EXPANSION AND EVALUATION OF DATA CHARACTERIZING THE STRUCTURAL BEHAVIOR OF THE PEDIATRIC ABDOMEN

John F. Lamp, Robert Salzar, Jason Kerrigan, Daniel Parent, Francisco Lopez-Valdez, Sabrina Lau, David Lessley, Richard Kent
Center for Applied Biomechanics at the University of Virginia

Jason Luck, Andre Loyd, Cameron Bass
Duke University

ABSTRACT – Despite the importance of abdominal injuries in children involved in motor vehicle collisions, only two papers have reported experimental data quantifying the pediatric abdominal response to belt loading. One developed and characterized a porcine model of the pediatric abdomen and the other presented a series of tests performed on a single pediatric (7-year-old female) post-mortem human subject (PMHS) and used the data to evaluate the efficacy of the porcine model. The current paper presents the results from an additional pediatric (6-year-old female) PMHS test series and an expanded evaluation of the porcine model using the combined PMHS data. The two PMHS exhibited remarkably similar abdominal stiffness, both by level (upper and lower) and by rate (quasi-static and ~2 m/s dynamic). Both PMHS and swine exhibited the same stiffness trend by abdominal level (lower stiffer than upper: 3444 N reaction force at 30.5 mm of displacement compared to 1756 N in the 6-year-old dynamic tests). The magnitude of lower abdomen stiffness was slightly less in the swine than in the PMHS (the average dynamic PMHS response was 1086 N greater than the porcine envelopes at 30.5 mm displacement) while the upper abdomen PMHS responses fit within the porcine response envelope.

INTRODUCTION

The abdomen is the second most commonly injured body region in young children wearing seat belts during an automobile collision, and can be associated with significant health care costs and extended hospitalization (Bergqvist et al. 1985, Tso et al. 1993, Trosseille et al. 1997, Durbin et al. 2001). Despite the importance of abdominal loading as an injury mechanism in children, especially for lap-belt loading, benchmarking data for pediatric models of this region are lacking. Although several studies have reported dynamic test results on the pediatric abdomen, most exclude a measure of deformation (Kallieris et al. 1976, Gögler et al. 1977, Wismans et al. 1979, Lopez-Valdes et al. 2009).

The largest dataset for this purpose employed a juvenile swine model (Kent et al. 2006, 2008). The sub-injury, quasi-static response of this model compared well with pediatric human volunteer tests performed with a lap belt on the lower abdomen (Chamouard et al. 1996), and a necropsy study revealed that injuries generated in the porcine model matched the distribution of injuries sustained by children in the field (Arbogast 2007). The high-rate, high-deformation response of the porcine model was not, however, benchmarked against any human pediatric response due to the lack of relevant data.

One subsequent study has provided relevant benchmarking data, albeit from a single pediatric post-mortem human subject (PMHS). Kent (Kent et al. 2009) tested a 7-year-old female PMHS in three different abdominal loading conditions while measuring belt tension, posterior reaction force, and belt displacement. Data from the pediatric PMHS abdomen exhibited a reaction force response similar to the porcine model with several important distinctions. The stiffness of the PMHS lower abdomen was slightly greater than the swine's while the upper abdomen response data fell within the porcine corridor. Furthermore, while both models (PMHS and swine) exhibited greater stiffness in the lower abdomen than in the upper, the degree of this difference was greater in the PMHS. Rate dependence in the pediatric PMHS, quantified by an analysis of the force relaxation response to a 60 second hold, was likewise similar between PMHS and swine. While the results from the pediatric PMHS tests generally confirmed that the porcine model is a reasonable benchmarking tool for the abdominal belt loading response in children, the study was limited by its reliance on a single PMHS. The objectives of this study are 1) to increase the available pediatric PMHS abdominal benchmarking data by reproducing the experiments conducted by Kent (Kent et al. 2009) using a second pediatric

PMHS, 2) to compare the results to the existing pediatric data, and 3) to expand the assessment of the porcine model using the combined PMHS data.

