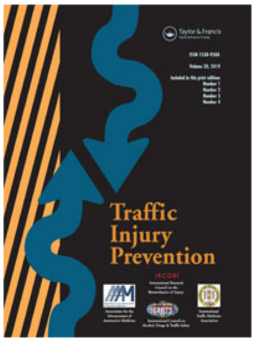

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Cervical and thoracic spine injury in pediatric motor vehicle crash passengers

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ABSTRACT

Objective: Motor vehicle occupants aged 8 to 12 years are in transition, in terms of both restraint use (booster seat or vehicle belt) and anatomical development. Rear-seated occupants in this age group are more likely to be inappropriately restrained than other age groups, increasing their vulnerability to spinal injury. The skeletal anatomy of an 8- to 12-year-old child is also in developmental transition, resulting in spinal injury patterns that are unique to this age group. The objective of this study is to identify the upper spine injuries commonly experienced in the 8- to 12-year-old age group so that anthropomorphic test devices (ATDs) representing this size of occupant can be optimized to predict the risk of these injuries.

Methods: Motor vehicle crash cases from the National Trauma Data Bank (NTDB) were analyzed to characterize the location and nature of cervical and thoracic spine injuries in 8- to 12-year-old crash occupants compared to younger (age 0–7) and older age groups (age 13–19, 20–39).

Results: Spinal injuries in this trauma center data set tended to occur at more inferior vertebral levels with older age, with patients in the 8- to 12-year-old group diagnosed with thoracic injury more frequently than cervical injury, in contrast to younger occupants, for whom the proportion of cases with cervical injury outnumbered the proportion of cases with thoracic injury. With the cervical spine, a higher proportion of 8- to 12-year-olds had upper spine injury than adults, but a substantially lower proportion of 8- to 12-year-olds had upper spine injury than younger children. In terms of injury type, the 8- to 12-year-old group's injury patterns were more similar to those of teens and adults, with a higher relative proportion of fracture than younger children, who were particularly vulnerable to dislocation and soft tissue injuries. However, unlike for adults and teens, catastrophic atlanto-occipital dislocations were still more common than any other type of dislocation for 8- to 12-year-olds and vertebral body fractures were particularly frequent in this age group.

Conclusions: Spinal injury location in the cervical and thoracic spine moved downward with age in this trauma center data set. This shift in injury pattern supports the need for measurement of thoracic and lower cervical spine loading in ATDs representing the 8- to 12-year-old age group.

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Introduction

Pediatric spine injuries, especially those in the upper spine, can be catastrophic. These injuries are often associated with brain stem disruption, paralysis, neurological impairment, or other long-term degradation in motor function associated with spinal cord damage (Cirak et al. 2004; Stawicki et al. 2009; Vogel et al. 2011). Motor vehicle crashes are the most common source of traumatic spine injury in children under age 8 and cause as many debilitating spine injuries as sports or falls in children over the age of 8 (Leonard et al. 2014). Spinal injuries often occur in crashes where the child is not in an age-appropriate restraint situation (Rasouli et al. 2011). Forward-facing, rear-seated pediatric occupants who have transitioned from child restraint or booster seat to vehicle belt before they are anthropometrically ready are especially at risk because they are not tall enough for the belt to fit properly. Even when a child is properly restrained, oblique loading can occur due to a precrash avoidance maneuver or offset crash component, both of which can move the occupant's head out of position within the vehicle compartment and increase the risk of upper spine trauma (Arbogast et al. 2004, 2012; Bilston and Brown 2007; Brown and Bilston 2007; Durbin et al. 2003). Spine injuries have been observed in restrained children and adolescents under age 17 by Zonfrillo et al. (2014). In 42 cases where the occupant sustained at least one Abbreviated Injury Scale (AIS) 2+ injury, they found 97 AIS 2+ spine injuries (27 cervical, 22 thoracic, and 48 lumbar), indicating that not only are restrained children at risk for spinal injury but that those injuries are distributed along the vertebral column. They

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also found that the spine was the most frequently injured body region in this data set, which further emphasizes the importance of monitoring the risk of these injuries in both properly and improperly restrained children and adolescents. Because rear-seated child occupants in this transitional 8- to 12-year-old age group are often graduated from a booster seat to the vehicle belt before they are anthropometrically ready, they may be more susceptible to being out of position in a crash than other segments of the occupant population. Therefore, the potential for debilitating injury in the neck and spine needs to be assessed in the 8- to 12-year-old population so that these injuries can be prevented in this age group transitioning from child restraints and booster seats to the vehicle belt.

Neck and spine injury risk assessment in 8- to 12-year-old occupants is challenging because it is an age group in transition, not only from a vehicle restraint standpoint but also from a skeletal development perspective. Mobility within the spine structure is greater for younger children than for older children because of anatomic factors that include relative head mass, elastin composition in spinal ligaments, and underdeveloped vertebral bone geometry (Barros et al. 2002; Mortazavi et al. 2010; Reddy et al. 2003). Several biomechanical studies have demonstrated that the pediatric spine is significantly more flexible than the adult spine at motor vehicle crash-level speeds due to these developmental variants (Clarke et al. 2007; Luck et al. 2008; Nuckley et al. 2013).

