Small female rib cage fracture in frontal sled tests

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\textbf{ABSTRACT}

Objectives: The 2 objectives of this study are to (1) examine the rib and sternal fractures sustained by small stature elderly females in simulated frontal crashes and (2) determine how the findings are characterized by prior knowledge and field data.

Methods: A test series was conducted to evaluate the response of 5 elderly (average age 76 years) female postmortem human subjects (PMHS), similar in mass and size to a 5th percentile female, in 30 km/h frontal sled tests. The subjects were restrained on a rigid planar seat by bilateral rigid knee bolsters, pelvic blocks, and a custom force-limited 3-point shoulder and lap belt. Posttest subject injury assessment included identifying rib cage fractures by means of a radiologist read of a posttest computed tomography (CT) and an autopsy. The data from a motion capture camera system were processed to provide chest deflection, defined as the movement of the sternum relative to the spine at the level of T8.

A complementary field data investigation involved querying the NASS-CDS database over the years 1997–2012. The targeted cases involved belted front seat small female passenger vehicle occupants over 40 years old who were injured in 25 to 35 km/h delta-V frontal crashes (11 to 1 o’clock).

Results: Peak upper shoulder belt tension averaged 1,970 N (SD = 140 N) in the sled tests. For all subjects, the peak x-axis deflection was recorded at the sternum with an average of −44.5 mm or 25% of chest depth. The thoracic injury severity based on the number and distribution of rib fractures yielded 4 subjects coded as Abbreviated Injury Scale (AIS) 3 (serious) and one as AIS 5 (critical). The NASS-CDS field data investigation of small females identified 205 occupants who met the search criteria. Rib fractures were reported for 2.7% of the female occupants.

Conclusions: The small elderly test subjects sustained a higher number of rib cage fractures than expected in what was intended to be a minimally injurious frontal crash test condition. Neither field studies nor prior laboratory frontal sled tests conducted with 50th percentile male PMHS predicted the injury severity observed. Although this was a limited study, the results justify further exploration of the risk of rib cage injury for small elderly female occupants.

Introduction

Injuries to the chest are a major source of morbidity and mortality in motor vehicle crashes (Nirula and Pintar 2008), especially for older people (Kent et al. 2005; Morris et al. 2002, 2003). In fact, the rapid societal aging of most developed countries and the inability of older people to tolerate restraining forces on the chest are the primary impetus for passive safety research (e.g., Bostrom and Haland 2003; Forman et al. 2006; Rouhana et al. 2003). Rib and sternal fractures are the most frequently observed thoracic injuries in occupants loaded by contemporary restraint systems (Kent et al. 2003). In frontal crashes, the increase in risk in thoracic injury with age, predominantly rib cage fractures, is significantly higher for women than for men (Ridella et al. 2012). Although accidents resulting in an occupant sustaining many rib cage fractures are dangerous for occupants of all ages, even a few fractures can be life threatening for elderly occupants, especially those with preexisting pulmonary disease (Bulger et al. 2000; Kent et al. 2008). The pain associated with fractures can restrict breathing, resulting in decreased vital capacity, diminished ability to clear secretions, and retention of carbon dioxide (Cogbill and Landercasper 1996). Restricted breathing and sequelae can result in pneumonia and late pulmonary effusion, which are reported to be more common rib cage fracture complications among the elderly (Bulger et al. 2000).

Recognizing that elderly females are at increased risk of rib cage fracture, we examined the results of a test series that was designed to characterize the rib cage deflection response of small stature elderly females in simulated frontal crashes. The study presented here examines the unexpectedly high number of sustained rib and sternal fractures, how the findings are characterized by prior knowledge, and field data.

Method

A sled test series that provided the injury data analyzed here was conducted to evaluate the response of 5 female postmortem
Table 1. Tests and subject characteristics.

| Test date          | October 29, 2013 | November 5, 2013 | November 12, 2013 | November 19, 2013 | November 21, 2013 |
|--------------------|------------------|------------------|-------------------|-------------------|------------------|
| Cadaver ID no.     | 509              | 517              | 568               | 656               | 657              |
| Age at time of death | 75               | 95               | 57                | 88                | 65               |
| Body mass (kg)     | 36.7             | 30.8             | 39.5              | 54.4              | 46.7             |
| Stature (mm)       | 1486             | 1550             | 1615              | 1640              | 1515             |
| Seated height (mm) | 833              | 842              | 1035              | 1074              | 877              |
| Shoulder breadth (mm) | 330             | 308              | 340               | 314               | 325              |
| Chest breadth (at fourth rib, seated) (mm) | 251 | 228 | 262 | 268 | 248 |
| Chest depth (at eighth rib, seated) (mm) | 181 | 173 | 194 | 186 | 172 |
| Fracture risk      | Moderate         | High             | High              | Moderate          | High             |

