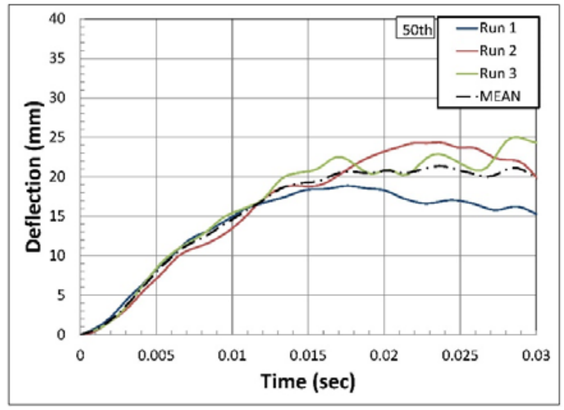


Figure 11: PSE Pendulum Thoracic Impact Lateral Full Chest Deflection v. Time Data Comparison (3-year-old (Top Left); 6-year-old (Middle Left); 10-year-old (Bottom Left); 50th male (Top Right)

Peak full chest deflection, peak force, and peak T1 accelerations and times of occurrence from the thorax impact tests as well as peak force and peak resultant T14 and L6 accelerations and times of occurrence from the abdominal impact tests are provided in Table 8 for reference.

Table 8: Peak Values and Time of Occurrence

Subject	Run	Peak Full Chest Deflection (mm)	Time (sec)	Peak Thoracic Force (kN)	Time (sec)	Peak Thoracic T1 Acceleration (G)	Time (sec)
3-Year-Old PSE	*Run 1*	17.03	0.0144	0.52	0.007	31.09	0.0083
	Run 2	19.28	0.0188	0.60	0.006	30.42	0.0082
	Run 3			0.46	0.003	23.05	0.0082
	MEAN	17.66	0.014	0.50	0.006	28.18	0.0083
6-Year-Old PSE	*Run 1*	20.64	0.0168	0.81	0.009	34.46	0.0101
	Run 2	17.25	0.016	0.93	0.007	38.59	0.0090
	Run 3	21.29	0.0168	0.83	0.008	41.43	0.0089
	MEAN	19.71	0.0164	0.84	0.007	37.39	0.0091
10-Year-Old PSE	*Run 1*	29.64	0.0208	1.38	0.008	32.55	0.0101
	Run 2	20.64	0.016	1.43	0.009	30.60	0.0114
	Run 3	22.27	0.0136	1.52	0.01	37.01	0.0100
	MEAN	23.53	0.0164	1.44	0.008	32.73	0.0105
50th PSE	*Run 1*	18.86	0.0176	3.14	0.014	30.35	0.0140
	Run 2	24.35	0.0236	3.60	0.011	31.31	0.0143
	Run 3	25.03	0.0288	3.02	0.016	34.81	0.0143
	MEAN	21.35	0.0236	3.22	0.011	32.12	0.0142

