Elderly PMHS Thoracic Responses and Injuries in Frontal Impacts

Yun-Seok Kang, Amanda M. Agnew, Chang-Bong Hong, Kyle Icke, John H. Bolte IV

Abstract As the number of elderly drivers and occupants continues to increase, it is important that vehicle safety equipment and restraint systems are investigated to understand if current systems are protecting these occupants during frontal collisions. The objective of this study is to examine thoracic injury to post mortem human subjects over the age of 65 that were exposed to frontal impacts with changes in velocity of 46 km/h. Six frontal impact sled tests were conducted using elderly PMHS. Each PMHS was screened to ensure the specimens had similar bone mineral density within the osteopenic to osteoporotic range. Two different restraint systems were used: one used an adaptive seat belt with two load limiters, an airbag with an inner air distribution chamber and a knee airbag (n=3); the other was a typical configuration and utilized a seat belt with one load limiter and an airbag with no inner chamber (n=3). Maximum percent chest deflection for the adaptive restraint system was 21.4 ± 4.7%, while that for the typical restraint system was 24.1 ± 8.4%. Rib fractures, a sternum fracture, and a spleen laceration were among the resulting injuries identified.

Keywords Elderly PMHS, Frontal impact, Restraint system, Rib fractures, Thoracic injury.

I. INTRODUCTION

The elderly population, i.e. people aged 65 years and older in the USA, was approximately 34 million, or roughly 13% of the total US population, in 2008 [1]. Approximately 91% of the elderly still maintain driver licenses, and of these 183,000 people were injured due to car crashes during 2008 [1]. High percentages of moderate to severe thoracic injuries (AIS2+) in elderly people have been reported, based on an analysis of the National Automotive Sampling System/Crashworthiness Data System (NASS-CDS) for the years 1998–2007 [2]. The mechanism of these AIS2+ thoracic injuries was identified as interaction with the belt restraint resulting in fractures of bony structures, such as the ribs and sternum [2]. Thoracic injuries are numerous for all age groups, but when considering severe injuries to the elderly population, thoracic injuries dominate in frontal impacts [3]. Thoracic injury risk with respect to age has been investigated using NASS-CDS data, and from these studies it was found that thoracic injuries are dominant for elderly occupants in frontal impacts, and that thoracic injury of elderly occupants was more frequent than that of young occupants [2-4]. According to NASS-CDS for the years 1998–2007, thoracic injuries (AIS2+) of elderly occupants age 65 and older occurred at a crash delta-v (ΔV) of 37 km/h or less, while young occupants age 25–44 sustained AIS2+ thoracic injuries at a crash ΔV of 46 km/h [2]. As the number of elderly drivers and occupants continues to increase, it is important that current vehicle safety equipment and restraint systems are investigated to understand if they are capable of sufficiently protecting this portion of the population in frontal collisions.

Studies on thoracic responses and injuries using post mortem human subjects (PMHS) in frontal impacts have been extensively conducted in different loading conditions (e.g. hub, seat belt, airbag, and combined loading conditions) [5-19]. However, few studies have investigated small elderly PMHS responses and injuries in frontal impact scenarios with controlled PMHS selection criteria, such as bone mineral density and anthropometry [19]. The main objective of this study, therefore, was to investigate thoracic injury to PMHS over the age of 65 that were exposed to frontal impacts with a ΔV of 46 km/h.

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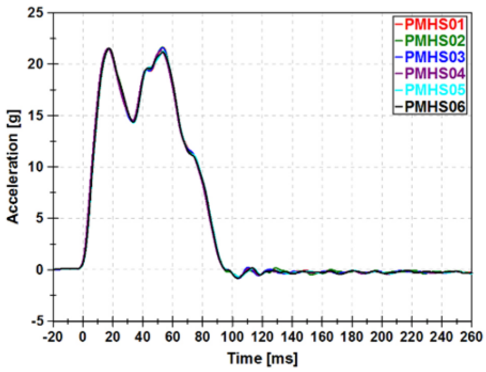
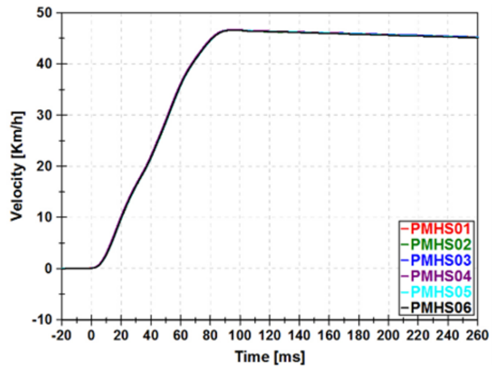
II. METHODS

Frontal impact HYGE sled tests were conducted using PMHS over 65yo (average age of 84 ± 10 years, height of 158.8 ± 5.6 cm and weight of 57.0 ± 5.2 kg). A total of six frontal impact sled tests with a ΔV of 46 km/h (Fig. 1) were performed using two different restraint systems: one was a novel design that included an adaptive seat belt with two load limiters, an airbag with inner air distribution chamber and a knee airbag shown in Fig. A1 in the Appendix (RS1); while the other was a standard configuration that included a seat belt with one load limiter and an airbag with no inner chamber (i.e. typical seatbelt with airbag) (RS2). Three PMHS sled tests were conducted for each restraint system. RS1 and RS2 were used for PMHS1-3 and PMHS4-6, respectively.



(a) Sled acceleration.



(b) Sled velocity.

Fig. 1. Sled pulse

Subject Selection

Six elderly PMHS were obtained through Ohio State University's Body Donor Program and all applicable ethical guidelines were followed. Each PMHS underwent a dual-energy x-ray absorptiometry (DXA) scan to measure area bone mineral density (aBMD) in the lumbar vertebrae. This was done to ensure the specimens had similar clinical fracture risk assessments. aBMD t-scores ranged from osteopenic to osteoporotic, with an average of -2.5 ± 0.6 (Table I). Following DXA, a whole-body CT scan was performed to document potential pre-existing injuries and any anatomical anomalies of the PMHS. The PMHS were then frozen (-20°C) until needed for testing. Each PMHS was removed from the freezer 48–72 hours before the data collection phase, to ensure they were properly thawed and had reached room temperature. All PMHS anthropometry are provided in Table I.

