Comparison of Small Female and Mid-sized Male PMHS Response with an Inflatable Seatbelt System during Frontal Impacts

Xin Jin, Paul Begeman, Derek Board, Kevin Pline, Ming Shen, Srinivasan Sundararajan, King H. Yang

Abstract Previous studies showed that an inflatable seatbelt system could better protect occupants subjected to frontal crash by reducing the head excursion, chest deflection, and cervical spine injury. The main reasons for these reductions are because the inflatable seatbelt system is designed to distribute the crash force over a wider area of the body and to reduce body forward displacement by tightening the belt during deployment of the seatbelt airbag. Small female occupants are considered vulnerable during vehicle collisions, but the vulnerability was not studied for the inflatable belt system. This study evaluated the impact response of small female and mid-sized male occupants using an inflatable seatbelt system and compared their biomechanical response and injury outcomes.

Frontal-impact sled tests were conducted with eight small female postmortem human subjects (PMHS) and four mid-size male PMHS using a generic inflatable seatbelt system. Occupant kinematics, sensor data, and injury outcome were analyzed and compared. These results correlate to the reported PMHS data during frontal impacts using the inflatable belt system. It was also observed that small females sustained more rib fractures than mid-sized males, which was likely due to their poor bone conditions.

Keywords inflatable seatbelt, small female, rib fracture, occupant kinematics

I. INTRODUCTION

Inflatable seatbelts, which incorporate inflatable components to the traditional three-point seatbelt systems, have been adopted by car manufacturers in the restraint system for rear-seat occupants. The protection mechanism of the inflatable seatbelt is to distribute the thoracic load to a larger contact area and to alter the loading path of the head and neck. The distributed restraint force is expected to reduce rib fractures. In addition, the increased contact area is expected to reduce the rotation of the torso around the seatbelt thus limit head excursion.

The protective effects of inflatable seatbelts have been investigated from the 1970s. Burkes et al. [1] evaluated the performance of the “inflataband”, an inflatable belt system, on dummies and twelve human volunteers. The impact velocity is ranged from 20 kph to 52 kph at a peak sled deceleration of 20 g. As the authors described, this inflatable belt system can effectively distribute the impact load over the chest and control the occupant kinematics without generating significant trauma. The major complaints of volunteers include redness of the skin and temporary neck sourness. Horsch et al. [2] compared the performance of inflatable belts to 3-point seatbelts on Hybrid III dummies. Authors concluded that the inflatable belts can reduce injury risks than the traditional 3-point seatbelts. Kent et al.[3] performed frontal sled impacts on three male post mortem human subjects (PMHS) using an inflatable should belt and a non-inflatable lap belt (the “Airbelt”). The test results showed that the Airbelt generated lower head, neck, and thoracic injury metrics and PMHS trauma than non-inflatable restraint systems. Sundararajan et al. [4] conducted frontal sled tests on dummies and six PMHS (three mid-size males and three small females). It was found that the inflatable belt system can reduce forward head excursion and thoracic and neck injuries.

Small female occupants are considered vulnerable in motor vehicle crashes [5,6]. In the context of the inflatable belt system, the vulnerability of small female occupants has not been studied. Sundararajan’s study has shown that although the inflatable belt system can effectively reduce rib fractures, one small female PMHS still sustained 22 rib fractures, which is likely because of poor bone density [4]. In addition, the published studies using PMHS, especially small female PMHS, are still very limited. The objective of this study is to experimentally study the impact response and injury outcome of small female PMHS using the inflatable belt system and to compare the response with that obtained from mid-sized male PMHS.

II. METHODS

Testing Setup

Frontal-impact sled tests were conducted on the HYGE sled at Wayne State University Bioengineering Center. Two configurations of the inflatable belt system were used in this study. Configuration A (shown in Figure 1) uses an inflator in the buckle and inflates the bag inside the webbing. Configuration B has an inflator at the anchor and inflates through the webbing across the lap belt to the shoulder bag portion. Both systems have 4 kN force-limiting shoulder retractors. A buckle pretensioner was used in configuration B with a pretension force of 1.5 kN. In this study, the two configurations were treated as a generic inflatable belt system. The difference between the two configurations was neglected and the aim was to study the impact responses of the small female and mid-sized male PMHS. The crash pulse representative of a 40 kph (25 mph), frontal rigid barrier impact is shown in Figure 2.

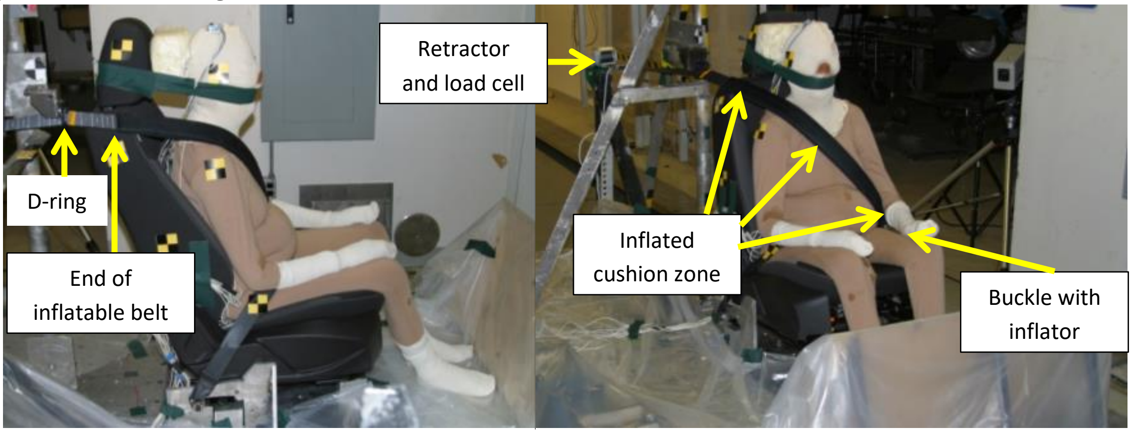

Figure 1. Side (left) and side-oblique (right) views of PMHS test setup.