METHODS

A series of three tests was conducted on a pediatric PMHS abdomen: a quasi-static and a dynamic test of the lower abdomen and a dynamic test of the upper abdomen. The experimental protocols, loading conditions, and PMHS preparation procedures were identical to those described by Kent (Kent et al. 2009). A limited description of those methods is given here.

Test Specimen

One female PMHS, deceased at six years of age, was obtained and tested in accordance with the ethical guidelines established by the Human Usage Review Panel of the National Highway Traffic Safety Administration, and with the approval of the Office of the Chief Medical Examiner of Virginia, the Office of the Vice President for Research and an independent Oversight Committee at the University of Virginia, and Institutional Review Boards at Duke University and The Children's Hospital of Philadelphia. Computed tomography (CT) scans verified the absence of preexisting fractures or other bone pathology. The cause of death was germ cell malignancy, but no acute gonadal tumors were found either in the CT scans or during a post-test thoracoabdominal necropsy. Prior to the time of death the subject was on a ventilator and pre-test CT scans revealed an L5 vertebra plana, several cystic lung lesions, which is consistent with ventilator pneumonia, as well as visceral gas, evidence of postmortem putrefaction. The subject was 128 cm in stature with a whole-body mass of 24 kg. This is approximately the 95th percentile stature for a 6-year-old female, and between the 75th and 90th percentile for mass (Ogden, 2002). The stature and mass of the 7-year-old PMHS reported by Kent were 119 cm and 26.8 kg, which corresponds to between the 25th and 50th percentile for stature and the 90th percentile for mass (Kent et al. 2009). Detailed measurements of the thorax and abdomen are presented in Table 1. Upon receipt, the PMHS was stored in a freezer (-15ºC) until it was removed and thawed at room temperature for 36 hours prior to testing.

Table 1. Thorax and abdomen anthropometry measurements of the 6-year-old PMHS listed adjacent to the 7-year-old measurements reported by Kent (Kent et al. 2009)

Specimen Anthropometry (mm)			
Specimen		6 yr	7 yr
Torso breadth	4th Rib	217	273
	8th Rib	202	270
	Umbilicus	217	278
Torso depth	4th Rib	142	155
	8th Rib	140	172
	Umbilicus	122	161
Torso circumference	4th Rib	602	695
	8th Rib	593	698
	Umbilicus	590	701
Anatomical Lengths (along axis of body)			
Sternal notch to xiphoid		130	114
Xiphoid to umbilicus		159	131
Vertex to pubic symphysis		640	625

Test Hardware

The tabletop testing device described by Kent (Kent et al 2009) was used for the current test series. It utilized a hydraulic master-slave cylinder arrangement connected to a high-speed material testing machine (Instron, Canton, Massachusetts) to drive the belt assembly. The test rig consisted of a frame made of steel tubing that supported slave cylinders (Figure 1), which attached directly to the belt via steel cables that passed through channels cut in the specimen supporting hardware.

A 5-cm-wide Polyethylene fiber reinforced composite (Spectra®, E = 97 GPa) belt (identical to that used in Kent et al. 2006, 2008) was used rather than a standard seatbelt webbing to isolate the abdominal response from a combined effect that includes belt stretch. The top of the test rig consisted of an aluminum plate attached to a load cell used to measure posterior reaction forces and moments.

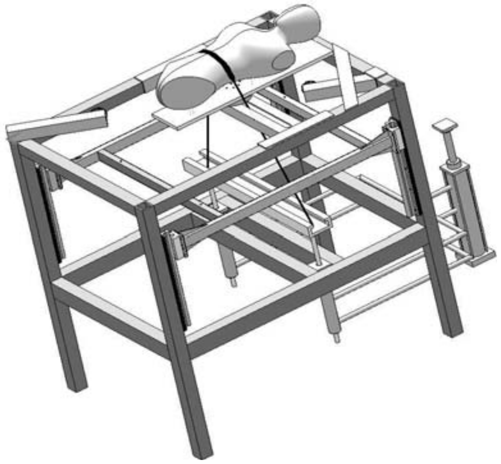

Figure 1. Illustration of tabletop testing device

Plywood sheets were used to adjust the specimen's height on the table.