TABLE I
PMHS INFORMATION

	Age	Sex	Cause of Death	Height [cm]	Weight [kg]	aBMD [t-score]	BMI	Chest Circumference [cm]	Chest Breadth [cm]	Chest Depth [cm]
PMHS01	74	Male	COPD*	165	61	-2.3	22.5	90.5	35.0	18.0
PMHS02	83	Male	COPD*	163	64	-2.2	24.2	92.0	28.3	22.0
PMHS03	70	Female	Lung Cancer	162	56	-1.6	21.3	78.0	22.5	17.5
PMHS04	94	Female	Cardiac Arrest	150	53	-2.9	23.6	77.0	25.5	18.5
PMHS05	87	Female	Pneumonia	155	50	-3.5	20.8	84.3	26.8	22.0
PMHS06	94	Female	Pneumonia	158	58	-2.5	20.3	83.9	27.5	22.0
Mean (SD)	84 (10)	N/A	N/A	158.8 (5.6)	57.0 (5.1)	-2.5 (0.6)	22.1 (1.6)	84.3 (6.2)	27.6 (4.2)	20.0 (2.2)

*COPD = chronic obstructive pulmonary disorder.

Subject Instrumentation

In order to quantify chest deflections, a chestband (40 gages, Humanetics Innovation Solutions, Plymouth, MI) was wrapped around the PMHS thorax at the level of the xiphoid process. Uniaxial strain gages (Model CEA-13-062UW-350/P2, Vishay Micro Measurements, Wendell, NC) were attached on the anterolateral aspect of ribs 2–9 bilaterally, as shown in Fig. 2. For PMHS04, PMHS05 and PMHS06, eight additional strain gages were installed on the posterolateral aspects of ribs 6–9. Strain gages were also attached to the left clavicle (two), manubrium (one), and mid-sternum (one), as shown in Fig. 2. Three seat-belt tension load cells were placed on the belt, as shown in Fig. 3. Five pressure sensors (50 mm x 50 mm, SensorTech Corporation, Greenville, SC), which were thin and pliable (Fig. 3), were attached to the underside of the seat belt, so that pressure between the seat belt and the thorax could be quantified during the event. Detailed specifications of the pressure sensor are provided in Table AI (see Appendix A).

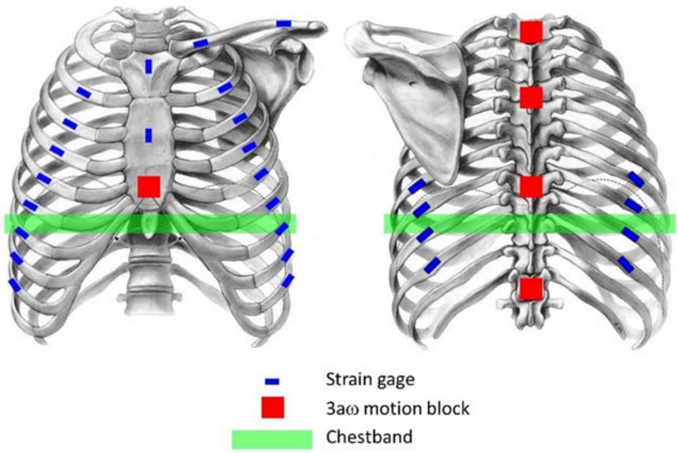


Fig. 2. Thoracic instrumentation: strain gages (blue), 3aω motion blocks (red), and chestband (green).

Fig. 3. Seat-belt instrumentation: three tension load cells (orange) and five pressure sensors (blue). Numbers represent sensor IDs.

Sled Set-up

A sled buck was built using a body in white (BIW), shown in Fig. 4. The front seat, as well as front interior vehicle structures (e.g. dash-board, steering wheel, etc.), restraint systems and seat-belt anchor locations, were not modified and reproduced production conditions (Fig. 4). Before seating, each PMHS was dressed in a cotton shirt and pants. The PMHS's lumbar spine was placed against the seat-back of the experimental seat such that the centre of the mid-sagittal plane of the PMHS was aligned with the centre of the seat-back. The PMHS head was supported by a head-harness suspended with string. A three-point belt with two different load limiter systems (Fig. A1) was used to restrain the PMHS on the seats, with initial belt tensions of 17.8 N (4 lb) for the lap belt and 26.7 N (6 lb) for the shoulder belt. The initial seat-back angle was approximately 25 degrees from vertical. The seat and restraint systems (e.g. seat belt and airbags) were replaced following each sled test. Sled set-up and initial position for each PMHS are presented in Fig. A2.

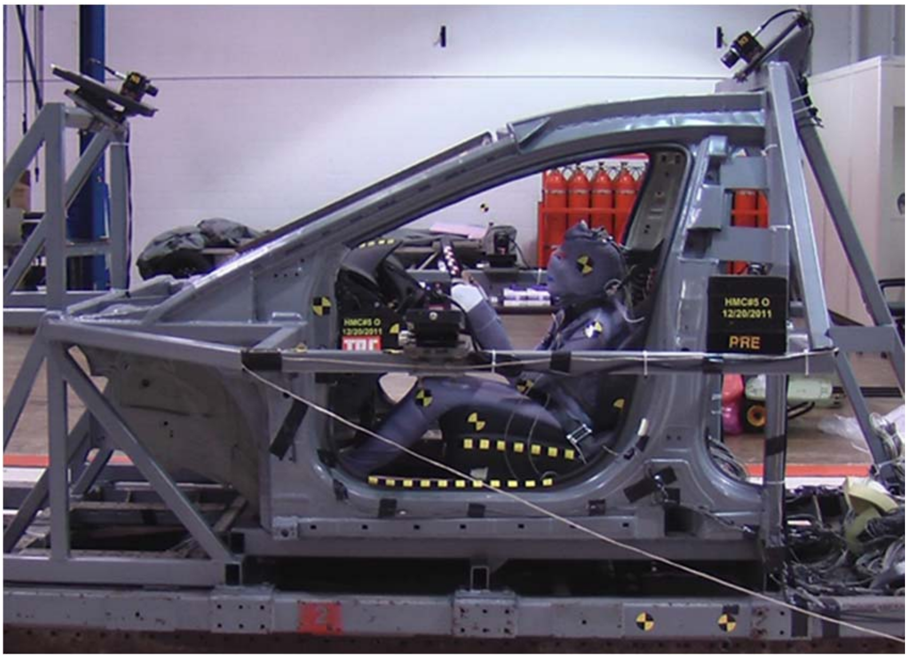


Fig. 4. General set-up for sled tests.

Data Processing

The sampling frequency used in all sled tests was 12,500 Hz, and all data obtained from the tests were filtered according to SAE J211 [20]. Strain gage and chestband data were not filtered. Chestband data were processed using CrashStar (version 2.7) [21] to calculate chest deflection and to obtain chest contour changes during the event. Chest deflection was calculated two different ways using chestband gages: (1) relative displacement between the spine gage and sternum gage (SS), which represents deflection measures from the Hybrid III 50th chest potentiometer; and (2) relative displacement between the spine gage and any gage that yielded maximum deflection (SMax). The strain gages installed on the ribs were used to identify time of fracture of each rib, consistent with previously published methods [14][16-18][22]. Data from the pressure sensors were normalized by the sum of all five pressure sensors to yield percent pressure distribution on the shoulder belt.