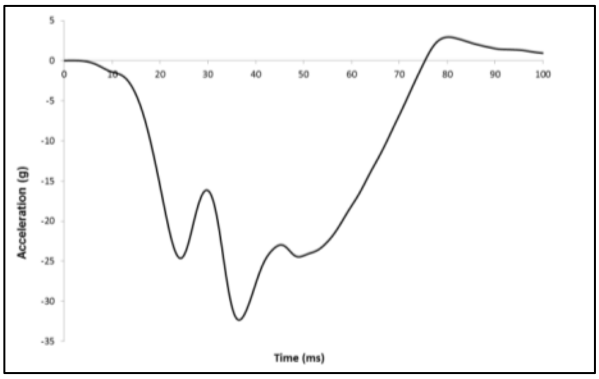

Figure 2. Crash pulse for HYGE sled test.

Twelve PMHS (four mid-sized males and eight small females) were tested to simulate a rear seat application in this study. PMHS was seated on a single occupant production seat. Belt positioning was conducted in a similar fashion to [4]. The lap portion of the belt was placed to not promote submarining by positioning against the iliac crests. The shoulder portion of the belt was positioned in such a manner to be proximal to the neck but not promote slippage of the shoulder during the loading phase. Anthropometric data of the PMHS are listed in Table 1. Subject instrumentation included three linear accelerometers and three angular rate sensors on the head top. Three linear accelerometers were mounted to the PMHS by screwing into the bony structures of the first and twelfth thoracic vertebra (T1 and T12) and sacrum on the posterior torso. X-ray was taken to ensure the screws going into the desired location during instrumentation (Figure 3). Shoulder belt tension was measured using the belt load cell in configuration A while using a load cell (1010AF-5K, Interface) connecting retractor to the sled in configuration B. On-board and off-board high-speed video cameras were used to collect frontal and lateral views at 2000 Hz. PMHS instrumentation measurements were filtered using CFC filters reported by Sundararajan et al [4]. Accelerations at the head center of gravity (CG) were converted from the linear accelerations and angular velocities at the head top using the method described by Bartsch et al [7].

Bone mineral density information was collected for all the PMHS. The data source was listed in Table 1. T-score obtained from computed tomography (CT) scan and bone mineral density (BMD) reported from dual-energy X-ray absorptiometry (DXA) on the lumbar spine were used to evaluate bone conditions for PMHS. For the specimens without scanning, bone ash test was performed. Two-centimeter rib segments were dissected from the fourth to the sixth ribs. Rib segments were dried at 120°C for 2 hours. The mass of the dry bone was measured. Dry ribs were burned to ash at 700°C for 8 hours and the ash mass was measured. The ratio between ash and dry bone was used as an indicator of bone mineralization [8].

Table 1. PMHS anthropometry information

PMHS No.	age	gender	Height (m)	Weight (kg)	Inflatable belt configuration	Data source of bone density
UM 34204	74	M	1.73	86.9	A	DXA + Ash
UM 34290	43	M	1.70	62.3	A	DXA + Ash
WSU 938	72	F	1.58	59.0	A	DXA
WSU 944	88	M	1.80	68.1	A	DXA
WSU 967	49	M	1.78	86.2	B	DXA
OSU 6675	80	F	1.63	43.0	B	CT
OSU 6696	88	F	1.55	54.0	B	CT
OSU 6721	85	F	1.56	51.8	B	CT
UM 34931	82	F	1.70	54.6	B	Ash
WSU 625	86	F	1.55	38.7	B	Ash
WSU 660	69	F	1.58	37.3	B	Ash
WSU 719	85	F	1.52	32.8	B	Ash

III. RESULTS

Kinematics

The representative kinematics of a mid-size male and a small female PMHS restrained by the inflatable belt system is shown in Figures 3 (frontal view) and 4 (lateral view). The shoulder belt was fully inflated at 30 ms. In both cases, the belt was deployed without noticeable chin-belt interaction. Throughout the whole impact process, head translation and rotation caused by the inflatable belt deployment was not observed.