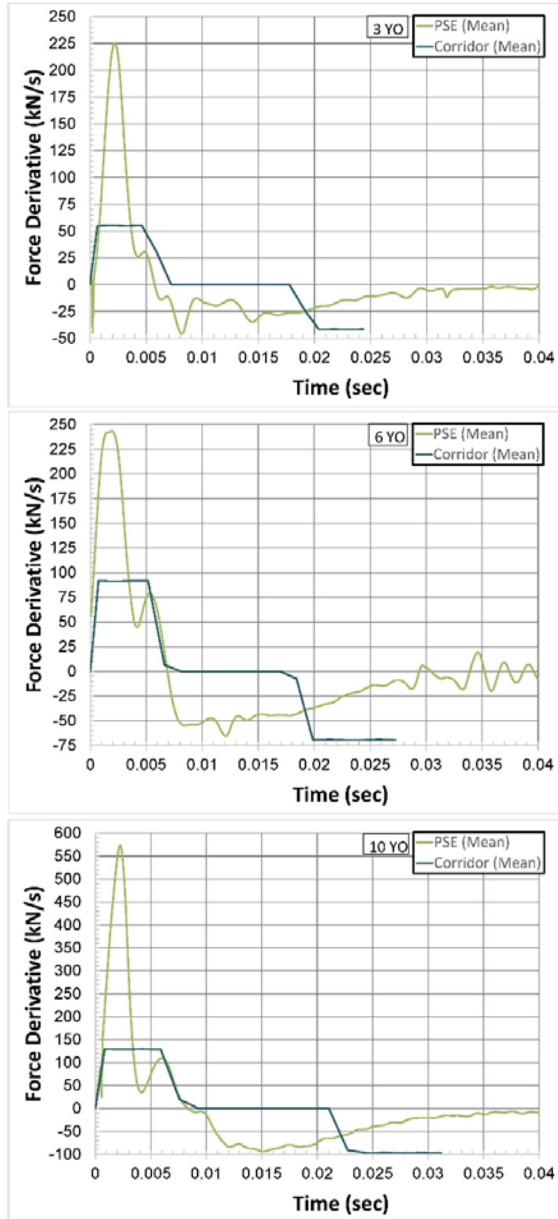
Subject	Run	Peak Abdominal Force (kN)	Time (sec)	Peak Abdominal T14 Resultant Acceleration (G)	Time (sec)	Peak Abdominal L6 Resultant Acceleration (G)	Time (sec)
3-Year-Old PSE	*Run 1*	0.34	0.0224	13.27	0.0168	10.21	0.0234
	Run 2	0.33	0.0215	20.46	0.0158	10.54	0.0236
	Run 3	0.34	0.0221	15.52	0.0154	12.24	0.0213
	MEAN	0.34	0.0219	16.14	0.0159	10.04	0.0247
6-Year-Old PSE	*Run 1*	0.52	0.0255	10.19	0.0211	11.52	0.0256
	Run 2	0.57	0.0237	12.25	0.0177	12.67	0.0228
	Run 3	0.45	0.0256	13.68	0.0172	6.60	0.0243
	MEAN	0.51	0.0242	11.65	0.0175	9.86	0.0242
10-Year-Old PSE	*Run 1*	1.06	0.0270	25.38	0.0206	14.96	0.0272
	Run 2	1.03	0.0260	16.67	0.0227	9.63	0.0275
	Run 3	1.06	0.0273	17.27	0.0216	12.81	0.0252
	MEAN	1.04	0.0262	18.70	0.0214	11.82	0.0270
50th PSE	*Run 1*	2.73	0.0360	16.00	0.0225	10.79	0.0281
	Run 2	2.68	0.0367	13.40	0.0261	14.45	0.0335
	Run 3	2.45	0.0367	13.92	0.0308	19.29	0.0309
	MEAN	2.62	0.0355	13.28	0.0230	12.44	0.0307

DISCUSSION

Peak pendulum impact thorax T1 lateral (Y axis) accelerations for all PSE tested at all age equivalent levels were considerably higher in value than the corresponding scaled human upper response corridor boundaries. Peak PSE thorax T1 accelerations were 1.8 to 2.3 times greater than the human ISO upper boundary response corridors at the age levels tested. In addition, thorax impact pulse duration for all age level PSE T1 acceleration data is shorter than the corresponding human impact response corridors. Peak PSE thoracic pendulum impact force magnitudes essentially fell within the ISO scaled human impact response corridors for all ages; however, PSE thorax pendulum impact force pulse durations were less than the human impact response corridors by approximately 10 msec.

Peak PSE oblique abdomen pendulum impact force magnitudes essentially fell within the ISO scaled human impact response corridors for all ages. The PSE abdominal impact force pulse durations tended to be within or slightly longer than the human impact response corridors. Peak PSE oblique abdominal pendulum impact resultant T14 and L6 accelerations did not appear to increase based on the equivalent ages tested, with peak resultant T14 accelerations ranging from 10.19 to 25.38 g and L6 accelerations ranging from 6.60 to 19.29 g for all PSE tested. Time of peak resultant acceleration occurrence, however, generally increased with age for both T14 and L6 resultant accelerations with mean L6 peak accelerations generally lagging the T14 peak accelerations by approximately 5.6 to 8.8 milliseconds. Viano et al. (1989A; 1989B) provided peak T12-Y acceleration data from the 50th human male oblique lateral pendulum impact testing performed. Impactor test speeds for these tests ranged from 3.8 to 9.3 m/s. T12-Y peak accelerations for tests run at similar speeds to the abdominal tests performed at 4.8 m/s in the current study were documented as 12.6 g $\pm$ 8.5 g, which is comparable to the mean resultant 50th male PSE T14 acceleration of 13.28 g.