III. RESULTS

Since this study focused on thoracic responses, kinematic data of the PMHS were not provided in this manuscript but general kinematics of the PMHS captured from the high speed camera were presented in Fig. A2.

Injury Assessment

Rib fractures, a sternum fracture, and a spleen laceration were identified during the anatomical dissection performed on each PMHS following testing. Detailed injury summaries are provided in Appendix B. The majority of the injuries sustained from the sled tests were rib fractures: average numbers of rib fractures from RS1 tests were 7 ± 5 (MAIS ranged from 3 to 4), while those from RS2 were 19 ± 19 (MAIS ranged from 2 to 5). Table II describes AIS codes using *2000 NASS Injury Coding Manual* and associated timing for each AIS code. Five PMHS reached AIS3, and this level of injury severity occurred at various times (38.3–76.7 ms). Three PMHS reached AIS4, which occurred sequentially after AIS3 (39.4–57.0 ms), and only one, PMHS05, yielded AIS5 at 50.9 ms (Table II).

TABLE II
AIS CODE SUMMARY WITH INJURY TIMING

	AIS Injury Severity Codes	Injury timing (ms)	MAIS
PMHS01 (RS1)	Thorax - 450240.4 (≥3 rib fractures on both sides w/stable chest) Sternum - 450804.2 (fracture)	AIS3: 40.4 AIS4: 57.0	4
PMHS02 (RS1)	Thorax - 450230.3 (≥3 rib fractures on one side, <3 fractures on the other side w/stable chest)	AIS3: 42.4	3
PMHS03 (RS1)	Thorax - 450230.3 (≥3 rib fractures on one side, <3 fractures on the other side w/stable chest)	AIS3: 76.7	3
PMHS04 (RS2)	Thorax - 450240.4 (≥3 rib fractures on both sides w/stable chest) Spleen - 544222.2 (minor laceration)	AIS3: 38.3 AIS4: 39.4	4
PMHS05 (RS2)	Thorax – 450266.5 (bilateral flail chest) Sternum – 450804.2 (fracture) Lumbar Spine – 650620.2 (fracture of transverse process L1, L2, L3, L4) 650620.2 (fracture of the spinous process (L2) Spleen - 544222.2 (minor laceration)	AIS3: 43.0 AIS4: 47.4 AIS5: 50.9	5
PMHS06 (RS2)	Thorax – 450220.2 (≤3 rib fractures at any location w/stable chest)	AIS2: 77.8	2

Seat-belt Tension

Average maximum shoulder-belt tension force for RS1 (PMHS01–03) was 5435 ± 557 N, while that for RS2 (PMHS04–06) was 5904 ± 292 N (Fig. 5). Time history data for shoulder-belt tension are shown in Fig. 5. The times at which the resulting injuries crossed various levels of AIS (AIS3+) are also designated. The time of AIS was determined by the time of fractures from strain gage data.

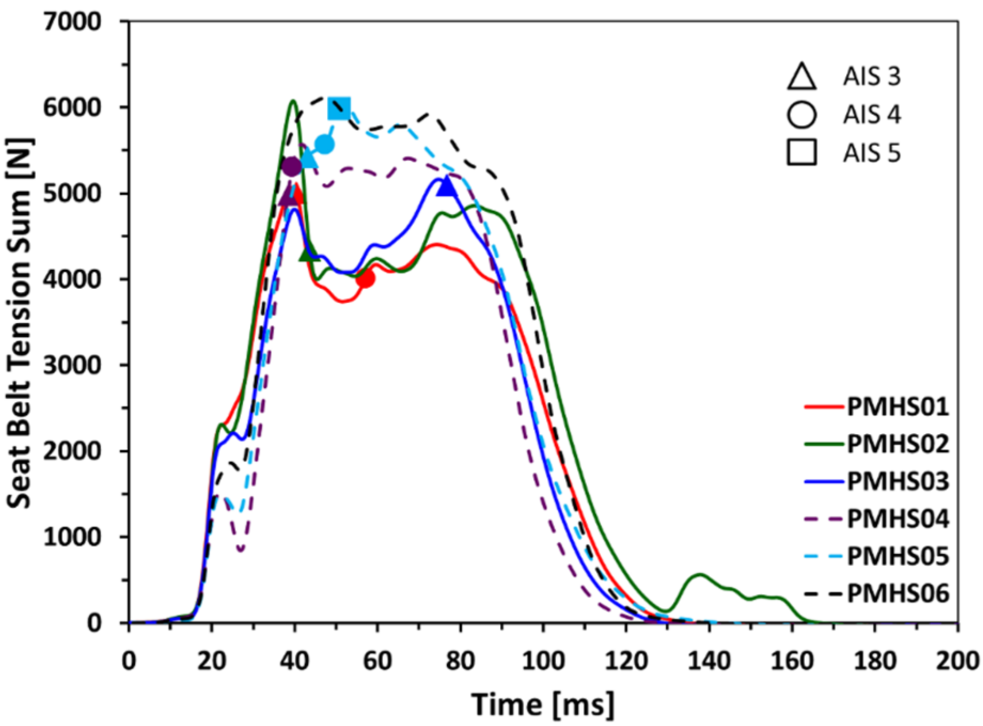


Fig. 5. Shoulder-belt tension AIS codes (AIS3: triangle, AIS4: circle and AIS5: square). RS1 was used in PMHS01–03 (solid line), while RS2 was used in PMHS04–06 (dashed line).

Chest Deflection

Chest deflection and percent compression for all six PMHS tests are shown in Table III. Average SS chest deflections for the RS1 and RS2 were 31.7 ± 15.1 mm (14.9 ± 9.3%) and 25.1 ± 11.0 mm (13.7 ± 6.3%), respectively (Table III). Average SMax chest deflection for the RS1 was 46.0 ± 2.4 mm (19.7 ± 2.7%), while that for RS2 was 41.7 ± 17.7 mm (18.5 ± 7.3%). Exemplar chest contour changes over time are provided in Appendix A (Fig. A3). Time history data for the SMax chest compression (%), with designated levels of AIS injury, are provided in Fig. 6.