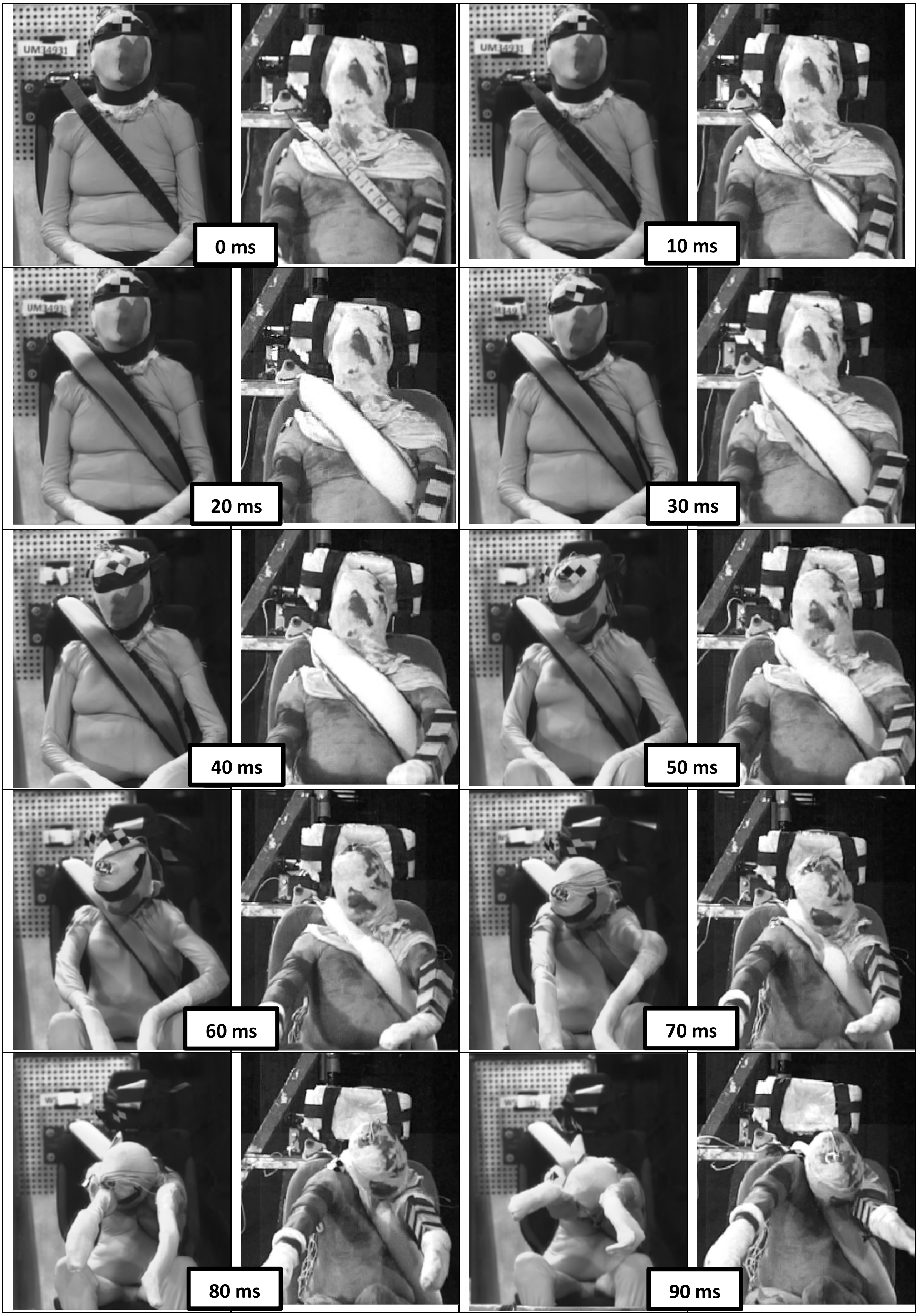
0 ms
10 ms
20 ms
30 ms
40 ms
50 ms
60 ms
70 ms
80 ms
90 ms

Figure 3. Front-view kinematics of small female (left, UM34931) and mid-size male (right, UM34290) PMHS restrained by the inflatable seatbelt system.

Figure 4. Lateral-view kinematics of small female (left, UM34931) and mid-size male (right, UM34290) PMHS restrained by the inflatable seatbelt system.

Sensor Data

Sensor data were averaged and compared between mid-size male and small female groups, as shown in Figure 6. The plot of raw data for each specimen is shown in the Appendix. Data failure was identified with WSU 625. In addition, pelvic acceleration of UM 34931 and shoulder belt loading of OSU 6675 and WSU 938 were not successfully recorded. Shoulder belt forces from UM34204 and UM34290 were removed from the data set due to potential sensor malfunction during data analysis.

The head CG resultant accelerations of both male and female groups showed a double-peak pattern. The average peak head acceleration of small female group was slightly higher than the male group. However, this difference may not be statistically significant given the fact that the variance of each group is very large.

Shoulder belt loading of small females was lower than the 4 kN of the retractor force limit. In addition, a longer duration (about 130 ms) was observed in the male group compared to the female group (about 110 ms). This difference may result from the larger inertia of the male group which caused the belt system to reach its force limit and to take a longer time to stop the torso.

Resultant accelerations at T1, T12, and pelvis showed similar patterns and peak levels for both male and female groups.