The derivative of force versus time data can provide insight into stiffness and relative response of the struck object, assuming the striking object is rigid and unyielding. Force derivative calculations were performed in the current study for the PSE force versus time impact data as well as for the corresponding average human impact response corridors for both the thorax and abdominal impacts. The corresponding PSE and human force derivative data was compared. Figure 12 shows the thorax force derivative data comparison for the PSE and human at all studied age levels. It should be noted that the derivation data was calculated from the filtered force versus time data. Although the change of slopes in this derivation data should be sharp, calculating it from the filtered data most likely caused the smoothing of the data presented.



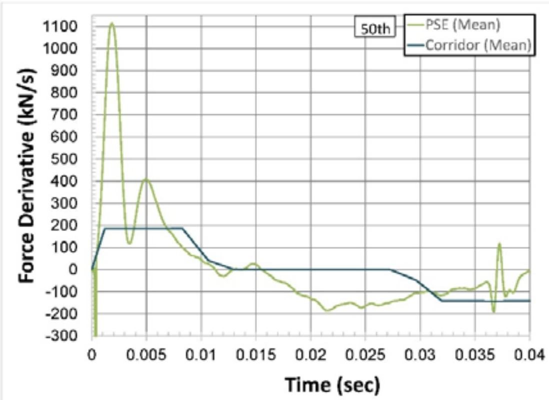
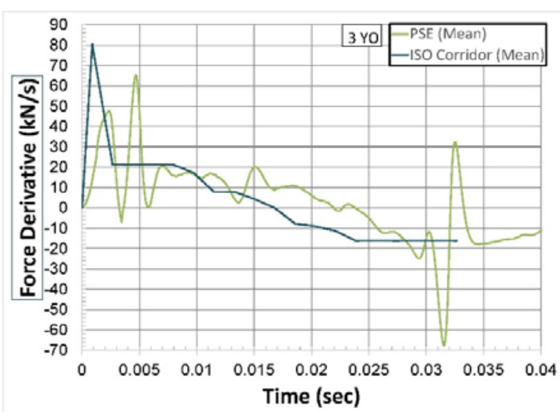
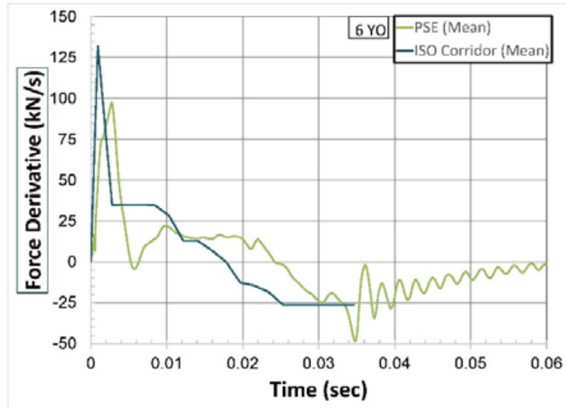


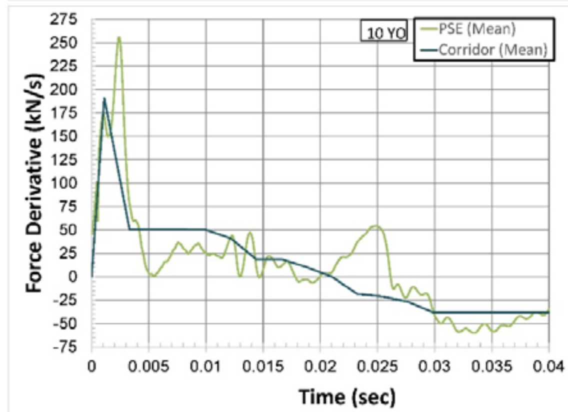
Figure 12: Thorax Force Derivative Data Comparison for the PSE and Human at all Studied Age Levels – 3-Year-Old (Top Right – Previous Page), 6-Year-Old (Middle Right – Previous Page), 10-Year-Old (Bottom Right – Previous Page), 50th Male (Above)

It can be seen from the thorax force derivative graphs provided in Figure 12, above, that for all ages, the force derivative of the swine is much higher in magnitude, shorter in duration, and passes through zero sooner than the human. The time location where the force derivative curve passes through zero is where the maximum impact force occurs and a common velocity between the two impacting objects is achieved.