To effectively study the risk of spinal injury in the 8- to 12-year-old group in the development and evaluation of motor vehicle crash protection, a model such as an anthropomorphic test device (ATD) with developmentally appropriate spinal flexibility can be used to measure the loads associated with the spinal injuries that are most frequent in this age group. Previously, human-like or biofidelic spinal flexibility has been limited in child ATDs representing 8- to 12-year-old occupants (Arbogast et al. 2009; Ash et al. 2009; Lopez-Valdes, Lau, et al. 2011; Lopez-Valdes, Seacrist, et al. 2011; Sherwood et al. 2002; Wu et al. 2013). As a result of this limited flexibility in the spine, the spine loads measured by child ATDs have been questioned with respect to injury risk. Seacrist et al. (2013) reported that axial force was underestimated and the bending moment overestimated in ATDs when compared to pediatric volunteers in a low-speed frontal loading scenario. Because this lack of biofidelity in the spine structure has limited accurate measurement of spinal loads, determination of the ideal location of spine instrumentation beyond the upper neck load cell in child ATDs has not been a priority. However, now that more biofidelic child ATDs such as the Large Omnidirectional Child (LODC) are available (Stammen et al. 2016), it is reasonable to assess spinal loads as they relate to injury. To use these ATDs to assess spinal injury risk, it is now necessary to identify the most frequent spinal injuries so that the ATDs can be instrumented to measure the spinal loading in the anatomical areas most vulnerable to injury in this unique age group of crash occupants.

Child ATDs are typically equipped with instrumentation to measure loading in the upper neck, with some ATDs having the option to also measure lower neck and lumbar spine loads. To optimize sensor locations in the child ATD spine to best assess spinal injury risk for 8- to 12-year-old crash occupants, it is necessary to investigate the relative frequencies of the spine injuries that occur in this age group. Although several clinical studies have examined the frequency and types of cervical, thoracic, and lumbar spine injuries (Carreon et al. 2004; Clayton et al. 2012; Hamilton and Mylks 1992; Kokoska et al. 2001; Ruge et al. 1988), these studies were based on small samples of patients at single health centers and included a wide range of injury sources and mechanisms, not limited to motor vehicle crashes. Though these studies identify potential trends with respect to age, such as a tendency for cervical spine injuries in older children to occur lower in the cervical spine and for dislocations to be less common than for younger children (Fesmire and Luten 1989; Hill et al. 1984; Patel et al. 2001), the small sample size and inclusion of non–crash injury sources prevents a comprehensive understanding of how pediatric spine injuries change with age in motor vehicle crashes specifically.

The objective of this study is to better understand the age-related characteristics of cervical and thoracic spinal injuries sustained by children in motor vehicle crashes. Ultimately, understanding spinal injury patterns in 8- to 12-year-old children will be useful in determining the spinal levels most vulnerable to injury and in evaluating the effectiveness of occupant protection against spinal injury for this age group. The National Trauma Data Bank (NTDB) was used to investigate the relative frequency of spine injuries by location and type in a very large sample of pediatric trauma patients involved in motor vehicle crashes. The NTDB is a collection of trauma registry cases collected by the American College of Surgeons (2015). It has been used previously to study pediatric injury in motor vehicle crashes (Mohseni et al. 2011; Polk-Williams et al. 2008) and is expected to provide guidance on what injuries are most frequent in the 8- to 12-year-old population and, consequently, what measurements are most important in the spine of a child ATD representing an occupant in this transitional age group.

Methods

Motor vehicle crash cases were drawn from the NTDB Research Data Set (RDS; American College of Surgeons 2015). The NTDB RDS is an incident-based compilation of trauma data provided by hospitals throughout the United States designated as level 1–4 trauma centers. Participating trauma centers submit deidentified case data using the National Trauma Data Standard. Although participation is voluntary, the majority of states submit data for at least two thirds of their trauma centers, making the RDS data set the largest collection of trauma data in the world (Chang 2016). Data from 2007 to 2014 NTDB RDS trauma center admissions were included in the current study. Passengers in motor vehicle crashes were identified in the data set by the ECODE variable. Although fatal cases were not excluded, only patients who survive long enough to be admitted to a

Table 1. Number of motor vehicle crash passengers included in the 2007–2014 NTDB data set with cervical or thoracic injury based on ICD-9 codes or AIS codes.

	Passengers in NTDB		Coded with ICD-9 codes		Coded with AIS codes		
Age (years)	Number	% of included cases	With cervical spine injury	With thoracic spine injury	Cases (%) coded with AIS injury codes	With AIS 2–6 cervical spine injury	With AIS 2–6 thoracic spine injury
0–7	31,325	13.1	1,173	576	12,740 (41)	328	176
8–12	19,880	8.3	620	699	8,043 (40)	180	261
13–19	71,925	30.2	5,750	5,596	30,705 (43)	2,001	2,392
20–39	115,421	48.4	12,146	9,590	47,191 (41)	4,204	3,780

trauma center are documented in NTDB. Occupants who die at the scene or in transport are therefore not included in this study. Drivers were excluded because pediatric spinal injury is the focus of this study and adults are included only for comparison. Eliminating drivers from the comparison reduced the potential for confounding effects of seat position. No further data on the crash, such as impact direction or severity, restraint use, or passenger seat position, were available in the data set. Patients with unknown age were excluded.