Fracture risk: Moderate = Osteopenia, High = Osteoporosis

| Fracture risk | Designation | T score range     |
|---------------|-------------|------------------|
| Moderate      | Osteopenia  | > −2.5 SD, < −1 SD |
| High          | Osteoporosis| < −2.5 SD        |

Human subjects (PMHS), similar in mass and size to a 5th percentile female (Table 1), in 30 km/h frontal sled tests that included a 115-ms trapezoidal acceleration pulse with a 75-ms plateau peak of 9 g.

All PMHS procurement and experimentation procedures were approved by the University of Virginia Institutional Review Board–Human Subject Use. The subject selection process excluded subjects that were nonambulant for an extended period prior to death and subjects with bony pathology in the thorax as determined from pretest computed tomography (CT) scans. A standard dual-energy x-ray absorptiometry study was conducted to provide bone mineral density, a parameter that has been correlated with fracture risk (Wuermser et al. 2011). The selected PMHS were preserved by freezing and confirmed free of the infectious diseases, HIV, and hepatitis B and C.

The subjects were restrained on a rigid planar seat by bilateral rigid knee bolsters that were in contact with the proximal tibias at the start of the event and a custom 2-kN force-limited 3-point shoulder and lap belt (Figure 1, Figure A1, see online supplement). Seat and belt restraint geometry approximated that of the front passenger position of a standard sedan. Subject positioning began with placing the greater trochanter at a defined location on the seat corresponding to that of the Hybrid III 50th percentile male H-pt. Once the lower body was positioned, the primary positioning target was 10° reclined torso angle as defined by the angle of an anthropometer contacting the spinous process of T3 and L1. Once the subject position and torso angle were established, the shoulder belt upper anchor was adjusted to provide a qualitatively reasonable belt path over the shoulder. A secondary criterion for belt path was that it was similar to the initial subject in the test series. Anatomical variation prevented exact duplication of seated posture and belt fit. Table A1 (see online supplement) and Figure A2 (see online supplement) provide pretest subject positioning and belt path information.

Motion tracking marker mounts were installed on the posterior spine, pelvis, and anterior rib cage. Spherical markers were also mounted on the shoulders, head, and extremities (Figure 1; Figures A3 and A4, see online supplement). The mount position was documented via a pretest CT scan allowing transformation of marker location above the skin surface to the bony structure (Shaw et al. 2009). Immediately prior to testing, the subject’s lungs were inflated with 1.6 L of air. The tracheal tube through which the air was delivered was left open for the test.

Posttest subject injury assessment included identifying rib cage fractures by means of a radiologist read of a posttest CT and an autopsy. The autopsy involved denuding the torso and removing the organs so that the inner surface of the ribs could be examined and palpated in order to identify subtle fractures including incomplete (monocortical) or cartilage fractures. Fractures were classified and their location was measured from the center of the sternum along the rib.

Data acquisition and processing

Upper shoulder belt tension was recorded by a load cell between the D-ring and the shoulder and lower shoulder belt tension was recorded by a load cell near the shoulder/lap belt intersection.
The load cell data were acquired by an onboard data acquisition system at 10,000 samples/s, hardware-filtered to 3,000 Hz, deblised, and filtered to SAE J211CFC 60. The data from the motion capture camera system, captured at 500 Hz, were processed to provide 3D trajectories of the markers and marker arrays mounted to the subjects. For cases in which a 4-marker array was used, the motion of the underlying structure was obtained through a transformation from a marker-based coordinate system to the subject component coordinate system. This rigid-body analysis yielded chest deflection, the movement of the sternum relative to the spine at the level of T8, and was reported relative to an SAE coordinate system located on the posterior aspect of T8 (positive axes: x forward, y to the right, z down). Chest deflection also was expressed as a proportion of chest depth measured externally. This (normalized) chest deflection was calculated by dividing the skeletal rib cage deflection obtained from the rigid-body analysis by the external chest deflection at the level of the fourth rib laterally for the upper sites and for the sternum and the eighth rib laterally for the lower sites (Table 1). Further information about this test series including methods and results is available in the NHTSA Biomechanics Test Database (NHTSA n.d.).