Figure 13 provides the abdominal force derivative data comparison for the PSE and humans at all age levels studied.







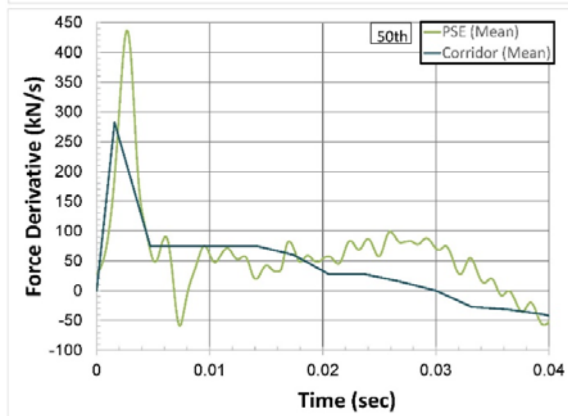


Figure 13: Abdominal Force Derivative Data Comparison for the PSE and Human at all Studied Age Levels – 3-Year-Old (Bottom Left), 6-Year-Old (Top Right), 10-Year-Old (Middle Right), 50th Male (Bottom Right)

The more compliant porcine abdomen force derivative data in Figure 13 does not pass through zero until much later in time compared to the thorax. The porcine abdomen force derivative data, is however, much higher in magnitude but typically longer in duration, passing through zero later in time than the human abdominal force derivative data. The force derivative data shows that the porcine thorax is stiffer than the human thorax, but the porcine abdomen tends to be as or slightly more compliant than the human abdomen.

Full chest force versus deflection and full chest deflection versus time were also documented during the thoracic pendulum lateral impact tests and were presented previously in Figures 10 and 11, respectively. The force-deflection response defines the compliance of the rib cage in lateral impact and the area under the curve designates the amount of energy absorbed through body deformation. Comparison of the current study 50th male PSE full chest force versus deflection data to the human and swine impact results presented for the 4.3 m/s testing performed by Viano et al. (1989B; 1989C), indicates the current study porcine thorax is much less compliant than either the human or swine specimens studied by Viano et al. in 1989 (Figure 14). That is to say, the current study 50th male PSE achieved a higher impact force over a shorter rib cage deformation that is representative of a stiffer rib cage. The difference in rib cage stiffness in the current study compared to that performed by Viano et al. (1989B; 1989C) is potentially due to the method used to determine deflection. The current study utilized a superior view high speed camera, a carbon-fiber rod secured to the impacted rib which passed laterally through the thoracic region to the non-impacted side of the pig, and tracking markers (one located on the end of the carbon fiber rod secured to the impacted side of the thorax and one located on the end of a rod secured to the non-impacted side). This technique is essentially measuring full rib cage deflection and not the muscle and adipose tissue that surrounds the thorax. Viano et al. (1989B; 1989C) also used high speed video analysis to determine deflection, but it is unclear whether any sort of tracking markers were used, and if used, where they were placed, and whether half or full chest deflection was measured. In addition, it is assumed that the Viano et al. (1989B; 1989C) deflections were measured from the exterior of the skin, muscle, and adipose tissue, which could account for additional chest deflection not observed in the current study. Further research should be considered to compare human and swine full chest force deflection using the technique incorporated in the current study to more appropriately compare stiffness properties.