Cervical and thoracic spinal injury patterns were compared for 3 pediatric age groups (0–7, 8–12, 13–19) and one adult age group (20–39).

Cervical and thoracic spine injuries were identified using the *International Classification of Diseases*, Ninth Revision (ICD-9, Henricksen et al. 2015) and AIS 98 Update (Association for the Advancement of Automotive Medicine 1998) injury codes in the NTDB data set. ICD-9 codes are the primary injury codes used in the NTDB data set. Not all participating trauma centers code injuries using the AIS system, so AIS codes are only available for a subset of cases in the NTDB data set. Analysis of AIS-coded injuries for the cases in which they were available (see Table 1; approximately 41% of NTDB cases include AIS coding of injuries) allows a more detailed analysis of the types of fractures and dislocations sustained.

In the analysis of the data set by ICD-9 codes, injuries were grouped into broad categories by spinal level and injury type. Sprain/strain injuries of the cervical and thoracic spine were not included in the analysis because it is difficult to identify the spine level of these injuries. The ICD-9 injury codes corresponding to each cervical and thoracic category are tabulated in Supplemental Tables S1 and S2 (see online supplement). The overall proportion of cases with injury by spinal level was estimated for each age group as a ratio of the number of included NTDB cases with an injury at the given spinal level to the total number of included NTDB cases in the age group. Therefore, this proportion represents the incidence of cases with spinal injury among the included passengers in the data set (i.e., motor vehicle passengers admitted to trauma centers as a result of crash trauma) rather than a rate of injury among all passengers exposed to crashes.

In the analysis of the subset of the NTDB data set that includes injuries coded using the AIS, the 7-digit AIS code was used to aggregate injuries by fracture type and by dislocation type for each age group separately for the cervical and thoracic spine. Injuries of AIS severity 1, which apply to strain injuries and ligamentous injuries, were excluded along with injuries with severity 9, which corresponds to unknown severity. Only AIS codes that were specifically coded by the admitting trauma center were included, not those that were translated from ICD-9 codes. The proportions of cases with specific types of fracture and dislocations among AIS-coded cases where these injuries were specified were compared between age groups.

Data in the NTDB RDS data set are not weighted. All calculations in this analysis are performed on raw counts of cases. Any calculation made using fewer than 20 raw cases is marked with an asterisk (*) and labeled with the number of cases on which it was based.

Pearson's χ^2 test was used to identify whether the difference between the frequencies of a type of injury in 2 age groups was statistically significant. McNemar's test was used to examine whether the frequency of a type of injury was significantly different from the frequencies of other types of injuries in a specific age group because injuries from the same individuals were compared and this was paired data. The significance level for this study was set as .05 ($\alpha = .05$). All statistical tests were conducted using SAS 9.4.

Results

The NTDB data from 2007–2014 contained a total of 238,461 motor vehicle crash passengers of known age, in the included age groups. Approximately 8% of these passengers were adolescents between 8 and 12 years old. Using ICD-9 codes, the 8- to 12-year-old age group included 620 patients coded with cervical spine injury and 699 patients with thoracic spine injury, not including sprain/strain injuries (Table 1). In all other age groups, the proportion of passengers with cervical spine injury outnumbered those with thoracic spine injury. Injuries were additionally coded with AIS injury codes in 41% (98,679) of the NTDB cases in the included data set. The cases with AIS injury codes also show that there were more 8- to 12-year-old occupants with thoracic injury than with cervical injury.

Frequency of cases with cervical and thoracic injury is shown in Figure 1 as a proportion of included NTDB cases, based on ICD-9 coding. For example, 3.8% of 0- to 7-year-olds in the included NTDB data set had cervical spine injuries compared to 8% of teens in the data set. Both cervical and thoracic injuries were coded more frequently for teen and adult patients than in patients age 12 and younger in this NTDB data set of injured passengers. However, though the proportion of cases with thoracic injury increased with

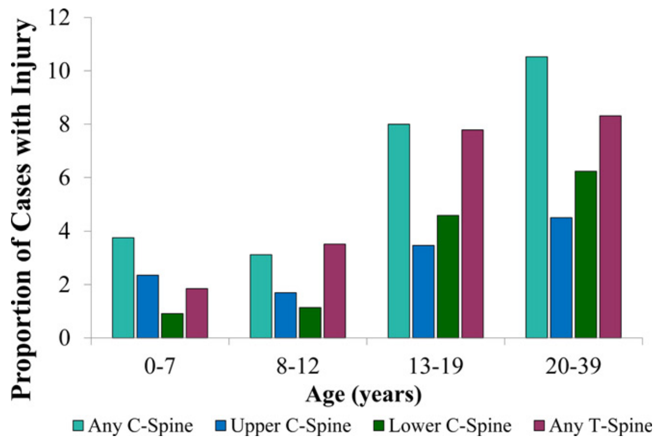

Figure 1. Proportion of motor vehicle crash passengers in NTDB with injury to the cervical and thoracic spine as a proportion of the total number of passengers in each age group, with cervical spine aggregated into upper (C1–C4) and lower (C5–C7) cervical spine for all injuries where location could be determined from ICD-9 injury coding. See Table 1 for the total number of cases in the denominator of each age group.