TABLE III
MAXIMUM CHEST DEFLECTION

	PMHS01	PMHS02	PMHS03	PMHS04	PMHS05	PMHS06
SS chest deflection (mm)	29.6	17.8	47.7	35.8	29.8	9.6
SS chest compression (%)	12.7	7.0	25.1	16.9	11.9	4.3
SMax chest deflection (mm)	47.1	43.2	47.7	37.6	61.1	26.4
SMax chest compression (%)	20.1	16.8	22.2	17.3	26.3	11.8

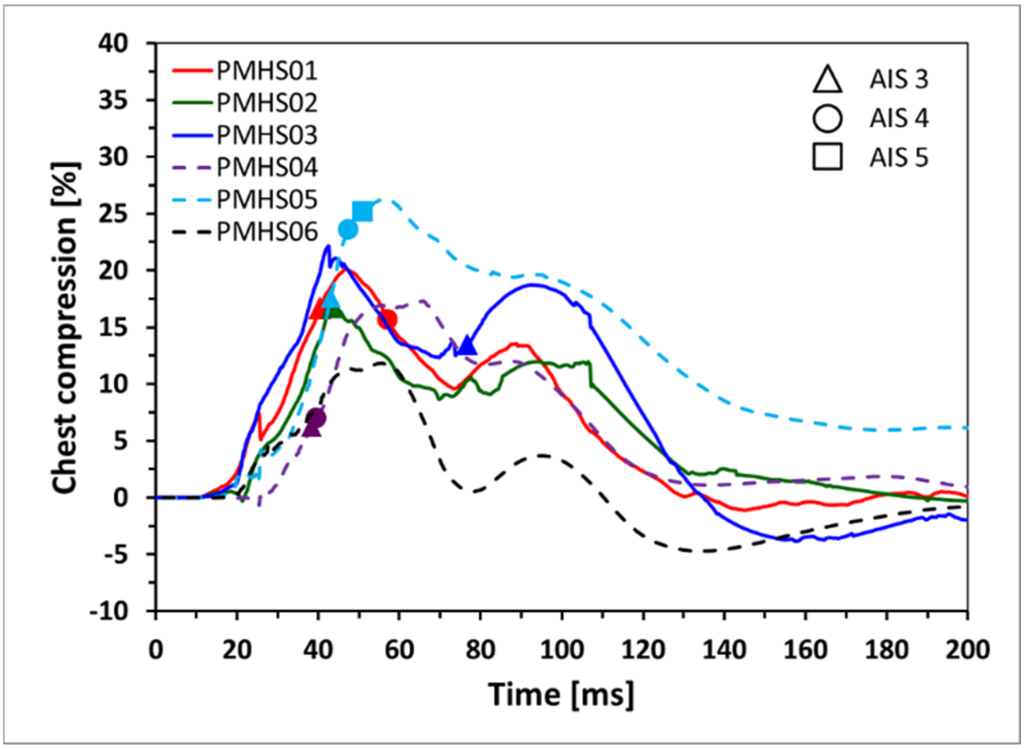


Fig. 6. SMax chest compression (%) with AIS codes (AIS3: triangle, AIS4: circle and AIS5: square).

Pressure Distribution on Shoulder Belt

Table IV shows percent pressure distribution on the seat belt by the thorax at the time of maximum pressure. The sensor IDs for the pressure sensors are indicated in Fig. 3. Average pressure distribution for each location was 27.1±10.2 for ID1, 23.1±15.0 for ID2, 19.0±5.2 for ID3, 15.5±8.0 for ID4, and 22.9±11.7 for ID5, shown in Table IV.

TABLE IV
SEAT-BELT PRESSURE DISTRIBUTION AT MAXIMUM OF SUM OF ALL PRESSURE SENSORS (%)

Sensor ID	PMHS01	PMHS02	PMHS03	Mean(SD)	PMHS04	PMHS05	PMHS06	Mean(SD)
1	34.6	30.8	32.3	32.6(1.9)	27.9	6.8	30.0	21.6(12.8)
2	23.6	13.0	6.5	14.4(8.6)	*	45.6	27.0	36.3**
3	19.4	10.4	22.9	17.6(6.5)	15.4	22.6	23.4	20.5(4.4)
4	22.3	7.9	18.0	16.1(7.4)	26.3	6.6	12.1	15.0(10.2)
5	*	37.9	20.2	29.0**	30.4	18.5	7.5	18.8(11.5)

*sensors did not record properly during the event.
**standard deviation was not calculated since only two data points are used.

IV. DISCUSSION

Injury Assessment

In this study, a series of sled tests was performed using elderly PMHS (four of six were over 80yo). Unlike other studies that require normal bone mineral density and control PMHS acceptance criteria [13][28-29], the PMHS used in this study had average aBMD t-scores of -2.5 ± 0.6 (Table I) and were small in both stature and mass (height of 158.8 ± 5.6 cm and weight of 57.0 ± 5.1 kg) compared to a midsize male (175.1 cm and 78.2 kg). However, the PMHS tested were generally larger than the 5th percentile female size of 151.3 cm and 46.7 kg [30]. Five PMHS resulted in AIS3+ thoracic injury. The injuries documented during this study were rib fractures, a sternum fracture, and a spleen laceration. The majority of the injuries sustained from this study were rib fractures: 13 rib fractures from PMHS01, 5 from PMHS02, 4 from PMHS03, 13 from PMHS04, 40 from PMHS05, and 3 from PMHS06. Time of rib fractures was measured using strain gages so that uncensored rib fracture data were collected [14][16-18], and AIS codes were summarized at each identified time (Table II).

Shaw *et al*. [19] reported an average of 10 ± 5 rib fractures (ranged from 4 to 15) from small female (n=5) frontal impact sled tests. The results from this study are very similar, with the exception of PMHS05. Kent *et al*. [13] reported that multiple fractures were found from two female PMHS, while no fractures occurred from two male PMHS in similar testing conditions (e.g. force-limiting three-point belt with airbag). One female (69 years old) had 25% chest compression, which resulted in 4 rib fractures, while the other (72 years old) had 34% chest compression with 11 rib fractures [13]. Shaw *et al*. [12] found that one female PMHS (57 years old) had 16 rib fractures, while three other PMHS had less than five rib fractures. Even though the sled input pulse used in those two studies [12-13] were comparable to that from this study, the number of rib fractures from this study was greater than those from the previous two studies [12-13]. This is likely due to both the differences in PMHS selection criteria (e.g. elderly with deliberately low aBMD t-scores in this study) and the restraint systems used.

Since the bone quality of elderly occupants is potentially different from typical, healthy adult occupants, a separate thoracic injury risk for elderly occupants needs to be established. Pilot studies for developing age-specific thoracic injury risk curves have been published [23-24]. However, due to a lack of biomechanical data from modern restraint systems (e.g. seat belt with pretensioner and load limiter with airbag), these injury risk curves had to rely on PMHS thoracic data from hub impacts or combined hub impacts with seat belt, airbag only, and both seat belt and airbag data. Novel scaling techniques for thoracic injury should be explored in future work and based directly on identified variation in rib/thoracic responses. Furthermore, biologically based variables should be targeted to identify the source of differences in thoracic properties, as age has been shown to be a poor predictor of rib failure [31]. More data are required to create a feasible age-specific thoracic injury risk curve for the modern advanced restraint systems, especially for elderly occupants.