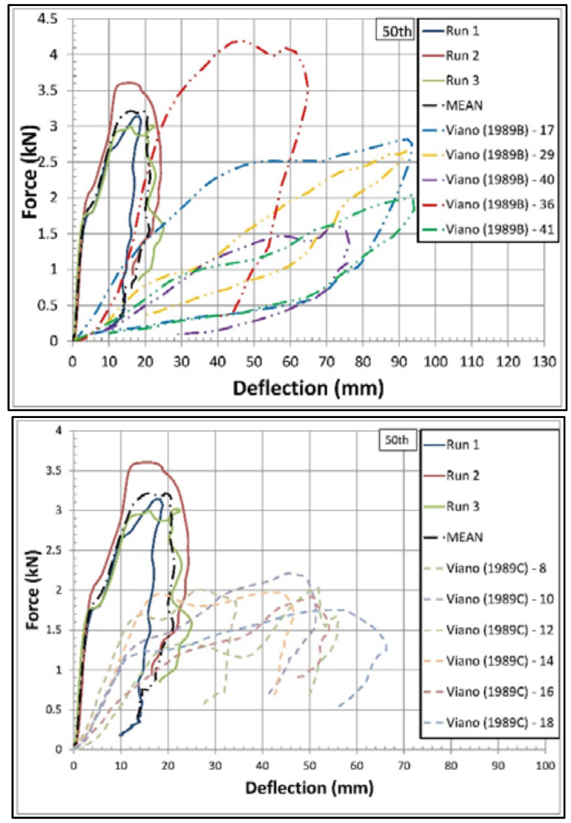


Figure 14: Comparison of Current Study 50th Male PSE Full Chest Force versus Deflection to Human (Top) and Swine (Bottom) Lateral Impact Testing in Viano et al. (1989B; 1989C) at a 4.3 m/s Pendulum Impact Speed

Kent et al. (2009), through their research of pediatric thoracoabdominal biomechanics in anterior-posterior belt loading and CPR analyses of children and adults suggested that a non-linear relationship may exist between age and thoracic stiffness, with peak thoracic stiffness occurring during the young adult phase of life and decreased thoracic stiffness for young children and the elderly. This study further suggested that current scaling methods might not adequately capture this behavior. Based on thoracic lateral impact force-displacement results for the PSE evaluated in the current study, there appears to be an increase in thoracic stiffness with age up to the 50th male adult equivalent. In addition, the current study, at least from a human-equivalent-age 3 to adult, follows the scaling laws currently established. Unlike the Kent et al. (2009) study, the current study does not take into consideration thoracic stiffness of PSE at an elderly human adult age level. Further investigation and study of PSE representing elderly humans would be needed to evaluate this hypothesis.

Post euthanized porcine surrogates lungs were not inflated, pressurization of the vascular system was not performed, and specimen muscles were not tensed in the current study since only whole body impact response data comparable to previous testing performed and data used to develop the human impact response corridors was sought during the current study. Since the lungs were not inflated in the study, the placement of the composite rod through the thorax, although potentially compromising the lungs to some degree, would be expected to have minimal influence on the impact response characteristics.

Porcine thoracic and abdominal impact force response data for all equivalent age levels studied tend to follow the scaled human ISO and van Rantingen response corridors, respectively. The current study has shown the adult PSE thorax tends to develop higher resistive forces sooner and does not compress as much as the adult human thorax in lateral impact. This is most likely due to the difference in shape of the swine and human thorax, with the swine rib cages tending to be thinner in breadth and longer in depth than the human rib cage (Sack, 1982). This can have an effect on the magnitude of lateral forces and accelerations documented in the current study. Adult human and porcine abdominal pendulum force impact data tend to be similar in pulse shape, magnitude, and pulse duration. Considering the size of the human impact response corridors, it would appropriate to compare scaling factors used in developing the response corridors to force ratios in this study. This additional work has been performed in this research and is intended to be provided in another research paper in the near future.

This study has some important limitations. Weight appears to be an appropriate factor in determining suitable porcine surrogates for human test comparison. However, based on the results of the current study, specifically the fact that the swine torso is stiffer than the human, it is clearly not the only factor. More research needs to be performed to determine if other factors, such as torso stiffness or even swine breed, in combination with weight, can be established for the determination of more suitable swine surrogate models for human pediatric level side impact research. In addition, further investigation is needed regarding the use of age development as a secondary determining factor. The current testing only evaluated whether current ISO lateral pendulum impact response corridors are comparable to PSE data for the thorax and abdominal regions, but it does not assess if the scaling laws are appropriate. Further research has been done in this area and will be provided in another research paper in the near future. The current study does not evaluate any other body region beyond the thorax and abdomen. In addition, the current study does not evaluate PSE to human children under age 3 or the elderly.