Lower abdominal loading was conducted with the belt centered on the umbilicus and upper abdominal loading was performed with the belt centered approximately 7 cm superior to the umbilicus and 5 cm inferior to the xiphoid process.

Instrumentation

The table-top was instrumented with a six-axis load cell (Denton, Rochester Hills, MI) under the posterior support plate and tension load cells (Honeywell, Morristown, NJ) attached to the cable-belt system. Load cell data were sampled at 10 kHz and hardware (anti-aliasing) filtered. The data were later processed with a lowpass 100 Hz 8-pole Butterworth filter (CFC 60).

Using a methodology reported by Lessley et al. (2009), kinematic data were sampled at 1000 Hz using an eight-camera Vicon MX™ three dimensional (3D) motion capture system that tracked the motion of retro-reflective spherical targets through a calibrated 3D space with less than 1 mm resolution and 3 mm optical error (Shaw et al. 2009). The input displacement to the subject for each test condition was measured using targets secured to the belt. While this measurement was taken at multiple sites (see Kent et al. 2009 for additional detail), abdominal displacement was defined using the single target at the intersection of the belt center line and the mid-sagittal plane.

Displacements for all tests were calculated with respect to a spine-based SAE occupant coordinate system, in which the positive Z-axis was directed inferiorly along the spine and the positive X-axis was directed perpendicularly to the spine and toward the sternum, lying in the midsagittal plane. For ease of interpretation, all of the results present the absolute value of the magnitude of the abdominal displacement, and the posterior reaction force (i.e., positive sign), though the direction of the displacement was toward the spine.

Test Procedures

A series of three displacement-controlled tests was performed in accordance with the procedures established by Kent (Kent et al. 2009) to measure the abdomen response. The three conditions are described in Table 2. A minimum of 10 minutes separated each test. Before each test a nominal pretension load of 8 N was applied to each end of the belt as a preload. Prior to testing the specimen was subjected to a low severity CPR machine test as described by Kent (Kent et al. 2009). After the three abdominal tests an additional series of tests was conducted on the thorax as described by Kent (Kent et al. 2009). The data from the CPR and thoracic tests is not presented here.

Injury Identification

After testing the specimen was denuded, necropsied, and CT scanned to identify injuries. The CT scan was taken at high resolution (.59 mm in-plane and .63 mm slice thickness) and occurred within three hours of the final test. Following the CT scan a radiologist read the scan to assist in the identification of trauma resulting from the test series.

RESULTS

The maximum magnitude of applied belt displacement ranged from 26.5 mm during test PEDVE24 to 39.7 mm during test PEDVE26, with corresponding peak posterior reaction forces ranging from 638 N during the quasi-static test to 4346 N in test PEDVE25. Posterior reaction force, belt tension, and displacement are plotted for each test in Figures 2, 3, and 4.

The average of the two PMHS responses and the range of swine responses at each condition are shown in Figures 5, 6, and 7. The quasi-static human PMHS response, depicted in Figure 5, was much stiffer than the corresponding porcine response. The belt loading rates achieved in the four dynamic PMHS tests, two on the 6-year-old and two from Kent et al. 2009, were comparable to each other (close to 2m/s) and correspond to the low rate dynamic swine tests (rate bin 1) reported by Kent (Kent et al. 2006). In

Test Matrix							
Test	DAQ Index	Location	Loading Type	Target Penetration (mm)	Target Penetration (%)	Actual Penetration (mm)	Actual Penetration (%)
1	PEDVE24	lower	Quasistatic	30.5	25	26.5	21.7
2	PEDVE25	lower	Ramp 60s-Hold	30.5	25	37.3	30.6
3	PEDVE26	upper	Ramp 60s-Hold	30.5	25	39.7	32.5