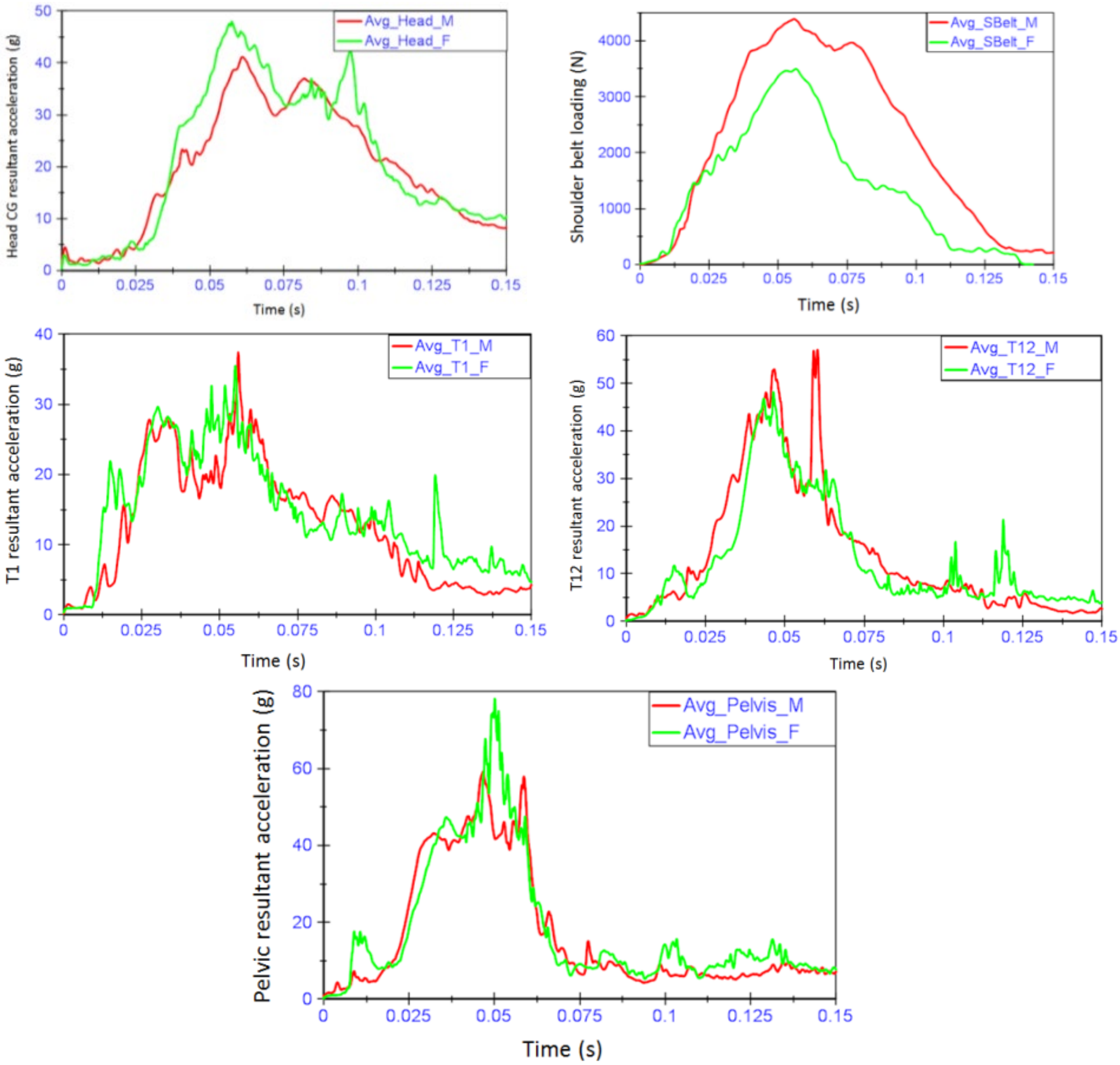

Figure 5. Comparison of small female and mid-size male PMHS responses.

PMHS injuries

The bone density information and injuries sustained by the PMHS in the sled tests are summarized in Table 2. Detailed locations of the rib fractures are provided in the Appendix.

Compared with rib fractures, mid-size male PMHS (8.5 fractures on average) sustained relatively fewer fractures than small female PMHS (15.5 fractures on average). Right clavicle fractures were observed in three subjects (WSU 944, OSU 6675, and WSU 719). One male subject (UM 34204) sustained disc separation between T2 and T3. The most severe spinal injuries were observed on one small female subject (WSU 719) with C6 vertebral transaction and anterior fracture on T1. One male subject (UM 34204) didn't sustain any injury during the sled test.

Bone condition directly affects the fracture outcome. Osteoporosis can be defined with a T-score less than -2.5 or with BMD less than 0.9 g/cm^2 [9]. Ash/bone ratio less than 0.48 was defined for osteoporosis by linear interpretation from the BMD values of UM 34204 and UM 34290. Based on these thresholds, UM 34204, WSU 944, WSU 625, and OSU 6696 are with the normal bone condition while the rest PMHS are of osteoporosis. The average number of rib fractures for PMHS with the normal bone condition is 9.5. This number increased to 15.0 for PMHS with osteoporosis.

Table 2. PMHS injury results

PMHS ID	Age (yrs)	Sex (M/F)	Belt Type	Number of Rib Fractures		Sternum Fracture (Y/N)	Other Injuries	T-score	BMD (g/cm^2)	Ash/Dry Ratio
				Left	Right					
UM 34204	74	M	A	0	0	N			1.134	0.56
UM 34290	43	M	A	8	11	Y	Disc separation between T2 and T3		0.727	0.39
WSU 938	72	F	A	2	6	Y			0.876	
WSU 944	88	M	A	4	5	Y	Right clavicle fracture		1.108	
WSU 967	49	M	B	3	3	N			0.805	
OSU 6675	80	F	B	4	4	Y	Right clavicle fracture	-3.90		
OSU 6696	88	F	B	2	8	N		-0.45		
OSU 6721	85	F	B	9	12	Y		-2.50		
UM 34931	82	F	B	6	10	N				0.37
WSU 625	86	F	B	14	5	Y				0.52
WSU 660	69	F	B	17	7	N				0.41
WSU 719	85	F	B	15	3	N	Right clavicle fracture, C6 vertebral transection, T1 anterior fracture			0.33

IV. DISCUSSION

In this study, a generic inflatable belt system was tested with PMHS. Despite the inflation path and the stitching method of the bag, both configurations successfully deployed at the desired timing without noticeable belt-chin interaction. Occupant kinematics and impact response were compared between small female and mid-sized male group and no distinguishable differences were found between these two groups. Shoulder belt loading of the small female group has less magnitude and shorter duration compared to the male group. It is possibly due to the less body mass of the small female subjects.

Sundararajan et al. [4] conducted similar sled tests with mid-size male and small female PMHS. Chest deflection was also measured in that study. During the post-test examination, it was suspected that some rib fractures were attributed to the mounting of the chest deflection transducer. As a result, chest deflection was not measured in the current study. The peak shoulder belt loads from both PMHS groups obtained from the current study were slightly higher than that reported by

Sundararajan et al [4] due to the different load limiter setting.

Injury outcomes showed a greater number of rib fractures in small female PMHS group. The average numbers of rib fractures in small female and mid-size male subjects were 15.5 and 8.5, respectively. This finding correlates with the results reported by Sundararajan et al. In that study, the average numbers of rib fractures in small female and mid-size male subjects were 12.7 and 3.7, respectively. However, with similar impact severities (40 kph delta V and 30 g peak acceleration), more rib fractures were observed in the current study. The cause of these differences is likely the bone condition, which is affected by both age and gender [10]. In the current study, six out of eight female PMHS have been identified with poor bone condition. The average numbers of rib fractures with normal bone condition and osteoporosis were 9.5 and 15.0, respectively. It is suggested that the higher number of rib fracture for small females is likely due to the poor bone conditions given the fact that shoulder belt loading on small females was lower and with less duration compared to males.