Since abdominal deflection was not measured in the 6-year-old ATD tests, it was not measured for the swine in the current study; however, analysis of the porcine abdominal force-deflection properties would be valuable in the development of ATD biofidelity design and should be considered in future studies.

In order to impact the pigs in their upright standing position, a fixture was fabricated to suspend the pigs from chains passed through the swine specimen's dorsal adipose tissue. Multiple impact tests were performed to verify that the chains suspending the swine did not have any significant effect on the response data prior to maximum impact, either from the added mass of the chains or motion limitations during impact. Any significant variation in chain placement could potentially have some effect on swine spinal bending during impact, and therefore, force and acceleration response data.

Any animal model has accompanying limitations in terms of its ability to represent human response. Although relative position of organs are similar, size, location, and geometry of organs are not entirely comparable from pigs to humans. There are other certain anatomical differences between pigs and humans that can have an effect on the limitations of the current study's findings. For instance, pigs are quadrupedal compared to humans, who are bipedal. As quadrupedal mammals, porcine thoracic and abdominal organs are forced anteriorly (ventrally) due to gravity, whereas a human's organs are forced inferiorly. It should be noted that research performed by Pope et al. (1979) illustrated that influences due to unnatural positioning of the swine could affect impact response results to the thorax and abdomen. Therefore, it was decided to position the pigs in their natural standing position for current study testing and evaluation. Not every domestic swine grows at the same rate or has the same structural makeup as the swine used in the current study. The current study used only Hampshire/Yorkshire Cross domestic pigs throughout testing and analysis. Further investigation should be made to determine how results might be effected by other swine breeds.

This author is not aware of any current or past thoracic or abdominal lateral impact research performed on human child PMHS. The only known human child PMHS research to date was performed in an anterior-posterior impact direction to the thoracic or abdominal region and was performed by Kent et al. (2006, 2009, and 2011) and Ouyang et al. (2006). Ramachandra et al. (2016) recently performed similar anterior-posterior loading to the abdomen with a transverse oriented seatbelt on adult human PMHS.

The Ouyang et al. (2006) research appears, at least in force magnitude, to be consistent with the magnitude ranges of the current study 3 to 10-year-old PSE as well as the scaled 3 to 10-year-old thoracic impact response corridors with respect to human lateral impact from Irwin et al. (2002). Similarity in thoracic force magnitude between the lateral impacts in the current study and the frontal impacts performed in the Ouyang et al. (2006) study is likely due to the inverse proportions of the human thorax breadth and depth to the swine breadth and depth (see Tables 2 and 3 for reference) and therefore the relative stiffness of the human thorax in frontal impact versus swine thorax stiffness in lateral impact. Further research would need to be performed to further verify this observation.

The Kent et al. (2006, 2009, 2011) and Ramachandra et al. (2016) studies with respect to abdominal force magnitude appear to be greater than what was observed in the PSE abdominal impact force tests in the current study as well as the scaled 3 to 10-year-old abdomen impact response corridors suggested by van Rantingen et al. (1997) with respect to human lateral impact testing. Differences in abdominal force magnitude between the oblique impact testing in the current study and the frontal impacts performed in the Kent et al. (2006, 2009, 2011) and Ramachandra et al. (2016) studies may be due to potential engagement of some of the ribs in the human studies versus positioning of the pendulum in the current study to purposely avoid impact with respect to any bony structure of the swine's abdominal region. Another factor may be the effect of gravity on the hanging abdominal region of the swine in their natural quadrupedal orientation compared to the more compacting effect gravity has on the human abdominal region in its seated orientation. Further research would be needed to further verify these observations.

CONCLUSION

The primary contributions of this study were to establish age equivalent PSE for the human 3, 6, 10-year-old, and the 50th percentile male; test the thoracic and abdominal regions of the PSE in lateral pendulum impact testing; and compare the results of the PSE lateral pendulum impact testing to established adult human and scaled child lateral impact response corridors for the thorax and abdomen.