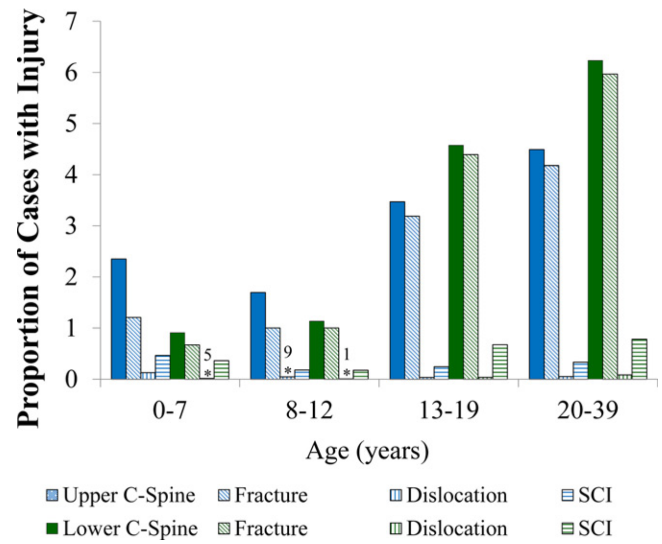

Figure 2. Proportion of motor vehicle crash passengers in NTDB with injury to the *upper* (C1–C4) and *lower* (C5–C7) cervical spine by injury type as a percentage of the total number of passengers in each age group. Estimates based on fewer than 20 cases marked with * and labeled with number of cases in numerator of rates. See Table 1 for the total number of cases in the denominator of each age group.

age across all age groups, cervical injury was more frequent among the youngest NTDB patients aged 0–7 (3.8%) than the 8- to 12-year-old group (3.1%; $P < .01$). The 8- to 12-year-old group is the only one in which thoracic injury (3.8%) was more frequent than cervical injury (3.1%; $P = .02$).

Cervical spine injury

For the cervical spine, the proportion of cases with ICD-9-coded injury to the upper cervical spine (C1–C4) versus the lower cervical spine (C5–C7) was compared across age groups (Figure 1; Supplemental Table S3, see online supplement). Cases with any cervical spine injury include those with documented upper or lower cervical injury or both, as well as cases where injury level within the cervical spine is unknown. The vertebral level of cervical spine injury tended to be lower for older passengers. The youngest NTDB patients (age 0–7) were 2.6 times (95% confidence interval, 2.26–2.96) as likely to have an upper cervical injury as a lower cervical injury. However, the proportion of cases with lower cervical injuries increased with age in this data set, with the 8- to 12-year-old group only 1.5 times (95% confidence interval, 1.26–1.76) as likely to have an upper cervical injury as a lower cervical injury.

In addition to a downward shift in the location of cervical injuries with age, the nature of injuries among the NTDB cases also appeared to change with age (Figure 2). Whereas 51% of children aged 0 to 7 years with upper cervical spine injuries sustained a fracture, 59% of 8- to 12-year-old children with upper cervical spine injuries sustained a fracture in this region. In both the teen and adult age groups, more than 90% of upper cervical spine injury cases involved a fracture. In the lower cervical spine, the large majority of coded injuries were fractures, regardless of age group.

Conversely, spinal cord injuries became relatively less frequent with age in cervical spine injury cases in the data set. Combining upper and lower cervical spine injuries, the percentage of cervical spine cases with spinal cord injury was highest among the youngest groups: 33% of 0- to 7-year-olds with cervical injuries were coded with spinal cord injury, compared to 19% of 8- to 12-year-olds, 13% of teens, and 11% of NTDB cervical spine injury patients aged 20–39 years.

Additional detail on the cervical spine injuries sustained by NTDB occupants in each age group was drawn from cases where injuries were also coded using the AIS system. Because a relatively small proportion of cases were coded using AIS, these additional case details are presented as a percentage of all occupants in each age group where AIS codes were available and the codes specified injury type. Cases without AIS codes or cases coded with dislocations or fractures not further specified were not included in the denominators of these estimates. As such, these values do not represent proportions of cases with each injury among all NTDB patients but rather a relative frequency of each type of injury among only those patients for whom cervical spine AIS codes were documented and injury type was known. Despite the smaller number of cases coded with AIS, the AIS codes offer additional detail on the nature of the fractures and dislocations reported in the data set. Figure 3 and Supplemental Table S4 (see online supplement) show the relative frequency of dislocation types among all included cases with AIS-coded cervical injury where dislocation type was specified, illustrating the types of cervical spine dislocation that are more frequent for younger NTDB patients. The differences are especially dramatic for C0–C1 dislocations, which are more frequent for the 0–7 (53.3%) and 8–12 (66.7%) age groups than for adult (18.5%) NTDB patients with AIS-coded dislocations (age 0–7 versus adult: difference = 34.9%, $P < .01$; age 8–12 versus adult: difference = 48.2%, $P < .01$), and for C1–C2 dislocations, which were more frequent in the 0–7 (40.0%) age group than among teens (11.0%) or adults (7.7%; age 0–7 versus teens:

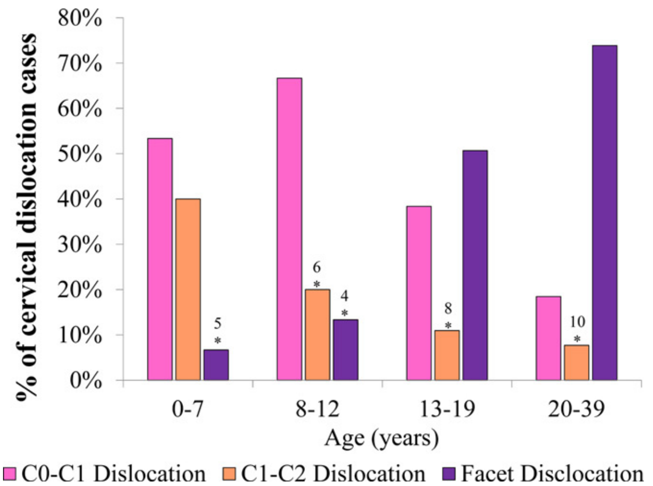

Figure 3. Distribution of cervical dislocations by dislocation type as a percentage of injuries where dislocation type is explicitly coded with AIS (e.g., 67% of AIS-coded cervical spine dislocations in 8- to 12-year-olds were C0–C1 dislocations).

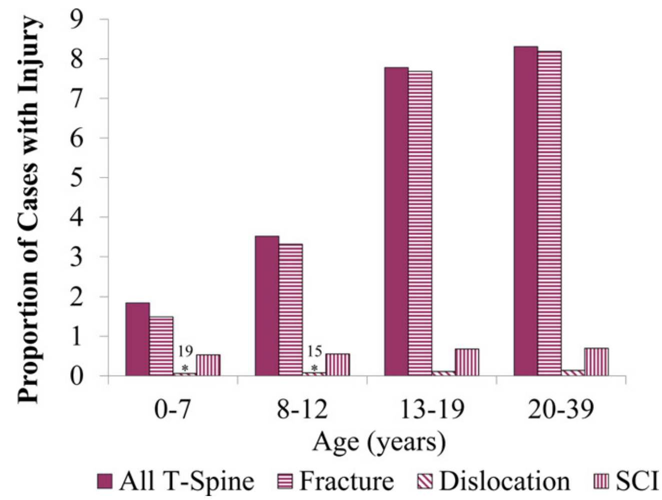

Figure 5. Proportion of motor vehicle crash passengers in NTDB with injury to the thoracic spine by injury type as a percentage of the total number of passengers in each age group.

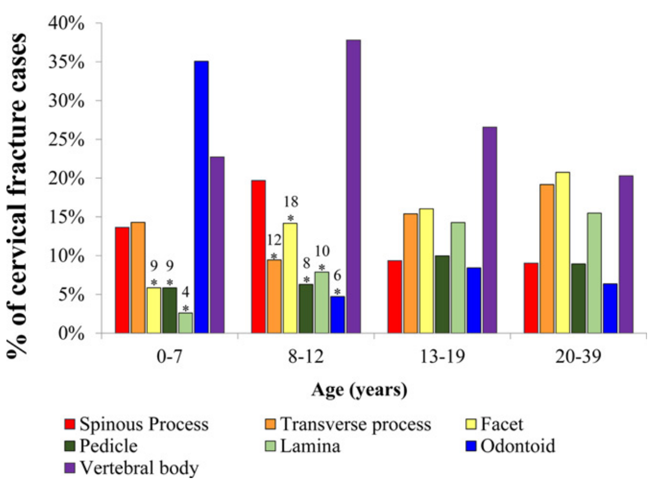

Figure 4. Distribution of cervical fracture type as a percentage of injuries where fracture type is explicitly coded with AIS (e.g., 38% of AIS-coded cervical spine fractures specified by location in 8- to 12-year-olds were vertebral body fractures).

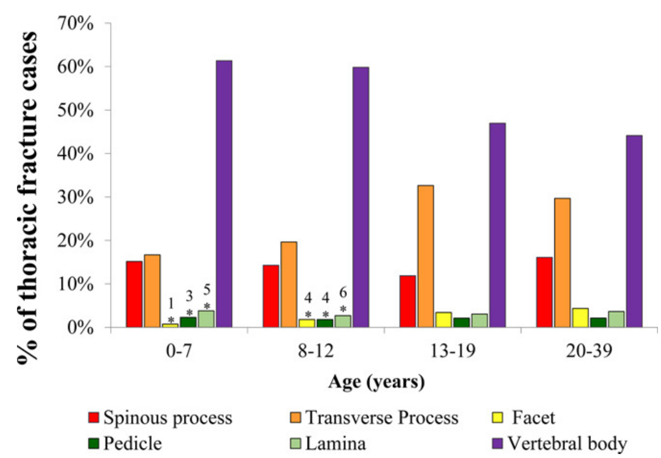

Figure 6. Distribution of thoracic fracture type as a percentage of injuries where fracture type is explicitly coded with AIS (e.g., 60% of AIS-coded thoracic spine fractures specified by location in 8- to 12-year-olds were vertebral body fractures).

difference = 29.0%, $P < .01$; age 0–7 versus adults: difference = 32.3%, $P < .01$).