Seat-belt Tension

Two different restraint systems were used in this study: one used an adaptive seatbelt with two load limiters, an airbag with inner air distribution chamber and a knee airbag; the other was a typical configuration of a seatbelt with one load limiter and an airbag with no inner chamber. Differences between these two systems were revealed in the time history of the seat-belt tension, shown in Fig. 5. Belt tension from PMHS01–03 (RS1) exhibited a sharp initial peak, followed by a quick relaxation phase, before building up slightly to a second peak tension. The shape of seat-belt tension responses from the PMHS04–06 (RS2) was a half sinusoidal shape without an initial peak (Fig. 5). The average maximum shoulder-belt tension force for the RS1 (5435 ± 557 N) was less than that determined from the RS2 (5904 ± 292 N). These differences were very minimal, however. Five PMHS yielded AIS3+, while one (PMHS06) only had MAIS2 with three rib fractures. It should be noted that AIS3 and AIS4 injury levels occurred before the peak shoulder tension in two PMHS tests (PMHS04 and PMHS05), while three PMHS (PMHS01, PMHS02 and PMHS03) reached AIS3 after peak tension. For PMHS05, AIS5 was reached even before the seat-belt tension peaked, as shown in Fig. 5. Although seat-belt tension has not been considered as a predictable variable for the thoracic injury, it is an important mechanical measure to understand thoracic responses and injuries, especially for elderly occupants.

A few studies have reported seat-belt tensions measured from PMHS frontal impacts with modern restraint systems (e.g. pretensioner and load limiter with different airbags) [13][15][19]. Kent *et al.* [13] conducted a series of frontal impact PMHS sled tests using ten PMHS (males and females, aged 47–85 years old) seated on a front passenger seat using different restraint systems. The input sled pulse used in Kent's study was very similar to this study. Four PMHS tested in Kent's study used a three-point belt system with a buckle pretensioner, a 3.5 KN load limiting retractor, and a depowered airbag, which is similar to the standard restraint system (RS2) used in this study [13]. Shaw *et al.* [15] also performed a series of frontal impact sled tests (40 km/h) using eight 50th percentile male PMHS. Shaw used a custom three-point belt with no pretensioner, which is commonly used in a typical mid-size US sedan [15]. Shaw *et al*. [19] investigated small female rib cage fractures in 30 km/h frontal sled tests using five elderly PMHS (average age of 76 years) that were similar in size (stature and mass) to a 5th percentile female. A custom 2 kN force-limited three-point seat belt system was used in this study [19]. The shoulder tension results from the current study are comparable to the average shoulder-belt tension measured from the Shaw study [19], but lower than those from both Kent [13] and Shaw [15], as shown in Fig. 7. The lower seat-belt tensions from the current study may be due to a number of factors: different restraint systems, different sizes of PMHS (especially Shaw *et al*., 2009), and different thoracic properties of PMHS due to anatomical variation. Shaw *et al.* [12] ran Hybrid III 50th percentile, THOR and three male PMHS tests in similar testing conditions (e.g. three-point belt with 1 kN buckle-side pretensioner) [12]. While the authors did not report actual values of shoulder-belt tension in the manuscript, a figure (shoulder-belt tension vs. time for Hybrid III, THOR and PMHS) revealed their results were approximately 3000–4000 N, which are similar to those determined from the current study.

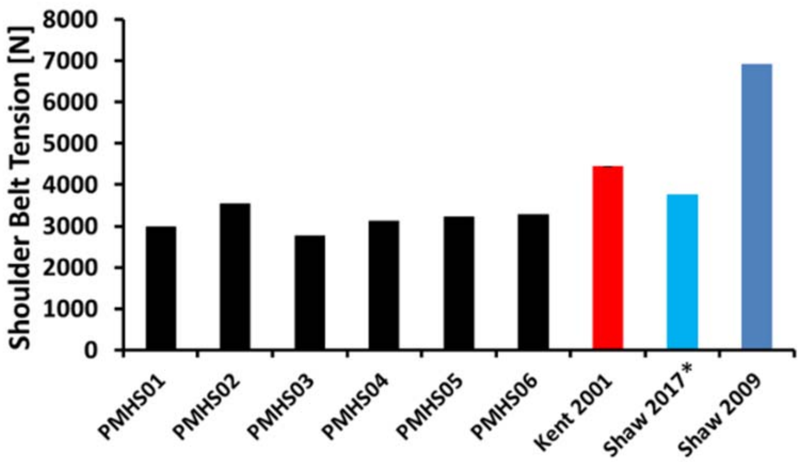


Fig. 7. Comparison of seat-belt tension forces (current study vs. previous studies).
(*Shaw 2017 reported average upper and lower shoulder-belt tension separately, so those two values were simply added.)

Chest Deflection

Chest deflection and percent compression are both considered as important predictor variables for thoracic injuries [23-25]. Therefore, both chest deflection and percent compression were quantified in this study (Table III) using two different methods (e.g. SS and SMax). It should be noted that the SS deflections were lower than SMax deflections due to the localized loading effect from the seat belt, as shown in Fig. A3 (i.e. maximum deflections did not occur at the sternum). This indicates that the Hybrid III ATD may not be capable of measuring maximum localized chest deflection since it only measures chest deflection in the anterior to posterior direction. This concern has also been discussed in previous studies, where authors used the chestband to directly measure chest deflection [18][26-27]. The SMax chest deflections and chest percent compression for both RS1 and RS2 were very similar: 46.0 ± 2.4 mm vs. 41.7 ± 17.7 mm, and 19.7 ± 2.7% vs. 18.5 ± 7.3%, respectively (Fig. A3), indicating that the effect of the two different seat-belt load limiter mechanisms on chest deflection was very minimal.

It should be noted that AIS3 occurred before the peak deflection for the PMHS01, PMHS02, PMHS04, and PMHS05, while it occurred later for the PMHS03, shown in Fig. 6. As mentioned, PMHS06 did not reach AIS3 level (MAIS2 with only three rib fractures). It is important to note that AIS5 was reached at 25.2% of chest compression before the maximum chest compression in PMHS05 (Fig. 6). The thorax of PMHS05 was extremely fragile and resulted in 40 rib fractures (Appendix B). For PMHS04, AIS3 occurred at only 6.2% chest compression, and consecutively AIS4 occurred at 7.2% chest compression. These results from PMHS04 and PMHS05 help explain how elderly occupants can reach AIS3 (even AIS4 and 5) level of thoracic injury before peak deflections occur. This finding is supported by previous studies [17-18]. Kemper *et al.* [17-18] found that AIS3 injuries occurred before peak sternum deflection and lower chest compression during two different test conditions (table-top seat belt tests and frontal sled tests). Increased chest deflection could occur due to the accumulation of rib fractures, since multiple fractures would allow for increased compression of the thorax.