Table 2. Test conditions for each of the three abdominal loading tests

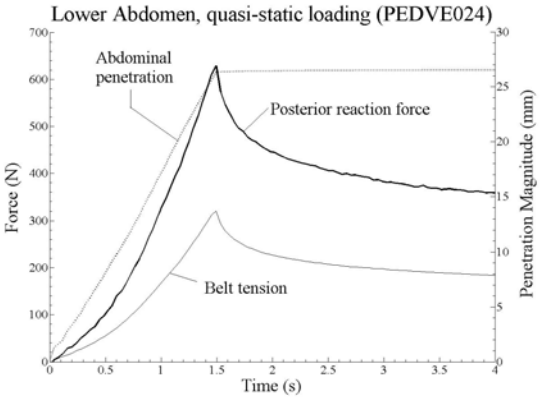

Figure 2. Lower abdomen quasi-static loading results

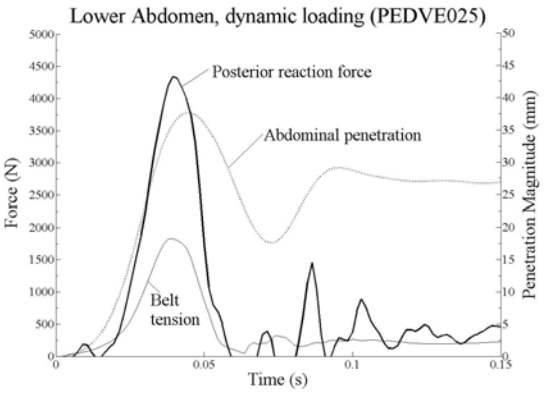

Figure 3. Lower abdomen dynamic loading results

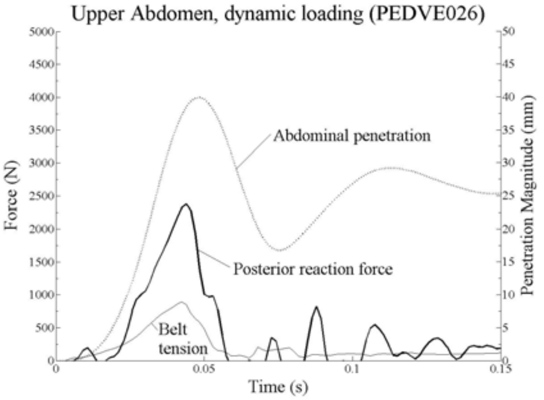

Figure 4. Upper abdomen dynamic loading results

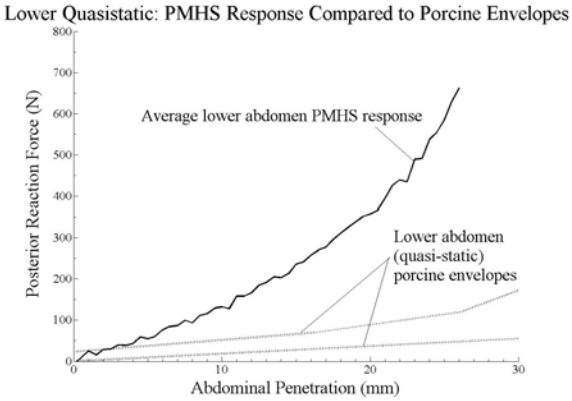

Figure 5. Lower abdomen quasi-static response comparing PMHS average to porcine model envelopes

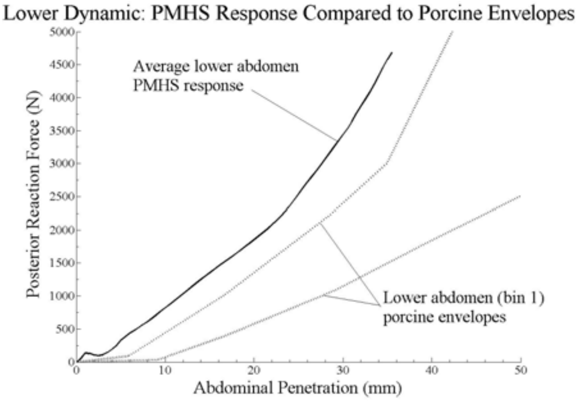

Figure 6. Lower abdomen dynamic response comparing PMHS average to porcine model envelopes