The overall findings of the current study confirm that lateral impact force response of the thorax and abdomen of appropriate weight porcine surrogates established for human-equivalent-age 3-year-old, 6-year-old, 10-year-old, and 50th adult male are consistent with the ISO human scaled lateral impact response corridors presented in Irwin et al. (2002) and van Rantingen et al (1997) and the potential applicability of current scaling laws. Peak PSE thoracic and abdomen pendulum impact force magnitudes essentially fell within the ISO human impact response corridors for all ages. PSE thorax pendulum impact force pulse durations were shorter than the human impact response corridors by approximately 10 msec, whereas the PSE abdominal impact force pulse durations tended to be within or slightly longer than the human impact response corridors. More work needs to be performed to better understand the discrepancy observed in the T1 lateral (Y axis) acceleration PSE data compared to the established human impact response corridors. The 50th male PSE peak resultant T14 accelerations were found to be comparable to the 50th male human T12Y data produced in Viano et al. (1989A; 1989B). Further research in establishing a comparison of 3 to 10-year-old human oblique abdominal pendulum impact response at the T12 and L5 regions to the data provided for the PSE in the current study would provide further support and validation for the use of swine in analyzing human thorax and abdominal testing and the more biofidelic design of ATDs ages 3 to adult. There appears to be a discrepancy in the deflection data measured in the current study to past studies for both swine and humans. Further research should be considered to compare human and swine full chest force deflection at the various age levels studied using the technique either provided in the current study or more comparable to the Viano et al. (1989B; 1989C) studies to more appropriately compare stiffness properties between human and swine.

Due to the scarcity of child PMHS data for research in occupant safety in vehicle crashes, porcine thorax and abdomen testing can provide applicable and definitive surrogate model to human force response at all equivalent age levels. Porcine surrogate testing in lateral impact proves to be a powerful research means with regard to vehicle safety.

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REFERENCES

Donnelly, B.R., Moorhouse, K., (2012). Optimized phasing of PMHS response curves for biofidelity targets. Paper presented at: IRCOBI Conference. IRC-12-51.

Eppinger, R., (1976). Prediction of thoracic injury using measureable experimental parameters. In: *Proc. 6th International ESV Conference,* Washington, DC. NHTSA, pp 770-779.

Foster, J.K., Kortge, J.O., Wolanin, M.J., (1977). Hybrid III – A biomechanically based crash test dummy. *Society of Automotive Engineers*. 770938.

Gogler, E., Best, A., Braess, H., Burst, E., Laschet, G., (1977). Biomechanical experiments with animals on abdominal tolerance levels. *Proc. 21st Stapp Car Crash Conference.* 770931.

Hybrid III 50th Male User Manual. Humanetics Innovative Solutions; 2012.

Irwin, A.L., Mertz, H.J., (1997). Biomechanical basis for the CRABI and hybrid III child dummies. *Society of Automotive Engineers*. 973317.

Irwin, A.L., Mertz, H.J., Elhagediab, A.M., Moss, S., (2002). Guidelines for assessing the biofidelity of side impact dummies of various sizes and ages. *Stapp Car Crash Journal*, Vol. 46, Paper No. 2002-22-0016, 297-319.

Irwin, A.L., Mertz, H.J., (2010). Rationale for and dimensions of impact surfaces for biofidelity tests of different sizes of frontal and side impact dummies. *Stapp Car Crash Journal*; 54, Paper No. 2010-22-0002, 19-35.

ISO/TR 9790 Technical Report. Road Vehicles - Anthropometric Side Impact Dummy - Lateral Impact Response Requirements to Assess the Biofidelity of the Dummy. First Edition 1999-12-01.

Kent, R., Stacey, S., Kindig, M., et al., (2006). 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 Journal*. Vol. 50, pp. 1-26.

Kent, R., Salazar, R., Kerrigan, J., et al., (2009). Pediatric thoracoabdominal biomechanics. *Stapp Car Crash Journal.* Vol. 53, pp. 373-402.