Sternum fracture was also observed in some tests. it happened on half of the male (2 out of 4) and female (4 out of 8) specimens. In addition, it seemed not directly dependent on the number of rib fracture or bone condition. We may have to use finite element modeling to study the sternum fracture mechanism under this loading condition as a future study.

The objective of this study is to evaluate and compare the performance of the inflatable belt system on small female and mid-sized male occupants. PMHS kinematics and impact response indicate the inflatable belt system can effectively restrain both mid-size male and small female occupants. However, injury outcomes suggested that small females are likely to have more rib fractures due to poor bone condition. Future studies are needed to discuss how to protect occupant with the poor bone condition more effectively (e.g. applying lower belt loading limit level with greater contact area).

V. SUMMARY AND CONCLUSIONS

In this study, frontal impact sled tests were conducted with mid-size male and small female PMHS with a generic inflatable belt system. Detailed analysis of PMHS kinematics, sensor data, and injury outcome was performed, from which the following were determined:

- Kinematics of both mid-size male and small female PMHS shows no noticeable belt-chin interaction during bag deployment.
- Sensor data of small female PMHS exhibit similar pattern and magnitudes compared to mid-size male, indicating the inflatable belt system effectively restrain both small female and mid-sized male occupants.
- Substantial rib fractures were observed on female PMHS, which is likely due to the poor bone conditions.

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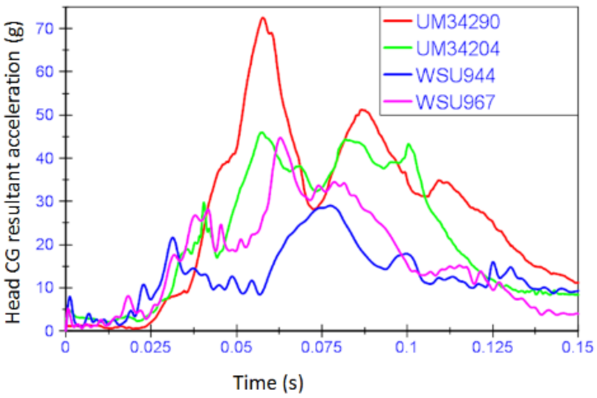
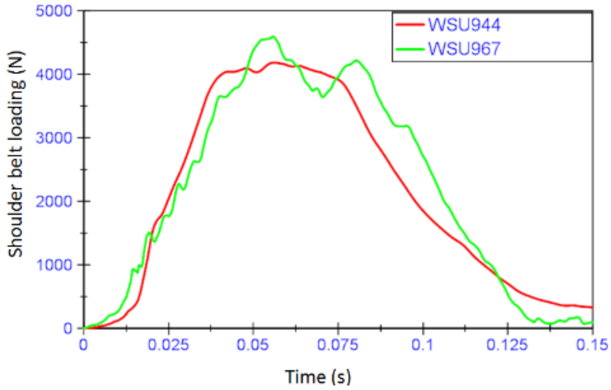
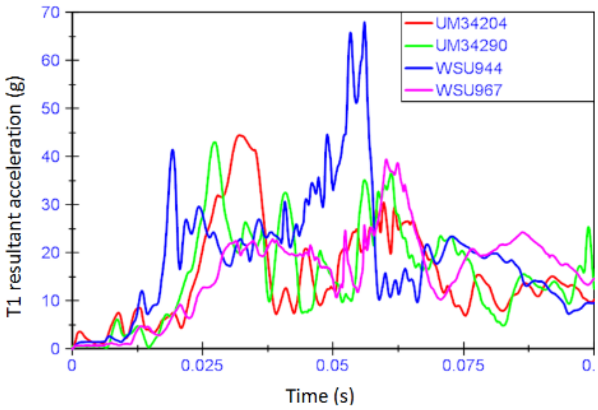
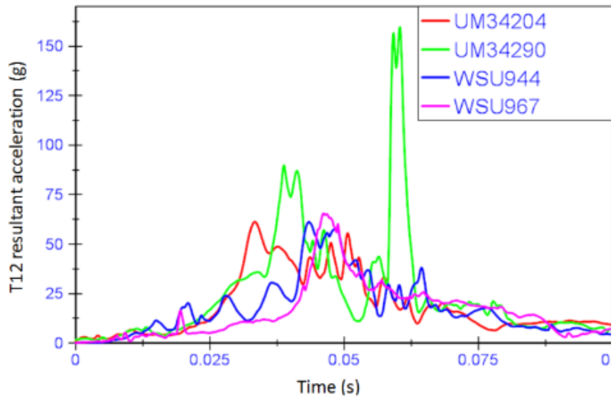
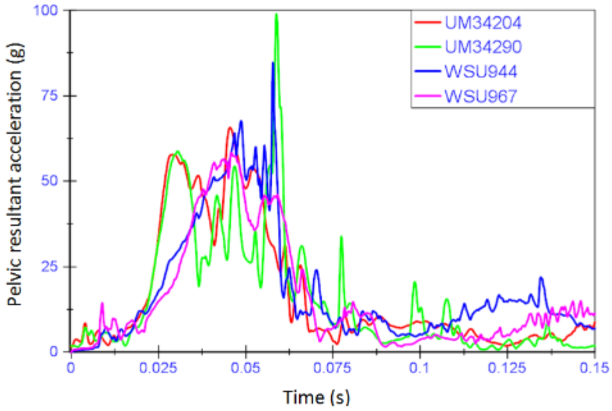
APPENDIX A - Mid-size male PMHS responses