AIS-coded injuries, where available, were also used to discriminate among types of fractures by age group (Figure 4; Supplemental Table S5, see online supplement). For the 8–12 age group, the relative frequency of vertebral body fractures versus fractures of the posterior elements, which include the pedicles, laminae, facets, and processes, was more similar to the teen and adult NTDB patient groups than to the youngest group. The only AIS-coded fracture that was substantially more frequent in the youngest age group than among older age groups of NTDB cases was odontoid fractures, which were documented in 16.5% of 0- to 7-year-old patients with cervical injury. Among 8- to 12-year-olds and teens, vertebral body fractures were more frequent than any other type of cervical spine fracture. The frequency differences between vertebral body fractures and spinous process, transverse process, facet, pedicle, lamina, and odontoid among 8- to 12-year-olds were 18.1, 28.4, 23.6, 31.5, 29.9, and 33.1%, respectively. Such frequency differences among 13- to 19-year-olds were 17.2, 11.2, 10.5, 16.6, 12.3, and 18.2%. All of the frequency differences were statistically significant ($P < .01$).

Thoracic spine injury

Among motor vehicle crash patients in the NTDB data set studied, the overall proportion of cases with thoracic injury (Figure 5) was substantially higher among teens and adults (7.8 and 8.3% respectively) than among children (1.8% for age 0 to 7 and 3.5% for 8- to 12-year-olds; $P < .01$). Additionally, thoracic injury was more frequent in the 8–12 age group than in the 0–7 age group ($P < .01$). In all age groups, the majority of those injuries in this trauma center data set were fractures (Figure 5; Supplemental Table S6, see online supplement). For all age groups, the vertebral body fractures were more frequent than any other types of injuries (i.e., spinous process, transverse process, facet, pedicle, lamina, and vertebral body; $P < .01$). The proportion of cases with thoracic spinal cord injury in the NTDB data set was less than 1% for all age categories compared.

In NTDB cases coded using the AIS system, there was little additional detail available on types of dislocation injuries in the thoracic spine, because in the small number of dislocation cases coded, the large majority were coded as dislocations not further specified (Supplemental Table S7, see online supplement). The distribution of thoracic fracture types, where coded with AIS, is shown in Figure 6 and Supplemental Table S8 (see online supplement). Among thoracic spine fractures specified by location in the NTDB cases, vertebral body fractures were coded most frequently in all age groups, followed by transverse process and spinous process fractures.

Discussion

In this study, cases from the NTDB were used to explore the characteristics of cervical and thoracic spinal injuries in 8- to 12-year-old motor vehicle crash occupants, relative to younger and older occupants. The 8- to 12-year-old group was isolated from younger children, older teens, and adults for 3 reasons. First, the LODC ATD is the size of an average 10-year-old child, so ±2 years encompasses a large portion of the population represented by this dummy size. Second, primary ossification of many of the spinal bone structures is usually completed by age 8, so the threshold between ages 0–7 and 8–12 made sense in terms of expecting there to be a shift in injury mechanisms with developmental/skeletal changes. Third, most U.S. states mandate booster seat usage until age 8. Therefore, the expectation is that most children will have moved from a booster to the vehicle belt at around age 8, which would provide another factor (restraint type) that might contribute to shifting injury patterns. The study was intended to determine the spinal levels and injury types most common among spine-injured occupants in this age group, which can be used to identify the ATD spinal loads that need to be reduced to prevent these injuries in motor vehicle crashes.

In this study, cervical spine injury was documented in approximately 3.5% of NTDB cases for ages 0 to 12 and thoracic spine injury in approximately 2.5% of cases for that aggregate age group (Table 1). Patel et al. (2001) reported a lower proportion of cases with cervical spine injury, at only 1.5% of the 75,172 injured children in the National Pediatric Trauma Registry over a 10-year period. That data set included all injury sources including motor vehicle crashes. In an analysis of NTDB cervical spine injuries from all types of trauma, Mohseni et al. (2011) showed a slightly lower proportion of cases with cervical spine injury that remained nearly constant (approximately 0.5–1.0%) until the age of 10, increasing up to 3% by age 17. The higher proportion of cases with spine injury among trauma patients in the current NTDB analysis of only motor vehicle crash passengers suggest that, relative to other body regions, the pediatric spine is more vulnerable to injury in motor vehicle crashes than in other types of trauma events, underlining the importance of using data specifically from motor vehicle occupant cases to evaluate the nature of pediatric spinal injuries in crashes.

Though the proportion of pediatric motor vehicle crash cases that involve cervical and thoracic spine injury is relatively low in comparison to other injuries to children or in comparison to the teens or adults in the NTDB data set (Figure 1), this lower incidence is offset by the fact that they are often very serious injuries. Although mortality rates associated with spinal injury were not estimated in the current study because of the difficulty isolating the mortality risk of spinal injuries from crash occupants' other injuries and the exclusion from NTDB of cases involving crash occupants who died at the scene or in transport, the mortality rate associated with cervical spine injuries in pediatric patients has been reported to be as high as 19–27% (Platzer et al. 2007). The high mortality rate associated with pediatric cervical spine injuries overall, combined with the high frequency of spinal injury in motor vehicle crashes relative to other trauma events as well as the elevated prevalence of thoracic injuries in 8- to 12-year-old occupants, underscores the need to assess the risk of cervicothoracic spine injury by monitoring lower neck loads in older child ATDs in motor vehicle crash testing.