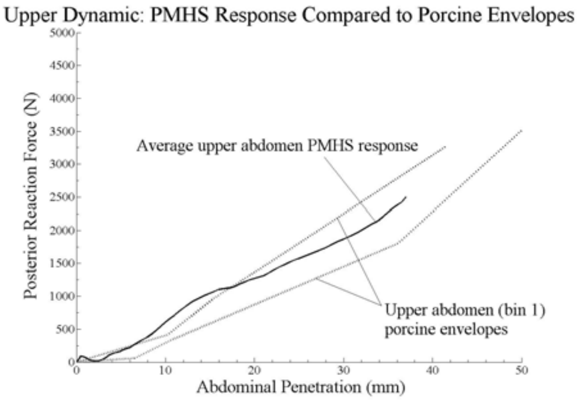

Figure 7. Upper abdomen dynamic response comparing PMHS average to porcine model envelopes

agreement with the findings of Kent (Kent et al. 2009), the average PMHS upper abdomen response agrees well with the porcine model (1901 N reaction force at 30.5 mm abdominal displacement is inside the porcine envelope), while the average PMHS lower abdomen is slightly stiffer than that of the swine (3552 N reaction force at 30.5 mm abdominal displacement is 1086 N above the porcine envelope).

The ramp-hold tests (PEDVE25 and PEDVE 26) reached peak displacement rates of 1.9 m/s to 2.0 m/s. Rates and displacement magnitudes from the three tests correspond well with analogous tests PEDVE09, PEDVE10, and PEDVE11 conducted on the 7-year-old PMHS described by Kent (Kent et al. 2009). Figure 8 depicts the posterior reaction force vs. displacement response results of the 6-year-old PMHS (the current study) in thick lines compared to the 7-year-old (Kent et al. 2009) in thin lines. At the target displacement of 25% abdominal depth (30.5 mm) the dynamic lower abdomen force response of the 6-year-old was 3444 N, while the upper abdomen response for the same displacement was 1756 N. In the 7-year-old PMHS data, the corresponding force responses at the same displacement were 3660 N in the lower abdomen and 2047 in the upper abdomen. At the onset of loading the two dynamic tests exhibited an initial spike in the force response followed by a drop until about 6mm of displacement; this detail was not present in the 7-year-old abdomen response.

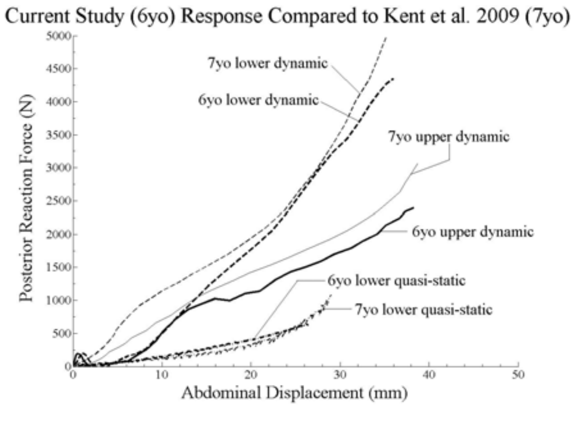

Figure 8. Current study (6yo) PMHS response compared to Kent (7yo) (Kent et al. 2009)

The 6-year-old PMHS sustained a single anterior rib fracture of the 3rd left rib. This injury was identified during the necropsy and by the radiologist in the CT report, but no other trauma was identified.

DISCUSSION

The 6-year-old female PMHS was subjected to three abdominal loading experiments identical to those reported by Kent (Kent et al. 2009) using a 7-year-old PMHS and by Kent (Kent et al. 2006, 2008) using juvenile swine. The objective of the PMHS tests was to increase the number of individual pediatric PMHS datasets available for consideration when benchmarking models of the pediatric abdomen under dynamic belt loading, and to expand the assessment of the porcine response envelopes generated in the 2006 study. While the number of pediatric PMHS that have been used for abdominal characterization (2) remains very low, the current study is an important confirmation of the general trends reported in the 2009 study. The stiffness of this 6-year-old PMHS was virtually identical to that of the 7-year-old despite a noticeable difference in the size of the two abdomens. The abdominal depth, measured from umbilicus to spine, in the 6-year-old was almost 4cm less than that of the 7-year-old; approximately equal to the displacement achieved during loading. Agreement in the belt force response between the two PMHS suggests that the overall size of the abdomen has little influence on the stiffness response (unless the belt engages the anterior surface of the spine); rather organ development, a factor of age (Haddad et al. 2001), appears to be the primarily predictor for abdominal stiffness. The concurrence between the two pediatric PMHS is at least weak evidence that the responses may be representative of the pediatric population. With a single data point the assertion was much less defensible.