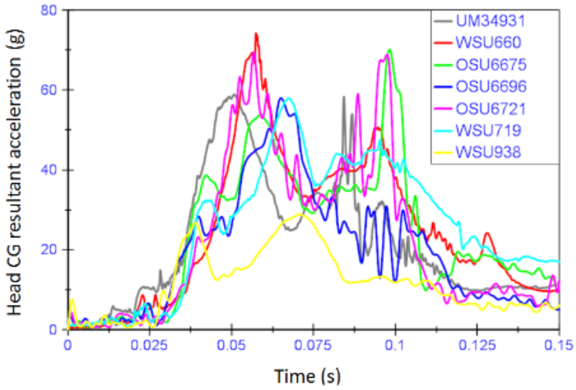


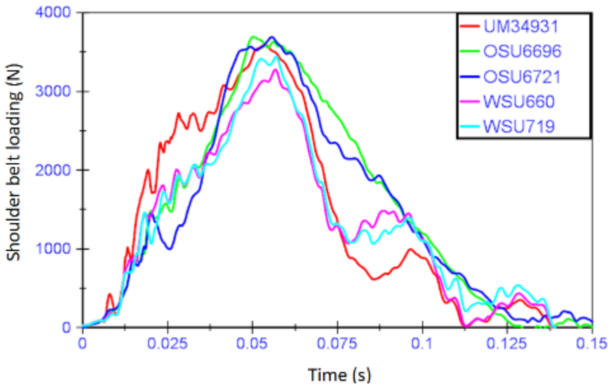


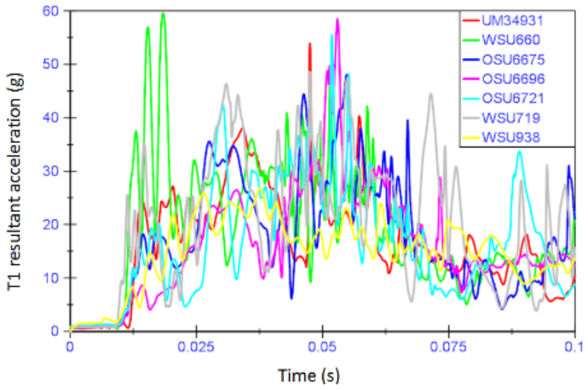


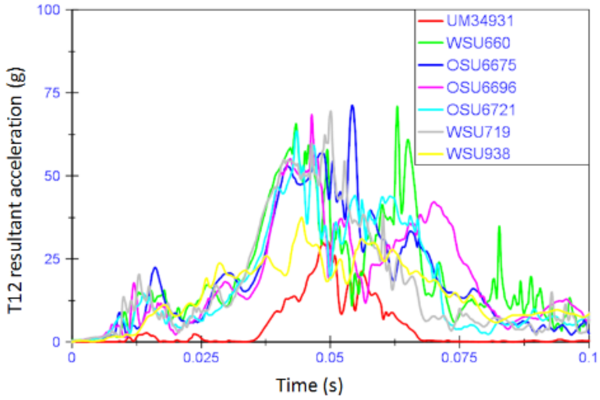


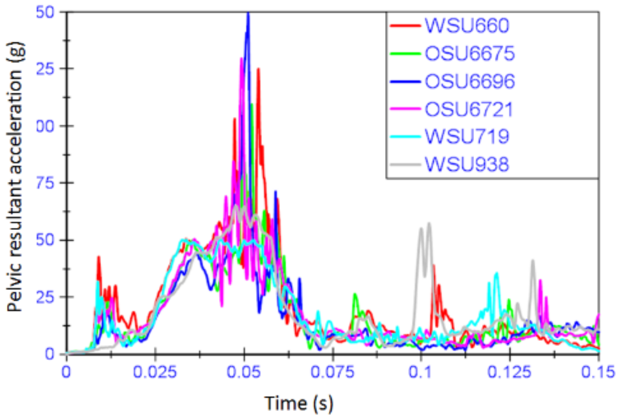
APPENDIX B – Small female PMHS responses



