IN-DEPTH FIELD INVESTIGATIONS OF BELT-RESTRAINED CHILDREN IN FARSIDE CRASHES

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ABSTRACT

Recent attention has focused on adults in farside crashes but little attention has been given to children in farside crashes. Thus, we sought to elucidate Injury Causation Scenarios (ICS's) in children in center and farside seat positions. Crash investigation cases were drawn from the Partners for Child Passenger Safety Crash Investigation database, and the Crash Injury Research and Engineering Network database. Included in the study were children aged 4 to 15 years, involved in a side impact crash, seated on the center or farside in the rear rows, restrained by a seat belt alone (no booster seats or side airbags) and who received an AIS 2+ injury. Excluded cases were those where the only documented AIS 2+ injury was an altered state of consciousness (concussion, amnesia, or brief loss of consciousness). Seventeen cases met the inclusion criteria for this study. The three most frequently injured body regions to receive an AIS 2+ injury were: head, abdomen, and thorax, with thoracic injuries being quite rare. Intracranial injuries included cerebral contusions, subarachnoid hematoma/hemorrhage, edema, and extradural/epidural hematoma. Skull and facial injuries consisted of vault, orbit and maxillary fractures. Eight occupants had torso injuries: lung contusion, clavicle fracture, spleen laceration or rupture, liver laceration or contusion, and laceration or contusion to the digestive tract organs of the lower abdomen. Our results indicate that injury patterns and mechanisms are unique to children, and thus require a mitigation approach different than the adult. Of note, thoracic injuries, which are common in adult farside crashes, are relatively rare in pediatric farside crashes. Farside abdominal injury patterns suggest a lap belt submarining mechanism in children, injuring primarily the intestinal viscera. These findings further support that children require a different approach to injury mitigation than the adult, and have abdominal injuries in farside crashes that may be addressed by injury mitigation solutions for frontal impact.

INTRODUCTION

Successful development of side impact safety systems for the rear rows of passenger cars requires an understanding of factors that contribute to injury causation and mitigation. When considering the rear row, of particular interest to the vehicle safety system designer should be injury to children, who are frequent occupants there. Development of pediatric vehicle safety systems is justified and should be guided by real world crash data. To set priorities for protecting specific age and restraint groups, safety system designers should use epidemiological data on the incidence and frequency of car crashes involving children. To set design specifications for safety systems requires an understanding of specific Injury Causation Scenarios (ICS's), including a complete description of injuries received, the components within the vehicle that contribute to injury, and the biomechanics of the injury. Using such ICS studies, biomechanical experiments with post-mortem human subjects, animal surrogates and/or human volunteers can be conceived which are reflective of real world impact conditions and injury outcome, but conducted within a controlled laboratory environment with appropriate instrumentation. Such tests then form the basis for biofidelic anthropomorphic test devices and associated injury criteria and, coupled with an appropriate safety system test procedure, can potentially lead to enhanced safety systems.

Seeking information on ICS's, the safety system designer can turn to detailed in depth case reviews of convenience samples of real world crashes. For example, Howard et al. (2004) studied 19 children aged 0 to 12 years involved in side impacts in all types of restraint conditions and seating positions, who were admitted to one of two children's hospitals in Canada. The authors found injuries occurred both with and without direct intrusion into the occupant compartment, suggesting that injuries may occur in center and farside seat positions, which are distant from struck side structures. As the Howard study attempted to describe injury causation across a wide range of restraint conditions, seating positions, and

occupant ages, the applicability of the results may be limited for restraint designers. Focusing on children 0 to 5 years old in child restraints, Sherwood et al. (2003) examined 92 reports of FARS crashes of all crash directions. Studying detailed crashes involving children by particular restraint type groupings is a useful approach to determine ICS's, as occupants are all exposed to similar restraint loading mechanisms. In a sample of 32 side impact crashes, for example, Arbogast et al. (2005a) studied CRS-restrained occupants, and noted the important role of intrusion, the forward component of the crash forces, and the rotation of the CRS toward the side of the crash, as common contributing factors to injury. Focusing on older children (4 to 15 years) not in CRS (belt-restraint only) in struck side crashes, Maltese et al. (2007) found the majority of head and face interior contact points were horizontally within the rear half of the window, and vertically from the window sill to the center of the window. In that same study, the most common cause of torso and abdominal injury was contact with the side interior structure.