The lower abdomen was stiffer in response to belt loading than the upper in all studies including the porcine model, although the trend was more pronounced in PMHS. This phenomenon is opposite to historical trends from hub loading, which show the upper abdomen to be stiffer and more prone to injury (Rouhana 2002). The explanation for the different trend with belt loading is not clear. The authors speculate that the new trend may be related to organ mobility and inertia as described by Rouhana (Rouhana 2002), with the solid organs of the upper abdomen able to translate during non-impact belt loading and less able to translate when impacted. The primary anatomical difference regarding the structural support of organs in the lower versus the upper abdomen is proximity to the pelvis. In humans, the pelvis forms a rigid bowl shape around much of the lower abdomen and may restrict organ mobility at the inferior boundary of the abdominal cavity. A mechanism whereby the organs in the lower abdomen are restricted from moving by the pelvis (and hence effectively stiffened) while organs in the upper abdomen are able to escape direct loading is a possible explanation for the observation. Upper abdominal expansion into the thoracic cavity during belt loading was demonstrated by Lamielle (Lamielle et al. 2008). In swine this stiffening effect is also present, but perhaps the smaller size of the porcine pelvis and its orientation explain the larger differential stiffness in the PHMS.

The results of the current study confirm the porcine responses as reasonable targets for the development of computational, analytical, or physical models of the pediatric abdomen (e.g., Elhagediab et al. 2007). Dynamically, the average PMHS upper abdomen stiffness response compared well with the porcine model, while the average PMHS lower abdomen response was slightly stiffer.

The single rib fracture that was identified was attributed to the series of thoracic belt loading tests that occurred after the abdominal tests. The lack of abdominal injury in this loading environment is not unexpected. The peak abdominal displacements in the dynamic tests were approximately 31% (lower) and 29% (upper) for the 6-year-old (the corresponding values were 24% and 23% for the 7-year-old in the 2009 study). According to the injury risk functions published by Kent (Kent et al. 2008), this range of displacement magnitudes corresponds to a 10%-27% probability of generating an AIS 3+ injury. The injury risk function based on belt force predicts higher probabilities than those based on displacement, but the difference is not sufficient to conclude that the lack of injury in these experiments is unexpected, nor that the swine-based injury risk functions are inappropriate for the human.

A limitation of the study is the range of displacement rates tested. The analytical model developed for the 7-year-old by Kent (Kent et al. 2009) indicates an insignificant effect on the force response from rate changes in the range of 1– 2 m/s, but rates well above or below this range should consider potential rate effects. Furthermore, it is likely that the effect of rate varies by loading location (Kent et al. 2006). While these effects were predicted to agree with those exhibited by the porcine model, loading rates in the range of the middle and high rate bins could not be tested to confirm the predictions of the analytical model or to assess the porcine model. Another limitation of this study is the use of an in-situ PMHS abdomen, deceased at six years of age, as a model for the pediatric abdomen. The effects of unknown pre mortem conditions such as pneumonia or post mortem processes such as putrefaction and autolysis on the mechanical properties of the abdomen cannot be quantified.

CONCLUSION

The purpose of this study was to expand the set of available data describing the pediatric abdomen, a region of the body that is a priority research area for pediatric occupants in motor vehicle crashes. The results from three belt loading tests conducted on the abdomen of a 6-year-old female PMHS were presented and combined with the results from the 7-year-old female PMHS presented in a previous study. The two studies comprise the only data available characterizing the mechanical response of the pediatric abdomen to dynamic loading. The force response of the 6-year-old female PMHS abdomen was remarkably similar to that of the previously published 7-year-old female PMHS, and the combined PMHS results indicate that the porcine model is a reasonable model for benchmarking the response of the pediatric abdomen to dynamic loading.

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