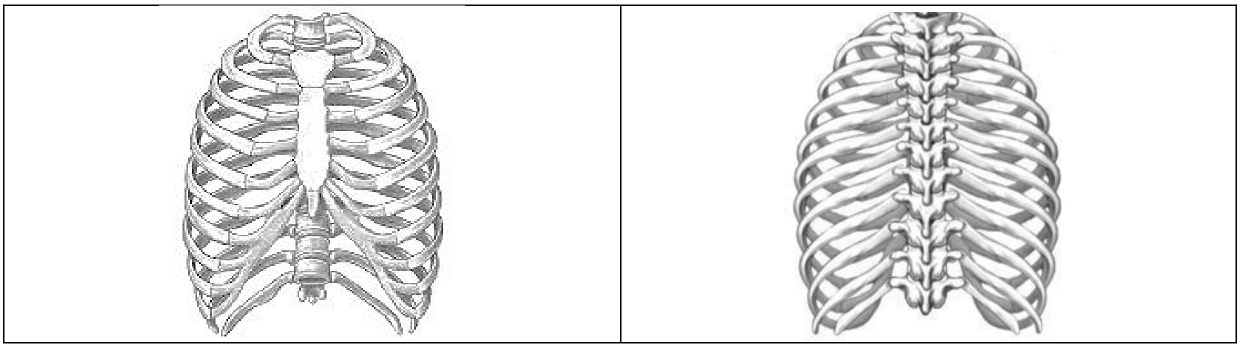




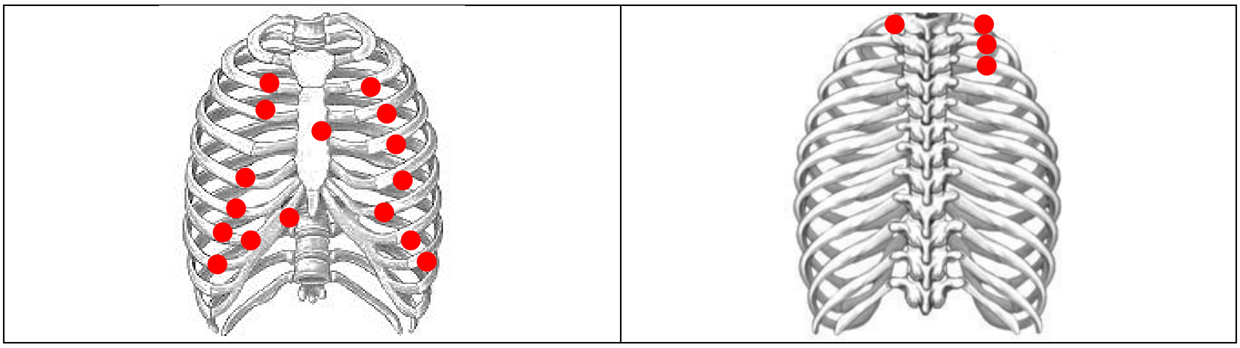




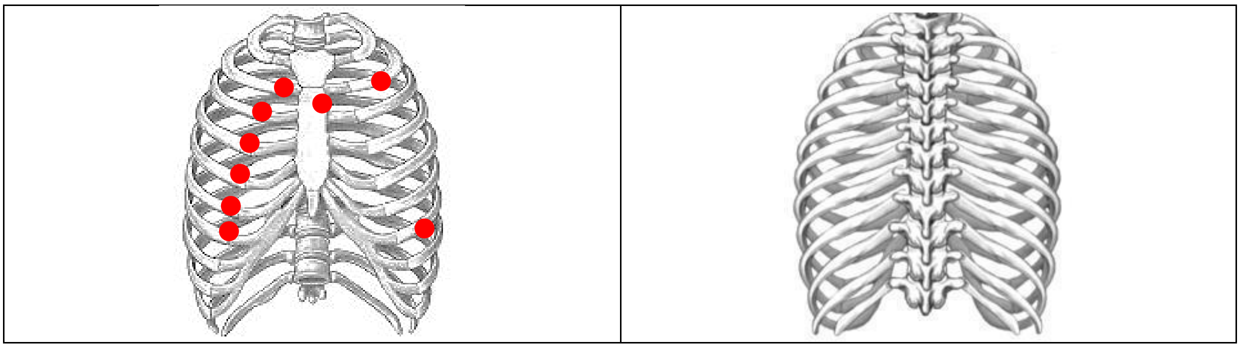
APPENDIX C - PMHS rib fractures



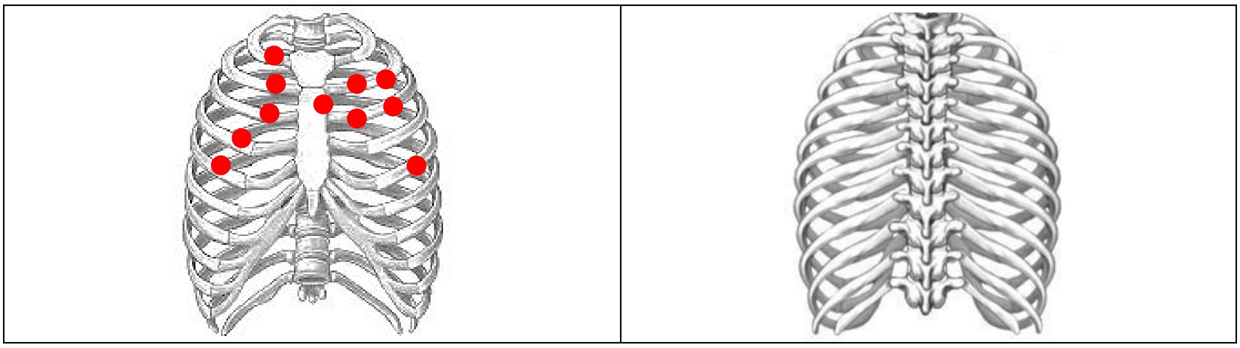
(A) Anterior and posterior views of the ribcage, illustrating fractures revealed upon autopsy of PMHS No. UM34204 (no fracture was found for this subject)



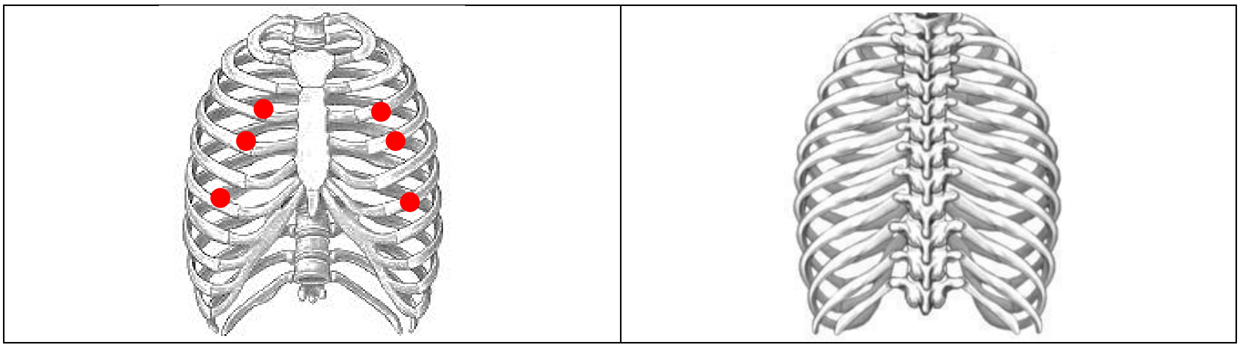
(B) Anterior and posterior views of the ribcage, illustrating fractures revealed upon autopsy of PMHS No. UM34290