Recent attention has focused on adults in farside crashes or side impact crashes where the occupant is seated opposite the struck side of the vehicle (Frampton et al. 1998; Stolinski et al. 1998; Gabler et al. 2005). For adults, the injury patterns in farside crashes differ from struck side crashes in meaningful ways. For example, Yoganandan et al. (2000) noted increases in liver and intestinal injuries, and decreases in splenic injuries, in belted and unbelted farside adult occupants, as compared to the struckside. To our knowledge, no farside studies have yet focused on children. Thus, the purpose of this research was to elucidate injury causation scenarios for children in farside crashes. These data are useful for guiding the development of vehicle injury mitigation concepts for children, and ensuring ATD biofidelity and injury criteria studies address injuries and injury mechanisms observed in the real world.

METHODS

The research presented herein was conducted in accordance with a protocol that has been approved by the Institutional Review Board of The Children's Hospital of Philadelphia.

Crash investigation cases were drawn from two databases: 1) the Partners for Child Passenger Safety (PCPS) Crash Investigation database, and 2) NHTSA's Crash Injury Research and Engineering Network (CIREN) database. The PCPS Crash Investigation database consists of crashes involving injured child passengers reported to an automobile insurance company in the United States, and selected for detailed crash investigation. The CIREN database obtains its data from patients admitted to a network of level-one trauma centers in the United States, who are subsequently selected for a detailed crash investigation. Inclusion criteria were as follows:

1. Occupants restrained by a 2-pt or 3-pt seatbelt, regardless of misuse,
2. 4 to 15 years of age,
3. Seated in one of the rear rows and in the center or farside (away from the side of the vehicle damaged during the crash) position during a side impact crash, and
4. Received a maximum Abbreviated Injury Scale (MAIS) injury of 2 or more (AAAM 2001).

A "side impact" was defined as one in which the case occupant's vehicle sustained damage to its side plane with a principle direction of force that is 45 to 135° or 225 to 315°. Excluded cases were those where the only documented AIS 2+ injury was an altered state of consciousness (concussion, amnesia, or brief loss of consciousness), as such a diagnosis does not provide sufficient physical evidence to support determination of an ICS.

Crash investigators examined the interior and exterior of the vehicles involved, looking for evidence of occupant contact, including scuff marks and tissue, hair, bodily fluid and clothing fabric transfer, and associated such evidence with injuries to specific body regions. Occupant contact points on the interior side structure are thus identified by photograph and included in the detailed crash report. Cases meeting the inclusion criteria were subject to a preliminary quality control review including checks for sufficient information on occupant injuries, vehicle dynamics and damage, and interior contact points. To determine ICS's, a multi-disciplinary Case Review Team (CRT) was established consisting of trauma surgeons, emergency medicine physicians, bioengineers, crash investigation specialists, and database analysts. The case review process included review of crash conditions, restraint and occupant characteristics, occupant injuries, and occupant contact points within the vehicle.

Following review of the case, AIS 2+ injuries were coded using the CIREN BioTAB method developed by Schneider (2005). The BioTAB approach to analyzing occupant injuries in a crash allows the researcher to attribute one or more injury causation

scenarios (ICS) to each injury, where each ICS includes the set of all factors that the researcher believes are essential for the injury to have occurred. Each ICS includes "involved physical components" (things external to the occupant) that are thought to have played an essential role in the injury. Because it is not always possible to know for sure what caused an injury, the researcher must also assign confidence levels of "Certain", "Probable", and "Possible" to each ICS and to each involved physical component within each ICS.

Data was stored in a relational database for analysis. Data analysis, summary and presentation are divided into two stages. First, the crash environment and overall injury patterns are summarized. Second, the injury descriptions, and ICS's are presented.