The chest compression results from this current study were also compared to those from previous studies, shown in Fig. 8 [12-13][18-19]. Chest compressions obtained from this study were comparable to those from Shaw (2000) [12], Kent (2001) [13], and Shaw (2017) [19] studies, but lower than those from the Kemper (2016) study [18], shown in Fig. 8. Kemper *et al*. [18] ran dynamic frontal sled tests with two 50th percentile male PMHS (63 and 79 years), using a sled pulse that was designed to match FMVSS 208 (40 km/h). Kemper *et al.* [18] used a 4 kN load-limiting three-point seat belt with no airbags. They found that one PMHS had 23.9% chest compression, which is comparable to our result, while the other PMHS yielded 36.0% of chest compression, which is greater than the compressions from this study. The discrepancy between the current study and Kemper's could be simply due to a limited sample size (n=2) and the use of different restraint systems (i.e. no airbags were included in Kemper's study).

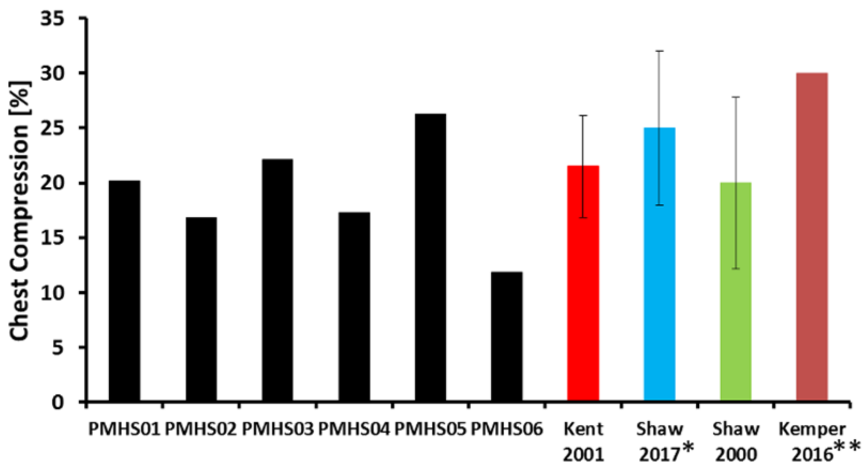


Fig. 8. Comparison of chest percent compression (current study vs. previous studies). The error bar indicates one standard deviation.

(*Sternum deflection was used from Shaw 2017; **Standard deviation was not calculated since only two PMHS were tested in Kemper 2016.)

Pressure Distribution on Shoulder Belt

Pressure distribution on the shoulder belt was also quantified in this study. In general, the sensors were located anatomically as follows: left clavicle (ID1); left ribs 2 & 3 (ID2); sternal body (ID3); right ribs 6 & 7 (ID4); right ribs 9 & 10 (ID5). Sensors ID1 & ID2 showed higher pressure values than other locations. This result correlated well with rib fracture locations. All six PMHS had rib fractures on either rib 2 or 3, but did not have clavicle fractures. Sensor ID1 on PMHS05 was located higher than the target location (i.e. superior to the clavicle), and as a result ID2 showed higher pressure than all other pressure sensors. Due to the lack of comparable data in the literature, it is difficult to verify the feasibility of the results from the pressure sensors.

Limitations

Results from this study were not normalized to a representative size (e.g. 50th percentile male or 5th percentile female) since both male and female PMHS were used in the sled tests. It was difficult to assess the performance of the restraint systems (RS1 vs. RS2) in this study due to the limited number of PMHS tested. It was also hard to determine injury thresholds or to calculate injury risk, again due to the small sample size. Both female and male PMHS were utilized in this study since PMHS availability was limited due to the testing timeline. Even though aBMD t-scores were used to select PMHS, it should be noted that aBMD did not correlate to the number of rib fractures documented in this study, and may be a poor tool for predicting thoracic fragility. An index for quantifying bone quality should be developed to help better control PMHS selection and for normalization purposes. Even though two different types of the airbags were used in this study, it was difficult to quantify influence of the airbags on thoracic responses due to absence of airbag instrumentation and associated difficulty with installing instrumentation that can provide desired data. The absolute force data converted from the pressure sensors could not be used in this study since the pressure sensors were sensitive to contact surface properties of the thorax that varied between PMHS. Reliability of the pressure sensors was not evaluated as a part of this study so further investigation of pressure sensor is required. This study focused on investigating relationships between the variables measured for thoracic responses, such as chest deflection, seat belt tension, and seat belt pressure distribution and thoracic injuries. However, further analysis will be required to examine the relationship between thoracic injuries and other variables (e.g. size, mass, spine deformity, and rib angles).

V. CONCLUSIONS

Small, elderly PMHS, with aBMD of either osteopenic or osteoporotic, were tested in frontal impact scenarios using a HYGE sled. Thoracic responses (i.e. belt forces and deflections) were quantified with respect to injuries found from the frontal impact sled tests. Pressure sensors under the shoulder belt measured the greatest values just superior to ribs 2 and 3, which correlated well with injury outcomes (i.e. all six PMHS had fractures on rib 2, while five PMHS had fractures on rib 3). AIS3+ injuries occurred before maximum chest deflection but after maximum shoulder-belt tension. One PMHS (87yo female with -3.5 aBMD t-score) yielded 40 rib fractures, with a sternum fracture and a spleen laceration. Elderly-specific restraint systems need to be developed to protect this vulnerable population. More elderly PMHS impact data are required to develop elderly thoracic injury risk curves for modern restraint systems.

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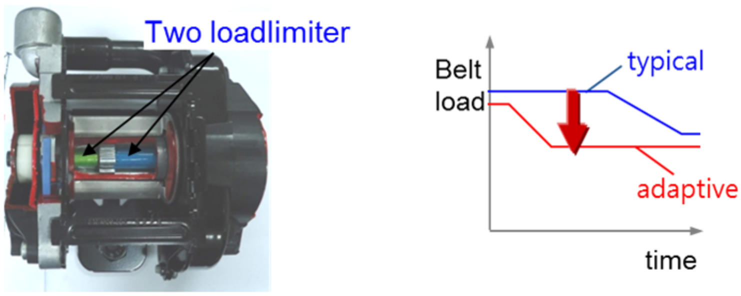
VIII. APPENDICES

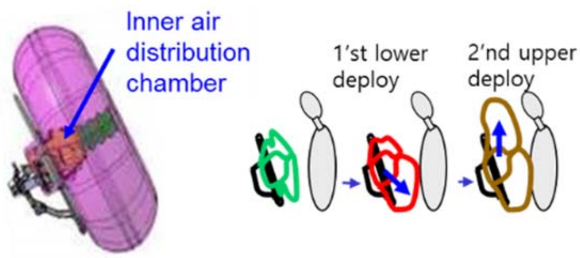
Appendix A

TABLE AI
PRESSURE SENSOR SPECIFICATIONS

Full scale	17.2 Mpa
Overload protection	82.7 Mpa
Zero balance	± 0.025%
Non-Linearity	± 0.4%
Repeatability	± 0.1%
Hysteresis	<± 0.5%
Temperature range	-32˚C to 71˚C
Force resolution	± 0.025% @ 50% FS & ± 0.15% @ 100% FS



(a) Seat belt.