A field data investigation involved querying the NASS-CDS database over the years 1997–2012. The targeted cases involved belted front seat small female passenger vehicle occupants over 40 years old who were involved in a 25 to 35 km/h delta-V frontal crash (11 to 1 o’clock) without a rollover event. The outcome of interest was the presence or absence of fracture(s) to the rib cage.

Results

Peak upper shoulder belt tension averaged 1,970 N (SD = 140 N). All subjects produced sufficient belt tension to engage the force-limiting function, which allowed belt “spool out” between 1,800 and 2,150 N. The lower shoulder belt average peak was slightly lower at 1,780 N (SD = 180 N; Figure 2). Table 2 summarizes chest deflection defined as the minimum distance from the measurement site on the anterior rib cage to the center of the T8 vertebral body along the x-axis. For all subjects, the peak x-axis deflection was recorded at the sternum with an average of −44.5 mm or 25% of chest depth (Figure 3).

The thoracic injury severity based on the number and distribution of rib fractures resulted in 4 subjects coded as Abbreviated Injury Scale AIS 3 (serious) and one as AIS 5 (critical) due to a bilateral flail chest (Table 3). Further fracture information is available in Table A2 (see online supplement).

The NASS-CDS field data investigation of small female occupants identified 205 cases. When accounting for the survey-weighted sampling design, these 205 cases represent 58,149 occupants without fracture were 55.3 years (range 40–91), on average, whereas those with rib fracture averaged 77.5 years (range 50–92).

Discussion

All subjects sustained substantial rib cage injury. One subject’s rib cage was structurally compromised. In test S0210, the 13 rib fractures and one sternal fracture apparently reduced the ability of the subject’s rib cage to elastically rebound to its original shape as indicated by the x-axis motion of the sternum and upper measurement sites (Figure 3).

Though it is well established that older female occupants face a greater risk of injury, the study findings that 100% of the study subjects sustained an AIS 3+ injury suggests a far greater risk than has been observed for a 30 km/h crash. A U.S. government NASS-CDS database study of 1994–1996 cases found that approximately 55% of all towed passenger cars involved in a frontal crash were estimated to have a delta-V of 18 to 32 km/h (US Department of Transportation, NHTSA 1999). An NASS study conducted by Funk et al. (2008) indicated that male and

Table 2. X-axis chest deflection.

| Test   | Upper right | Sternal | Upper left |
|--------|-------------|---------|-----------|
|        | Test mm | Norm. | Test mm | Norm. | Test mm | Norm. |
| S0209  | 26.5 | −0.15 | 35.1 | −0.19 | 17.0 | −0.09 |
| S0210  | 35.3 | −0.20 | 56.3 | −0.33 | 34.5 | −0.20 |
| S0211  | 25.7 | −0.13 | 53.7 | −0.28 | 23.6 | −0.12 |
| S0212  | 12.0 | 0.06 | 29.8 | −0.16 | 11.5 | −0.06 |
| S0213  | 26.5 | 0.15 | 47.5 | 0.28 | 26.1 | −0.15 |
| Average | 25.2 | 0.14 | 44.5 | 0.25 | 22.5 | −0.13 |
| SD     | 8.4 | 0.05 | 11.6 | 0.07 | 8.8 | 0.05 |

*Normalized chest deflection. See Methods section.

Figure 2. Shoulder belt tension.

Figure 3. Sternal deflection.
female occupants over 60 years of age involved in a 30 km/h delta-V frontal crash were at an increased risk of only 5% for sustaining any AIS+ injury, compared to those under the age of 60. Note that this study of 2000–2005 crashes included both belted and unbelted occupants. Ridella et al. (2012) analyzed NASS data and concluded that belted female drivers of average age similar to that of the study subjects (76) face only a 35% risk of AIS+ chest injury in a 51 km/h frontal crash. The NASS-CDS investigation we conducted identified few small females who sustained rib cage fractures in 25–35 km/h frontal crashes. Only 2.7% fractured at least one rib and only 0.8% sustained AIS+ thoracic injury based on rib fractures (Table A3; see online appendix).