RESULTS

Seventeen cases met the inclusion criteria for this study; nine from the CIREN database and eight from the PCPS database (Table 1). Before discussing the nature of the injuries, it is necessary to describe the circumstances of the crashes. The vehicles in which the case occupants were riding were most often passenger cars (82%), followed by Minivans (12%) and Sport Utility Vehicles (6%). The bullet vehicle type was most often a Sports Utility Vehicle (41%), followed by passenger cars (35%), and an equal number of minivans, pickup trucks, and large trucks (6% each). Contact with a narrow object (i.e. utility pole) made up 6% of impacting objects. The average Delta V was 23.2 km/h with a standard deviation of 9.1 km/h. 88% of impacts had a principle direction of force (PDOF) between pure lateral and 30 degrees forward of pure lateral. All cases had a non-zero frontal component in the PDOF of the crash. Side impacts to the case vehicles occurred most often on the right side due to the case vehicle turning left across oncoming traffic. The primary area of damage in case vehicles encompassed the passenger compartment and rear lateral side (47%). In 35% of cases, the damage was only to the passenger compartment, and in 18% it included the passenger compartment and the front lateral side of the vehicle. Case vehicle model year distribution was as follows: 29% of vehicles were manufactured between 1990 and 1994, 59% between the years of 1995 and 1999, and 12% of vehicles were manufactured in the year 2000 or later.

Table 1.
Vehicle and Crash Characteristics for Sample of Belt-Restrained Children in Farside Crashes

ID	Occupant's Vehicle Type	Bullet Vehicle Type	Impact Side	PDOF* (degrees)	CDC	Delta V (km/h)
1	4-dr Passenger	4-dr Passenger	L	40	10LYEW5	38
2	4-dr Passenger	SUV	L	30	10LZAW3	21
3	Minivan	Pickup	R	30	2 RZEW2	7
4	4-dr Passenger	4-dr Passenger	L	30	10LPEW2	18
5	4-dr Passenger	SUV	R	15	4 RZAW4	29
6	4-dr Passenger	4-dr Passenger	R	30	02RPEW3	n/a
7	4-dr Passenger	SUV	R	10	3 RPAW3	27
8	SUV	SUV	L	60	11LYEW4	33
9	Minivan	Pole	R	10	00RPAW3	20
10	4-dr Passenger	4-dr Passenger	R	10	03RPEW2	18
11	4-dr Passenger	Minivan	L	10	09LZEW1	n/a
12	4-dr Passenger	2-dr Passenger	R	30	02RZEW1	11
13	4-dr Passenger	SUV	R	20	02RZAW3	23
14	4-dr Passenger	4-dr Passenger	R	20	02RPAW3	19
15	2-dr Passenger	SUV	R	10	03RZAW3	38
16	4-dr Passenger	Large Truck	R	10	03RYAW3	n/a
17	4-dr Passenger	SUV	R	20	02RZAW4	23

*PDOF defined here as the angle with respect to pure lateral; positive value indicates an angle forward of pure lateral.

The average age of the case occupants was 8 years old, with a standard deviation of 2 years, and a range of 5 to 13 years (Table 2). 65% of the case occupants were male. Because our study examines the occupant's interaction with the seat belt and the vehicle interior – factors influenced by occupant size rather than age - we concluded that the occupants would be better grouped by height than by age. Using the Center for Disease Control (CDC) growth charts, we established height ranges according to 50th percentile 4 to 8 year olds, 9 to 12 year olds, and 13 to 15 year olds, then reclassified each occupant according to the equivalent 50th percentile for his or her height. The heights of two occupants were unknown; in these cases the actual age was used. 59% of case occupants fell in the 4-8 year equivalent height range (104 to 131 cm), 29% were in the 9-12 equivalent height range (132 to 152 cm), and the remaining 12% had a height equivalent in the 13-15 year range (153 to 172 cm).