(b) Airbag.

Fig. A1. Adaptive restraint system (RS1) in this study.

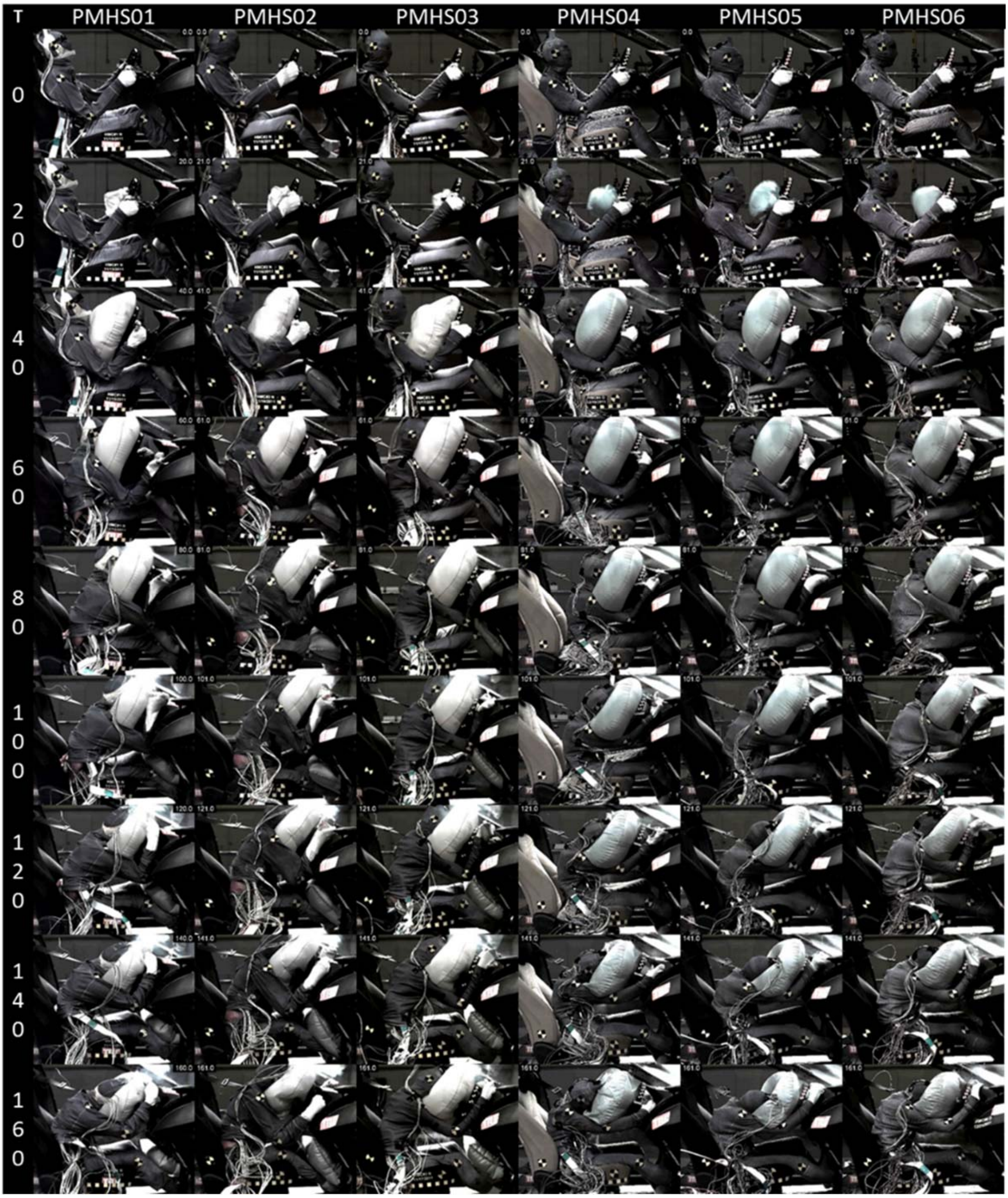


Fig. A2. Pre-test PMHS positions at time zero and PMHS kinematics during the event (0 to 160 ms)

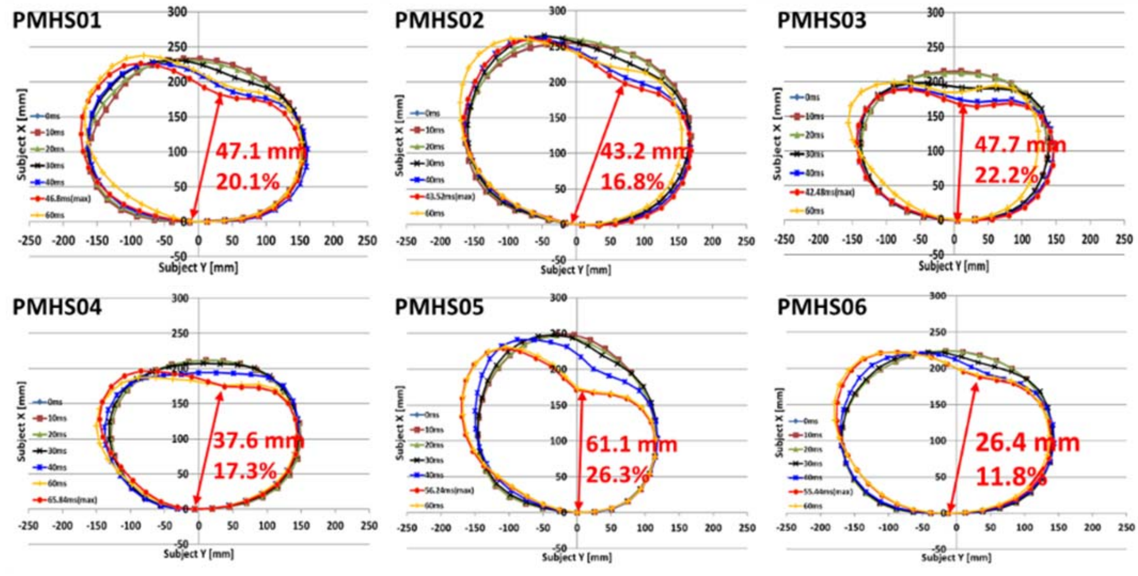


Fig. A3. Chest contour changes during the events, as measured by a chestband. Arrows show the calculated deflection between the spine gage and the gage where maximum deflection occurred.