The location of spinal injury tends to migrate to lower vertebral levels with age. Among 8- to 12-year-olds in the NTDB data set, a higher proportion had thoracic injury than cervical injury, unlike 0- to 7-year-olds, who were coded with cervical spine injury more than twice as often as thoracic spine injury (Figure 1). Similarly, the level of spinal injury within the cervical spine tended to be lower for the 8- to 12-year-old group than among 0- to 7-year-olds. The younger group was coded with upper cervical spine injury 2.6 times as often as lower cervical spine injury compared to 8- to 12-year-olds, for whom upper cervical spine injury was coded only 1.5 times more often than lower cervical spine injury; that difference between age groups was statistically significant. This trend was also documented by Mohseni et al. (2011), whose study of cervical spine injuries among children exposed to all types of trauma showed that C5–C7 injuries began to exceed C1–C4 injuries between preadolescent (aged 10–13 years) and adolescent (aged 14–17 years) groups.

Though ATDs representing the youngest occupants typically use injury criteria based on measurements at the upper cervical spine, the observations in the current study point to the need to additionally focus on the reduction of thoracic and lower neck injury in the 8- to 12-year-old motor vehicle crash population because this transitional age group appeared to be vulnerable to both types of injury. The addition of lower neck load cell monitoring in ATDs representing the adolescent 8- to 12-year-old age group would allow assessment of injury risk in the lower cervical spine and upper thoracic spine, areas where the NTDB trauma data set suggests that more injuries occur for this particular age group than for other child age groups. However, measurement of upper neck loads should not be dropped for 8- to 12-year-olds given that, as in younger children, upper cervical spine injury was documented even more often than lower cervical spine injury for the patients in the NTDB data set. In the absence of crash descriptions in NTDB crashes, a comprehensive analysis of automotive crash data to better understand the types of crashes in which spinal injuries occur could be useful for identifying the crash test configurations where upper spinal measurement would be beneficial.

Not only do injury locations in the cervicothoracic spine shift with age, but the type and nature of those injuries vary with age as well. Among cases in the NTDB data set, the proportion of cases with fracture increased with age in the upper cervical spine, though a majority of coded lower cervical injuries were fractures for all age groups (Figure 2). Figure 3 shows that in AIS-coded cervical injury cases, the proportion of cases with C0–C1 dislocation was higher in the youngest age groups than in teens and adults. For the 8- to 12-year-old group, the relative proportion of cases with vertebral body fracture compared to posterior element fracture was greater than in other age groups (Figures 4 and 6). In previous work, Patel et al. (2001) noted that dislocations were 5 times more common in the upper than in the lower cervical spine. Kokoska et al. (2001) reported a shift from soft tissue injuries to fractures with age, showing that children younger than age 10 had a higher incidence of dislocation and spinal cord injury than the older cohort, which had a greater number of fractures in the cervical spine. Zonfrillo et al. (2014) showed a similar increase in the incidence of fractures with age. These studies, along with the current study, confirm that in addition to a shift with age from injuries in the upper cervicothoracic spine to the lower cervicothoracic spine, there is a shift from more soft tissue/dislocation injuries in younger children to fractures in older children and teens. However, although the 8- to 12-year-old group was truly *transitional* in terms of injury location in that this group had an elevated proportion of cases with injury in the upper cervicothoracic spine similar to younger occupants and elevated proportion of cases with injury in the lower cervicothoracic spine similar to older occupants, 8- to 12-year-olds were more similar to teens and adults in the NTDB data set in terms of injury type. This age group had a lower proportion of cases with dislocations and a higher proportion of fracture cases than the youngest age group. Among fractures in the 8- to 12-year-old age group, loads that correspond with vertebral body fractures may be especially critical to measure given their frequency.

Where cervicothoracic injury locations in the 8- to 12-year-old group support injury evaluation at both the upper and lower cervical spine, the types of injuries sustained can be used to determine what loads are to be assessed at these locations. In the upper cervical spine, the relatively high proportion of cases with catastrophic atlanto-occipital (C0–C1) dislocations in this age group necessitates measurement of tension and flexion loading that has been associated with this type of dislocation (Babcock 1976; McElhaney et al. 2002; Pneumaticos 2015; Steinmetz et al. 2003; Van Ee et al. 2000). This age group also demonstrated a high proportion of cases with cervical vertebral body fractures, which are most often associated with compression and flexion loading (Babcock 1976; McElhaney et al. 1979, 2002). Based on these types of most frequently observed injuries, in addition to the inherent complexity of the cervical structure, it is apparent that the development of upper spine injury criteria in an ATD should take into account measures of both axial force and bending moment.