59% of the case occupants were seated in the farside position, which is the position furthest away from the impact. In the farside position, all case vehicles had a

Table 2
Occupant Characteristics for Sample of Belt-Restrained Children in Farside Crashes

ID	Height (cm)	Body Mass (kg)	Actual Age (yrs)	Height-Adjusted Age Range** (yrs)	Sex	Seat Position*	Restraint	MAIS
1	122	27	7	4-8	M	23	Lap/shoulder belt	3
2	115	20	7	4-8	F	23	Lap/shoulder belt	4
3	122	27	7	4-8	M	32	Lap belt improperly worn	3
4	114	16	6	4-8	M	23	Lap/shoulder belt	3
5	n/a	30	7	4-8	F	22	Lap belt	4
6	165	n/a	12	13-15	F	21	Lap/shoulder belt	5
7	122	25	7	4-8	F	21	Lap/shoulder belt with shoulder under arm	3
8	123	19	6	4-8	M	23	Lap/shoulder belt with shoulder behind back	3
9	152	40	11	9-12	M	31	Lap/shoulder belt	3
10	152	32	7	9-12	M	22	Lap belt	2
11	168	66	13	13-15	M	23	Lap/shoulder belt	3
12	122	n/a	6	4-8	F	22	Lap belt	3
13	132	24	8	9-12	M	22	Lap/shoulder belt with shoulder behind back	2
14	140	25	7	9-12	M	22	Lap belt	2
15	109	25	5	4-8	M	21	Lap/shoulder belt	3
16	n/a	n/a	5	4-8	F	22	Lap belt improperly worn	2
17	132	34	9	9-12	M	21	Lap/shoulder belt	2

* For seat position, the first digit indicates the row (2 = 2nd row, and 3 = 3rd row), and the second digit indicates the position on the row (1 = left, 2 = center, 3 = right).
** For height adjusted age range, we established height ranges according to 50th percentile 4 to 8 year olds, 9 to 12 year olds, and 13 to 15 year olds, and then reclassified each occupant according to the equivalent 50th percentile for his or her height.

lap and shoulder belt available; however 20% of the occupants misused the restraint, placing the shoulder portion of the belt behind their back or under their arm, so that they were effectively lap belt restrained only. 41% of case occupants were seated in the center position, where a lap belt was the only restraint available in 86% of these cases. However, all center-seated occupants were effectively lap belt restrained only due to misuse. Overall, for both the center and far-side seating positions, 53% of occupants were effectively lap belt restrained only. In addition, 12% of center-seated occupants misused the lap belt by wearing it very loosely.

It is important to note that over 70% of the children in our study were aged 4 to 7 years and are thus considered improperly restrained without a booster seat, according to recommended practice (AAP 2007). All case occupants had injuries of AIS 2 or greater, as it was an inclusion criterion. 71% of occupants had injuries of AIS 3 or greater and 18% had injuries that met or exceeded AIS 4. The three most prevalent injured body regions to receive an AIS 2+ injury were: head (71%), abdomen (36%), and thorax (12%). Specific injuries are described

Table 3
Head and Face Injury Characteristics for Sample of Belt-Restrained Children in Farside Crashes

ID	Body Region	IPC to Body Region Contacted	IPC Confidence	Specific Injury Description	AIS Code
2	Head	Other occupant to head	Certain	Cerebrum hematoma/hemorrhage epidural or extradural small	140632.4
				Vault skull fracture comminuted	150404.3
				Cerebrum subarachnoid hemorrhage	140684.3
3	Head	Window to head	Probable	Small right cerebrum contusion	140606.3
		C-pillar to head	Probable	LOC <1 hour with neurological deficit	160204.3
4	Head	Seatback to head	Probable	Left vault skull fracture comminuted	150404.3
		Other occupant to head	Possible	Left cerebellum subarachnoid hemorrhage	140466.3
5	Head	Window sill to head	Probable	Unconscious 1-6 hours (GCS <9)	160810.3
		Other occupant to head	Possible		
9	Head	Unknown to head	Unknown	Concussion (NFS)	161000.2
10	Head	Right interior surface hardware to head	Certain	Non-displaced frontal skull fracture	150402.2
11	Head	Unknown to head	Possible	Right anterior cerebrum contusion	140602.3
12	Head	Other occupant to head	Certain	Closed head injury with brief LOC (convulsions/combative)	160202.2
				Fractured right occipital bone	150200.3
13	Face	Door interior to face	Certain	Right orbit fracture	251200.2
				Right maxillary fracture	250800.2
14	Head	RF seatback to head	Possible	Concussion (NFS)	161000.2
		RF headrest to head	Probable		
15	Head	Other occupant to head	Possible	Brain "swelling" (induced coma)	140660.3
		Seatback to head	Possible		
16	Head	Unknown to head	Unknown	Severe head laceration (NFS)	190604.2
17	Head	Other occupant to head	Probable	Concussion (NFS)	161000.2