Appendix B

PMHS01

Injury findings

Skeletal (both right and left unless noted otherwise)

- Sternum
  - Transverse fractures in sternal body
- Ribs
  - Fractures (L = left, R = right)
    - L2: transverse, non-displaced anterior fracture
    - L4: hairline, non-displaced anterior fracture
    - L8: transverse, non-displaced anterolateral fracture
    - L9: transverse, non-displaced anterolateral fracture
    - R2:
      - non-displaced anterior fracture
      - non-displaced anterior fracture
    - R3: displaced anterior fracture
    - R4: displaced anterior fracture
    - R5:
      - displaced anterior fracture
      - transverse, non-displaced anterior fracture
    - R8: transverse, non-displaced anterior fracture
    - R9: transverse, non-displaced anterior fracture
    - R10: non-displaced lateral fracture

AIS code summary

- MAIS4
- Sternum – 450804.2 (Fracture)
- Thorax – 450240.4 (≥3 rib fractures on both sides w/stable chest)

PMHS02

Injury findings

Skeletal (both right and left unless noted otherwise)

- Ribs
  - Fractures (L = left, R = right)
    - R3:
      - transverse, non-displaced anterior fracture
      - transverse fracture on pleural surface only of *costal cartilage*
    - R4: transverse, non-displaced anterior fracture at costochondral junction
    - R5: transverse non-displaced anterior fracture (5 mm from costochondral junction)
    - R6: non-displaced anterior fracture through pleural cortex only

AIS code summary

- MAIS3
- Thorax – 450230.3 (≥3 rib fx on a side & <3 fx on the other side w/stable chest)

PMHS03

Injury findings

Skeletal (both right and left unless noted otherwise)

- Ribs
  - Fractures (L = left, R = right)
    - L2: non-displaced anterior fracture through cutaneous cortex only
    - R5: non-displaced anterior fracture through cutaneous cortex only
    - R6: non-displaced anterior fracture through cutaneous cortex only
    - R7: non-displaced anterior fracture through cutaneous cortex only

AIS code summary

- MAIS3
- Thorax – 450230.3 (≥3 rib fx on a side & <3 fx on the other side w/stable chest)

PMHS04

Injury findings

Skeletal (both right and left unless noted otherwise)

- Ribs
  - Fractures (L = left, R = right)
    - L3: transverse, non-displaced anterior fracture
    - R2:
      - non-displaced anterior fracture
      - transverse, non-displaced anterolateral fracture
    - R3:
      - transverse, non-displaced anterior fracture
      - transverse, non-displaced anterolateral fracture
    - R4:
      - transverse, non-displaced anterior fracture
      - transverse, non-displaced anterolateral fracture
      - hairline mid-axillary line fracture
    - R5: transverse, non-displaced anterior fracture
    - R6: transverse, non-displaced anterior fracture
    - R7: transverse, non-displaced anterior fracture
    - R9: transverse, non-displaced anterior fracture
    - R10: transverse, non-displaced mid-axillary line fracture

Viscera

- Spleen
    - small laceration on inferolateral surface

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AIS code summary

- MAIS4
- Thorax – 450240.4 (≥3 rib fractures on both sides w/stable chest)
- Spleen – 544222.2 (minor laceration)

PMHS05

Injury findings

Skeletal (both right and left unless noted otherwise)

- Sternum
    - Manubrium fracture originating from instrumentation site
- Posterior ribs
    - Fractures (L = left, R = right)
        - L7: transverse, non-displaced fracture, lateral to costal angle
        - L8: transverse, non-displaced fracture, lateral to costal angle
        - L9: transverse, non-displaced fracture, lateral to costal angle
        - L10:
            - non-displaced fracture, pleural surface only, at costal angle
            - transverse, non-displaced fracture, lateral to costal angle
        - L11:
            - non-displaced fracture, pleural surface only, at costal angle
            - transverse, displaced fracture, lateral to costal angle
            - transverse, displaced posterolateral fracture
        - L12:
            - transverse, non-displaced fracture, at vertebrocostal joint
            - transverse, non-displaced fracture, at costal angle
        - R6: crush fracture, at costal angle
        - R11: transverse, non-displaced fracture, at costal angle
        - R12: transverse, non-displaced fracture, at costal angle
- Anterior ribs
    - Fractures (L = left, R = right)
        - L1: buckle fracture in costal cartilage
        - L2:
            - transverse, non-displaced anterior fracture at costochondral joint
            - buckle, anterior fracture
            - transverse, non-displaced mid-axillary line fracture
        - L3:
            - buckle, anterior fracture
            - transverse, non-displaced anterolateral fracture
        - L4: buckle, anterolateral fracture
        - L5: buckle, anterolateral fracture
        - L6: transverse, non-displaced anterolateral crush fracture
        - L7: transverse, non-displaced anterolateral fracture
        - L8: longitudinal anterolateral crush fracture
        - L9: transverse, non-displaced mid-axillary line fracture
        - R1: buckle, anterior fracture
        - R2:
            - buckle, anterior fracture
            - transverse, non-displaced anterolateral fracture

        - R3:
            - non-displaced anterior buckle fracture
            - buckle, pleural cortex only, anterolateral fracture
            - transverse, non-displaced, mid-axillary line fracture
        - R4:
            - non-displaced anterior buckle fracture
            - transverse, displaced anterolateral fracture with punctured pleura
        - R5:
            - non-displaced anterior buckle fracture
            - transverse displaced mid-axillary line fracture
        - R6: transverse, displaced anterolateral fracture
        - R7: transverse, displaced mid-axillary line fracture
        - R8: transverse, displaced mid-axillary line fracture
        - R9: buckle, pleural cortex only, mid-axillary line fracture
        - R10: transverse, displaced mid-axillary line fracture
- Lumbar vertebrae
    - Right and left transverse processes of L1, L2, L3, and L4 fractured
    - Spinous process of L2 fractured

Viscera
- Lungs – no injury
    - Pleura – punctured in right 3rd intercostal space (pneumothorax)
- Spleen
    - Small rupture on inferolateral surface

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AIS code summary
- MAIS5
- Sternum – 450804.2 (fracture)
- Thorax – 450266.5 (bilateral flail chest)
- Lumbar Spine –
    - 650620.2 (fracture of transverse process (L1; L2; L3; L4))
    - 650620.2 (fracture of the spinous process (L2))
- Spleen - 544222.2 (minor laceration)

PMHS06

Injury findings

Skeletal (both right and left unless noted otherwise)
- Anterior ribs
    - Fractures (L = left, R = right)
        - R2: transverse, non-displaced anterolateral fracture
        - R3: transverse, non-displaced anterolateral fracture
        - R10: transverse, displaced lateral fracture

AIS code summary
- MAIS2
- Thorax – 450220.2 (≤3 rib fx any location w/stable chest)