Our prior testing experience also failed to predict the high number of rib cage fractures. We had conducted 2 test series with 50th percentile male PMHS using similar buck hardware and procedures. In the initial study, involving 8 subjects restrained by a non-force-limited belt subjected to a 40 km/h 14 g deceleration, we recorded a similar average number of fractures in which the average upper shoulder belt tension was 3 times as high (6 kN; Shaw et al. 2009). Moreover, in a second study, 2 50th percentile male PMHS restrained by a 3-kN force-limited belt subjected to a 30 km/h 9 g deceleration sustained no rib cage fractures (NHTSA 2014). These findings, as well as other published studies and recommendations, supported the choice of a tension level that would ensure a low number of rib fractures and therefore would not compromise rib cage response data.

Knowing that the small females would be more likely to sustain fractures than 50th percentile males, we elected to reduce the peak belt load to 2 kN, which is the equivalent mass-scaled peak for the average 5th percentile female in comparison to the average 50th percentile male (used in our similar 3-kN force-limited belt tests; Eppinger et al. 1984). Pilkey et al. (2010) reported that 2 kN is the lower bound for currently employed load limiters. Mertz and Dalmostas (2007) proposed that a force limit level of 2.5 kN would substantially reduce the risk of AIS+ chest injury in “99 percent of frontal collisions” (p. 372) for those front seat adult occupants whose bone strength was at least 40% that of the average young adult.

In addition, shoulder belt pretension levels of up to 2 kN have been explored. Zellmer et al. (2005) considered a 2 kN pretension level, optimum for reduction of (anthropomorphic test dummy) chest deflection (with the caveat that it was "close to biomechanical maximum values"; p. 10). A prototype 3-point belt system tested at the University of Virginia included a shoulder belt pretensioner that produced a 2- to 2.2-k/N peak level for 2 PMHS (70-year-old male and 71-year-old female) without producing rib fractures (Untaroiu et al. 2012). Supporting evidence that our chosen load limit would produce a low risk of severe thoracic injury included the 6-mm peak sternal deflection recorded in our Hybrid III 5th percentile female tests conducted using the same study conditions used for the PMHS (NHTSA database ref S0206-8). We calculate that 6-mm sternal deflection translates to less than 1% risk of AIS+ thoracic injury for the Hybrid III 5th percentile female dummy using scaled 50th percentile male dummy injury threshold data for belt loading reported by Mertz et al. (2003). Therefore, despite evidence to the contrary, 2-kN shoulder belt tension proved quite injurious for our test subjects and perhaps for motor vehicle occupants with similar characteristics.

### Possible reasons for severe rib cage injury

We explored several reasons why so many fractures were observed in the tests, including subject fragility, posttest fracture detection method, lack of precrash bracing, and the test hardware and methodology.

#### Fragile subjects

Rib cage fragility is the most likely reason for the large number of fractures. Rib fractures for older women have been associated with decreased bone mineral density (BMD), particularly as measured at the femoral neck (Wuermser et al. 2011). The age-matched BMD z-scores for the test subjects are within 1.5 standard deviations of the population mean for almost all of the measured sites (Table A4, see online supplement; Bonnick 2009). This finding does not suggest that the test subject BMD was substantially different from that of others of similar age.

Given that our test subjects appeared to be similar in BMD and, by extension, were presumed to be similar in rib cage fracture risk to the general population, we expected to find a correlation between individual subject BMD values and related factors such as age and rib cage fracture frequency.

However, neither the subjects’ age-matched z-score nor the femoral neck BMD correlated with the total number of rib cage fractures. Nguyen et al. (2005) reported a relationship between lumbar BMD and rib fracture risk, a finding also unsupported by our results.

Although we were unsuccessful in identifying a predictive factor for the number of fractures for individual subjects, the overall BMD assessment developed by the World Health Organization did suggest that our subjects were at increased risk for...
fracture (in general). This assessment used femur neck BMD for 4 of the 5 subjects.

Three of the 5 subjects, who sustained an average of 11 rib cage fractures, were classified as osteoporotic and the other 2, who sustained an average of 8 fractures, were osteopenic.

Therefore, the study findings are consistent with established prior research that has found that older women are at greater risks of fracture. Furthermore, at least as indicated by multisite BMD values, the study population is not substantially different from the age-matched general population in this regard.

Because PMHS exhibit a high degree of subject-to-subject variation in rib fracture tolerance (Kallieris et al. 1982; Kent et al. 2011; Verriest and Chapon 1994), our small convenience sample may have included subjects that happened to be more fragile than average.