With regard to injury criteria for the lower neck, Pintar et al. (2010) documented challenges in determining how ATD lower neck load cell measurements are correlated with human cervicothoracic spine injuries. It requires complex calculations involving inverse dynamics and knowledge of anatomical geometry of the patient and how it relates to the location of the load cell within the ATD structure. Kang et al. (2016) later improved upon this estimation of human specimen cervicothoracic loads by adding head–neck mass distribution and detailed cervical spine kinematic measurements to the lower neck load calculation. The information provided from this current study along with those earlier lower neck load calculation studies could be used together to position the lower neck instrumentation within child dummies for development of the best possible injury criteria.

Although the location and nature of spinal injuries in children shifts as a result of anatomical development during the transition from childhood to adolescence, the results in this study are also undoubtedly affected by the transition of children from child restraints to booster seats to vehicle belt restraints. However, the lack of information in NTDB on restraint use in each case makes it impossible to differentiate the effects of anatomical transition in the 8- to 12-year-old age group from the transition of most children from booster seats to the vehicle belt restraint.

Because the intent was to use the injury patterns in this NTDB study to inform the design of ATDs representing 8- to 12-year-olds, it could be argued that cases that are not typically simulated in testing would, ideally, be excluded from this analysis. By this logic, unrestrained occupants or occupants in crash configurations unlikely to be reproduced in crash testing might be excluded because a crash occupant restrained properly throughout a crash event may be expected to have a low risk of spinal injury, particularly thoracic spine injury, in standard crash directions (e.g., frontal). However, not only are restraint use and impact direction not documented in NTDB cases, but one of the big challenges for occupants in the 8- to 12-year-old age group is that they are often not appropriately restrained throughout the event, especially in nontypical crash directions and scenarios. The LODC ATD is designed to be omnidirectional and can therefore be used to explore situations where the occupant is not ideally restrained, even if he or she is outside of typical crash test configurations. Therefore, the injury patterns documented in the NTDB data set are still useful for identifying the injuries relevant for injury risk prediction in the LODC spine, despite the data set's lack of documentation on restraint status and crash configuration.

Use of trauma registry cases for this analysis means that injury frequency is being compared among occupants who are injured seriously enough to be admitted to participating trauma centers. This inclusion limitation decreases the number of noninjury or low-severity injury cases that would be included in a study of all motor vehicle crashes. Results therefore are not generalizable to spinal injury rates among all motor vehicle crashes. Additionally, fatally injured passengers who do not survive long enough to be admitted to trauma centers are not included in this study, eliminating these most severe injuries from the analysis. This exclusion is expected to lead to an underestimate of the relative frequency of the most life-threatening injuries, most notably in the high cervical spine.

The availability of multiple injury coding systems in NTDB offers a valuable opportunity to get a more detailed picture of the types of injuries sustained in a patient group than can be obtained with a single coding system. In the spine, for example, the ICD-9 coding system differentiated between injuries in the upper and lower cervical spine, whereas AIS coding identified the specific vertebral structures involved in fractures. In the years of NTDB data analyzed, AIS codes were only available for less than half of the included cases. Because submission of AIS codes by individual hospitals is voluntary, it is unclear whether there is selection bias among cases that included AIS codes.

Despite the absence of detailed crash information, the necessary exclusion of the most severe injuries from the analysis, and possible selection bias among cases that included AIS codes, the use of NTDB provided an opportunity to study a very large number of pediatric injury cases for identification of injury patterns unique to a specific age group. Use of AIS codes, as well as ICD-9 codes, provided additional detail on the injuries sustained in the studied age groups. These detailed injury data were particularly valuable for a spinal injury study in the 8- to 12-year-old age group because of the comparatively small number of such cases in other motor vehicle crash data sets. A similar analysis strategy may be useful for analysis of pediatric injuries to other body regions, such as the lumbar spine, in this transitioning age group.

NTDB provides detailed injury information from a large number of pediatric motor vehicle crash cases. The findings from this study corroborate age-related trends from previous studies with specific emphasis on motor vehicle crashes, add important information about thoracic spine injuries in children, and provide insight on where to place instrumentation and what to measure in ATDs to monitor the risk of cervical and thoracic spine injuries in the 8- to 12-year-old population.

The proportion of pediatric trauma center patients with cervical spine injury was higher among the motor vehicle crash cases included in the current study than in previous trauma center studies that included other traumatic events, suggesting that motor vehicle crashes are more likely to cause cervical spine injury than other pediatric trauma events.

Consistent with previous studies, the location of spinal injury in cases in the NTDB data set tended to migrate to lower vertebral levels with age. The 8- to 12-year-olds studied were the only age group where the proportion of cases with thoracic injury was higher than the proportion of cases with cervical injury. Within the cervical spine injury cases in this age group, the proportion of cases with lower cervical injuries was much higher than that among younger passengers. These findings highlight the need to reduce loading in the lower neck and thoracic spine, as well as in the upper neck, to address cervical and thoracic spine injuries in the 8- to 12-year-old population.

Although the proportion of dislocation cases appeared to decrease with age whereas the proportion of cases involving fracture appeared to increase with age, both types of injuries were frequent in the cervical and thoracic spine among the patients admitted to a trauma center in the transitional 8- to 12-year-old age group. Therefore, ATD measurements associated with both dislocation and fracture injury mechanisms in the cervicothoracic spine region should be considered for injury criteria in ATDs representing this age group.

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Disclaimer

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