below, grouped by regions of the body that have similar contact points within the vehicle: a) head and face injuries, b) thorax, abdomen, upper extremity, and pelvis injuries. No AIS 2+ injuries were suffered to the spine or lower extremities.

Head and Face Injuries

13 occupants received an AIS 2 or greater head or face injury (Table 3). 12 of the occupants had head injuries without accompanying facial injury, and the remaining case had facial injuries without accompanying head injury. Intracranial injuries included cerebral contusions (2 cases), subarachnoid hematoma/hemorrhage (2 cases), edema (1 case), and extradural/epidural hematoma (1 case). Extracranial injuries consisted of vault skull fractures (4 cases), and one case each of orbit and maxillary fracture. A severe scalp laceration was also an injury for one case. Loss of consciousness was coded for 6 of the cases, being the sole head/face injury for four cases. For three of these cases, the loss of consciousness was considered severe (AIS 3) due to an extended period of unconsciousness, convulsions/combative behavior, or resulting neurological deficit. For the remaining three cases, the diagnosis of concussion was not supported with additional medical evidence, and thus was given the outcome "not further specified."

The BioTAB method allows multiple ICS to be associated with a single injury in a single case, which occurs when the CRT concludes that there are multiple ways in which the injury occurred. For example, the head injury in case 15 may have been caused by contact with another occupant, or contact to the right front seatback.

Head and face injury was attributed most often to contact with another passenger seated between the case occupant and the impact (33%). This additional occupant was present in only 54% of cases with a head/face injury, but of this number, 86% of cases listed the other occupant as a source of injury. The second most common source of head and face injury was the interior structure on the struck-side door (28%), with one occurrence each of window, c-pillar, window sill, interior hardware, and door interior contact. For 22% of head/face injuries, contact was attributed to the seatback or headrest of the seat that was both in front of the occupant and closest to the side of impact. For the remaining 17% of head and face injury causation scenarios, the source of injury was unknown.

Thorax, Abdomen, Upper Extremity, and Pelvis Injuries

Eight occupants had injuries to the "trunk" of the body, consisting of the thorax, abdomen, upper extremity and pelvis (Table 4). Injuries included lung contusions (2 cases), spleen lacerations or ruptures (2 cases), liver lacerations and contusions (2 cases), jejunum-ileum lacerations (2 cases), colon lacerations and contusions (2 cases), and one case each of clavicle fracture, myocardium heart contusions, retroperitoneum hemorrhage, mesentery contusion, small intestine laceration, and displaced iliac wing fracture.

Overall, 88% of individual torso injuries were caused by contact with the belt, including the lap, shoulder, or some combination of the two. For the upper torso, encompassing the upper extremities, thorax, and superior abdominal organs (specifically the liver and spleen), the shoulder belt was the most common injury source (accounting for 75% of individual injuries and 66% of unique causation scenarios). In one of these cases, the shoulder belt was worn incorrectly under the occupant's arm, however for all others the shoulder belt was worn properly with the lap belt. Contact with another occupant or with a child restraint seat each account for an equal part of the remainder of upper torso injures. All injuries to the lower torso, consisting of the inferior abdominal organs (small intestine, mesentery and colon) and pelvis were attributed to contact with the lap belt. For 88% of injures and 80% of unique injury causation scenarios, the case occupants were effectively lap belt restrained only due to both belt availability and misuse. The remaining occupants with lower torso injuries were restrained by both lap and shoulder belt.