Kent, R., Lopez-Valdez, F.J., Lamp, J., et al. (2011). Characterization of the pediatric chest and abdomen using three post-mortem human subjects. *22nd Enhanced Safety of Vehicles Conference*, Paper No. 11-00394.

Lamp, J.F., Salazar, R., Kerrigan, J., et al., (2010). Expansion and evaluation of data characterizing the structural behavior of the pediatric abdomen. *Annals for Advances in Automotive Medicine.* Vol. 54.

Mertz, H., (1984). A procedure for normalizing impact response data. *Society of Automotive Engineers.* 840884.

Mertz, H.J., Irwin, A.L., Melvin, J.W., Stalnaker, R.L., Beebe, M.S., (1989). Size, weight and biomechanical impact response requirements for adult size small female and large male dummies. *Society of Automotive Engineers.* 890756.

Mertz, H.J., Weber, D.A., (1982). Interpretations of the Impact Responses of a Three-Year-Old Child Dummy Relative to Child Injury Potential. *Society of Automotive Engineers.* 826048.

Miller, M., (1989). The biomechanical response of the lower abdomen to belt restraint loading. *The Journal of Trauma.* 29(11), 1571-1584.

Ouyang, J., Zhao, W., et al., (2006). Thoracic impact testing of pediatric cadaveric subjects. *The Journal of Trauma* 61(6): 1492.

Petitjean, A., Troseille, X., Yoganandan, N., Pintar, F., (2015). Normalization and scaling for human response corridors and development of injury risk curves. In: Yoganandan, N., Nahum, A.M., Melvin, J.W., ed. *Accidental Injury*. New York: Springer Chapter 26.

Pope, M.E., Kroell, C.K., Viano, D.C., Warner, C.Y., Allen, S.D., (1979). Postural influences on thoracic impact. *Proc. 23rd Stapp Car Crash Conference.* 791028.

Prasad, P, Daniel, R.P., (1984). A biomechanical analysis of head, neck, and torso injuries to child surrogates due to sudden torso acceleration. *Society of Automotive Engineers*. 8401656.

Q6 (ADVANCED 6-YEAR-OLD CHILD) USER MANUAL. (2012). Humanetics Innovative Solutions.

Ramachandra, R., Kang, Y., Bolte, J.H., Hagedorn, A., Herriott, R., Stammen, J.A., Moorhouse, K., (2016). Biomechanical responses of PMHS subjected to abdominal seatbelt loading. *Stapp Car Crash Journal.* Vol. 60: pp. 58-87.

Rouhana, S.W., Kroell, C.K., (1989). The effect of door topography on abdominal injury in lateral impact. *Proc. 33rd Stapp Car Crash Conference*, SAE 892433, Warrendale, PA.

Sack, W.O., (1982). *Essentials of Pig Anatomy*. Ithaca, NY: Veterinary Textbooks.

SAE International Surface Vehicle Recommended Practice. Instrumentation for Impact Test - Part 1 - Electronic Instrumentation. SAE Standard J211 -1; 2003.

Van Ratingen, M., Twisk, D., Schrooten, M., Beusenberg, M., (1997). Biomechanically based design and performance targets for a 3-Year-Old child crash dummy for frontal and side impact. *Proc. 41st Stapp Car Crash Conference,* 243-260.

Viano, D.C., (1989A). Biomechanical responses and injuries in blunt lateral impact. *Proc. 33rd Stapp Car Crash Conference*, SAE 892432.

Viano, D.C., Lau, I.V., Asbury, C., King, A.I., Begeman, P., (1989B). Biomechanics of the human chest, abdomen, and pelvis in lateral impact. *Accid. Anal. & Prev.*, 21(6), 553-574.

Viano, D.C., Lau, I.V., Andrzejak, D.V., Asbury, C., (1989C). Biomechanics of injury in lateral impacts. *Accid. Anal. & Prev.*, 21(6), 535-551.

Yaek, J.L., Li, Y., Lemanski, P.J., Begeman, P.C., Rouhana, S.W., Cavanaugh, J.M., (2016). Biofidelity assessment of the 6-year-old ATDs in lateral impact, *Traffic Injury Prevention*, 17:5, 535-543, DOI: 10.1080/15389588.2015.1101080