Another possibility is that the studies to date have collected information on relatively few people who have sustained fractures in severe events such as motor vehicle crashes. The Wuermser et al. (2011) study population included only about 90 women who had sustained rib fracture in “severe trauma” situations such as motor vehicle crashes. Another study of 996 women age 60 and over that also found a relationship between BMD and rib fracture risk excluded severe trauma subjects (Nguyen et al. 2005).

Fracture detection method
One possible explanation for the unexpectedly severe injury outcome is our use of PMHS. Though some suggest that PMHS are more likely to sustain rib fractures than live individuals (Patrick 1994; Viano et al. 1977), a more defensible reason is that many more rib cage fractures can be observed in autopsies of PMHS compared to a clinical x-ray or CT of a living motor vehicle crash survivor, resulting in an inflated injury severity assessment. Crandall et al. (2000) reported that plane x-rays allowed the detection of less than 40% of the rib fractures confirmed by autopsy and that CT was 20% more accurate in identifying fractures. These findings were supported by this study in which the radiologist reported an average of 5 rib fractures per subject based on a review of the posttest CT scans. Five rib fractures is 51% of the per subject average identified in autopsy (Table 3). This translated into a lower average AIS severity score of 2.8 vs. the 3.4 autopsy average. The CT report missed the AIS 5 bilateral flail chest for the subject in test S0211. Nevertheless, both the autopsy and posttest CT injury assessment scored the injuries of 4 subjects as AIS 3 (severe).

Lack of precrash bracing
The average PMHS is more likely to sustain rib fractures than a live individual because PMHS lack the ability to brace in anticipation of a crash. Petit et al. (1998) estimates that 50% of drivers are aware that a crash is imminent and have the time to protectively tense their extremities in anticipation of the impact. Volunteers with extended tensed arms are reported to be able to provide torso restraint sufficient enough to reduce chest deflection (Shaw et al. 2005). Kemper et al. (2011) reported that 5 volunteers who braced prior to impact in a low-speed frontal crash were able to reduce sternum-to-spine deflection from a relaxed test average of approximately 7.5 to 0%.

Test hardware and methodology
It is possible that the severity of the observed injury may be due to the test condition and test hardware that deviated from the original equipment manufacturer (OEM) condition in terms of rigid support structures. For example, the aluminum channel knee bolster was positioned pretest to be in contact with the proximal leg. In an actual vehicle, the lower body and knees move forward several centimeters in a frontal crash before being arrested by the knee bolster. However, early and effective restraint of pelvic forward motion is recommended for encouraging forward torso pitch, more belt loading of the shoulder complex, and less rib cage loading and fracture (Schneider et al. 1992). Further investigation is required to explore the effects of early lower body restraint on rib cage deformation in response to both belt and inertial loads.

In conclusion, there are reasons that the level of injury observed in the study may be somewhat higher than that sustained by older female motor vehicle occupants in a real-world crash of similar delta-V. However, no one factor or factors in combination accounted for the large disparity between rib cage fracture risk for the test subjects relative to that of vehicle occupants.

Small elderly PMHS sustained an unexpectedly high number of rib cage fractures in what available information indicated was a minimally injurious frontal crash test condition. Though studies of real-world crashes confirm that older females sustain more fractures than the general occupant population, neither these field studies nor laboratory sled tests predict the injury severity observed. In particular, the sled test chest deflection results for the Hybrid III 5th percentile female dummy substantially underestimated the observed rib cage risk for PMHS of a similar size. Although the study design and the choice of subjects may have resulted in a somewhat greater injury severity level than that sustained by older female motor vehicle occupants in real-world crashes of similar delta-V, these factors do not completely explain the consistently severe thoracic injuries observed. Note that caution should be exercised when drawing conclusions from such a limited study—5 subjects tested in a single condition. However, we believe that the unequivocal results indicating risk of severe thoracic injury in a moderate crash justifies further investigation.

Possible future studies should include a test series designed to find the fracture threshold that was exceeded by the test conditions in this study. One strategy would involve estimating the fracture threshold level and conducting tests both less severe and more severe in the hopes of bracketing the threshold. Alternatively, it may be possible to detect the onset of fracture with acoustic sensors, strain gages, or accelerometers in a test condition now known to be injurious for the average subject. Another study should examine whether there are parameters such as rib cortex strength or rib cage geometry that may render small females substantially more vulnerable than average stature males to frontal crash loading.

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