DISCUSSION

Our work presented herein is the first that investigates ICS's in belt-only restrained children in farside crashes, and complements other population-based injury risk and in-depth crash investigation studies of the same restraint and age group (Maltese et al. 2005a; Maltese et al. 2005b; Maltese et al. 2007), as well as studies of children in forward facing child restraints in side impacts (Arbogast et al. 2004a; Arbogast et al. 2005a), and children in booster seats in side impacts (Arbogast et al. 2005b). These data provide guidance for increasing protection of children in these distinct restraint conditions.

Table 4
Thorax, Abdomen and Pelvis Injury Characteristics for Sample of Belt-Restrained Children in Farside Crashes

ID	Body Region	IPC to Body Region Contacted	IPC Confidence	Specific Injury Description	AIS Code
1	Abdomen	Lap belt to abdomen	Certain	Inferior/lower jejunum-ileum laceration/perforation (OIS Grade III)	541121.3
5	Thorax	Other occupant to torso	Certain	Bilateral inferior lower lung contusion	441410.4
	Upper Extremity	CRS to shoulder	Certain	Left clavicle fracture (OIS Grade I or II)	752200.2
6	Thorax	Shoulder belt to chest	Certain	Bilateral lung contusion	441410.4
				Minor central myocardium heart contusions	441004.3
	Abdomen	Shoulder belt to abdomen	Certain	Right complex liver laceration	541828.5
				Right minor liver contusion	541812.2
7	Abdomen	Incorrectly worn shoulder belt to abdomen	Certain	Moderate spleen laceration (OIS Grade III)	544224.3
8	Abdomen	Lap belt to abdomen	Certain	Retroperitoneum hemorrhage	543800.3
				Jejunum-ilium laceration	541422.2
				Mesentary contusion	542010.2
				Colon contusion	540810.2
9	Pelvis	Lap belt to pelvis	Certain	Right comminuted superior anterior displaced iliac wing fracture	852604.3
11	Abdomen	Lap/shoulder belt to abdomen	Certain	Lacerated/ruptured spleen	544220.2
				Lacerated small intestine	541020.3
16	Abdomen	Loosely worn lap belt to abdomen	Certain	Torn colon with internal bleeding	540822.2

Over the past several years, our research Center has studied children in side impact crashes who are restrained by seat belts and who are seated on the rear rows. As rear rows of many vehicles accommodate three seat positions (struck-side, center, and farside), our studies compare injury rates and patterns for all three positions across each rear row. This research line has yielded several important findings that help elucidate the injury problem in side impact. For example, the farside injury risk for belt-restrained children is nearly half that of struck side children (OR:0.55, 95% Confidence Interval: 0.33-0.93), however, the center seat position has injury risk comparable to the struck side (OR; 1.15, 95% CI: 0.50, 2.66) (Maltese et al. 2005b). Our population-based studies provide context for studies such as those presented herein. That is, the present study is a convenience sample, with no formal consideration for sample representativeness to the population. Thus, where possible it is important to compare variables common to both population and convenience studies to validate the latter. Toward this end, the most frequently injured body region for belt restrained farside child occupants in population-representative studies (Maltese et al. 2005a) is the head (56% of occupants have head injuries) followed by the face (24 %), abdomen (11 %) and then the chest (8%). The data presented herein also reflect this injury pattern, as 13 of 17 cases had head and face injuries, 6 of 17 cases had abdominal injuries, and 2 of 17

cases had chest injuries. The head injuries in our cases consisted of common adult intracranial injuries including hemorrhage/hematoma (subarachnoid, epidural, or extradural, but no subdural), contusion, concussion, and loss of consciousness. Extracranial injuries included vault fractures and facial bone fractures. All brain injuries were attributed to contact with a vehicle interior or exterior structure. No brain injuries were associated with "non-contact" events, where the occupant receives a brain injury but does not strike their head on any surface or structure.

Our finding of infrequent chest injury among farside child occupants herein and in our population-based study (Maltese et al. 2005a), stands in stark contrast to farside adult occupants analyses, where the chest is highlighted as the most frequently injured body region (34% of all injuries), followed by the head (27%), extremities (25%) and abdomen (7%) (Gabler et al. 2005). This suggests that children present a farside injury mitigation problem that is different than the adult's.

The question then arises as to the reason for the fewer thoracic injuries in children compared to the adult – is it biomechanical, environmental, or a combination thereof? One could argue that there are environmental differences between Gabler's farside population, who are largely front seated, and the data presented herein which are exclusively seated in the rear rows. Gabler notes that the primary injury source in the farside crashes with adults is the struck side front seatback, whereas herein the injury sources in the two cases with thoracic injuries were the belt and the adjacent occupant.

From a biomechanical standpoint, inspection of the torso maturation process reveals substantial differences in the structure and material composition between the adult and child chest. The sternum consists of 6 main bones – the manubrium superiorly, followed by sternebrae 1 through 4 and the xiphoid process. The 4th sternebra appears at age 12 months, while the xiphoid process appears at 3 to 6 years. Fusing between sternebrae begins at age 4 years and continues through age 20 years. The sternum as a whole descends with respect to the spine from birth up until age 2 to 3 years, causing the ribs to angle downward when viewed laterally, and the shaft of the rib to show signs of axial twist deformation (Scheuer and Black 2000). The costal cartilage also calcifies with age, likely influencing its flexibility. As discussed by Kent et al. (2005), aging bone shows a decrease in elastic modulus beyond adult middle age, and ribs alone in bending demonstrate decreased breaking strength with increased age. These material and morphological changes during the maturation and aging phases of human life likely influence the injury response of the chest. For example, no rib fractures were found in a recent series of blunt impacts into the thoraces of nine post-mortem human subjects ages 2 to 12 years (Ouyang et al. 2006), yet the same type of test performed on adults produced rib fractures in 18 of 22 subjects (Kroell et al. 1974). These maturation-related changes of the chest highlight the uniqueness of the pediatric restraint problem from the perspective of ATD design, injury criteria selection and tolerance, and design of restraints such as seat belts.

Behind the head, the abdomen was the second most frequently injured body region (6 of 17 cases), the same injured body region rank as population-representative studies (Maltese et al. 2005a). Elucidation of the mechanism of these injuries can be found by first comparing struck-side abdominal injuries vs. center and farside abdominal injuries. Our previous study of struck side injuries revealed primarily spleen or liver injuries, with the injury (liver vs. spleen) depending on which organ was on the struck side of the crash. However of the 11 AIS coded abdominal injuries presented herein, only 4 injuries were those similar to struck side child victims (spleen and liver); the remaining 7 were injuries to the viscera of the abdomen (jejunum-ileum, retroperitoneum, mesentery, colon, small intestine). These highlight a decidedly different injury mechanism for the farside / center occupants that bears resemblance to abdominal injuries in frontal crashes. That is, in a population-representative study of abdominal injuries in children, stomach and intestinal injuries were represented in 77% of those children with AIS2+ abdominal injuries involved in frontal crashes, and injuries to the liver, spleen and kidney were each less than 10% (Arbogast et al. 2004b). The high incidence of stomach and intestine injuries in the frontal impacts was attributed to lap belt submarining, where the boney pelvis slides under the lap portion of the belt and the abdominal viscera are exposed to compression by the belt (Arbogast et al. 2007). Despite the fact that the cases presented herein were side impacts, the injury patterns observed are similar to lap belt submarining injuries observed in frontal crashes.

CONCLUSIONS

Injury causation scenarios for belt restrained children in farside crashes have been delineated. Combined with data from the literature, our results indicate that thoracic injuries are the predominant injury in adult

farside crashes, but are rare in pediatric farside crashes. Further, farside abdominal injury patterns suggest a lap belt submarining mechanism in children, injuring primarily the intestinal viscera. These findings further support that children require a different approach to injury mitigation than the adult, and have abdominal injuries in farside crashes that may be addressed by injury mitigation solutions for frontal impact.

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