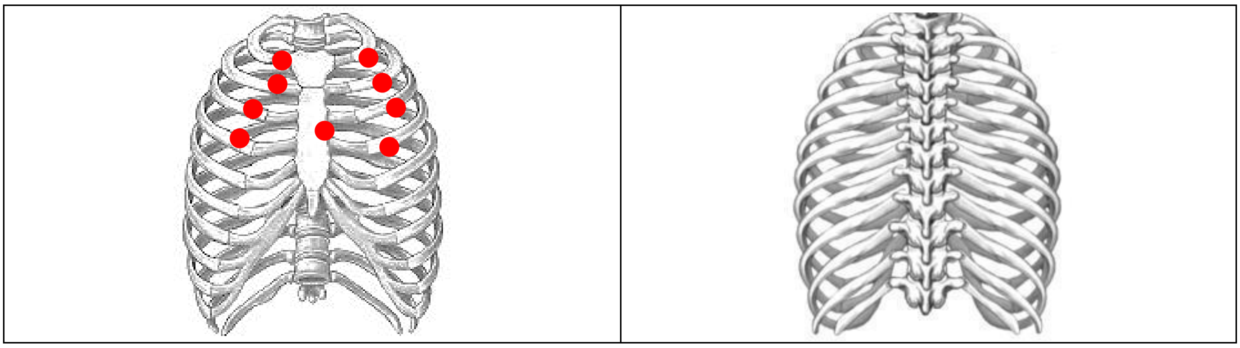
(C) Anterior and posterior views of the ribcage, illustrating fractures revealed upon autopsy of PMHS No. WSU 938



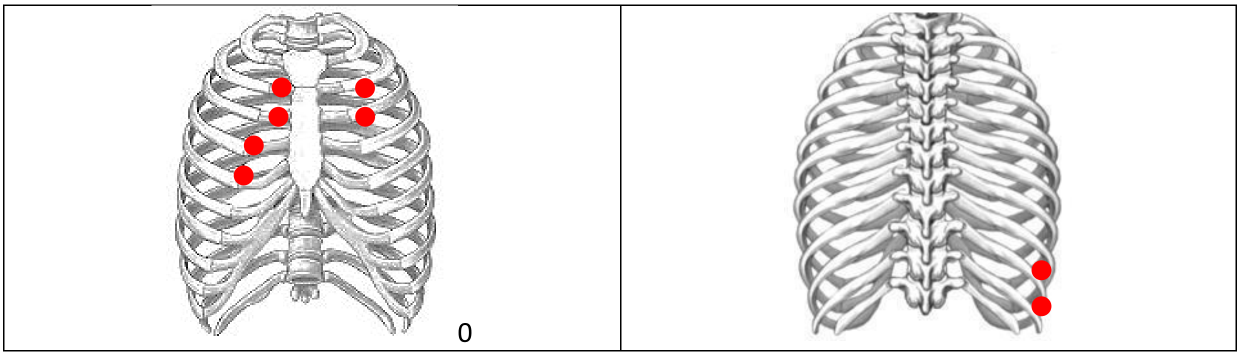
(D) Anterior and posterior views of the ribcage, illustrating fractures revealed upon autopsy of PMHS No. WSU 944



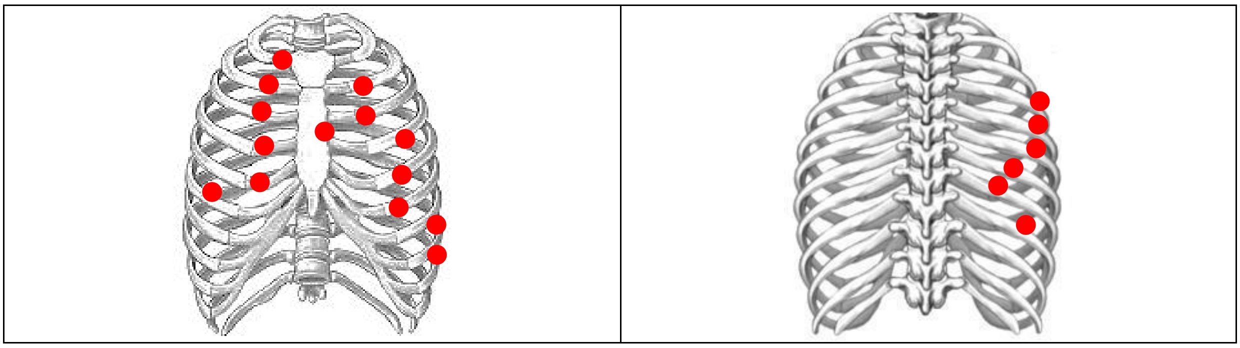
(E) Anterior and posterior views of the ribcage, illustrating fractures revealed upon autopsy of PMHS No. WSU 967



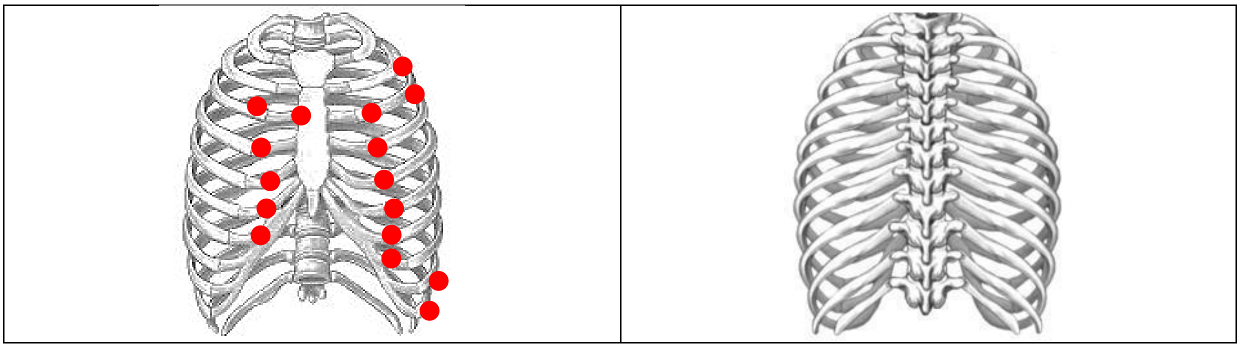
(F) Anterior and posterior views of the ribcage, illustrating fractures revealed upon autopsy of PMHS No. OSU 6675



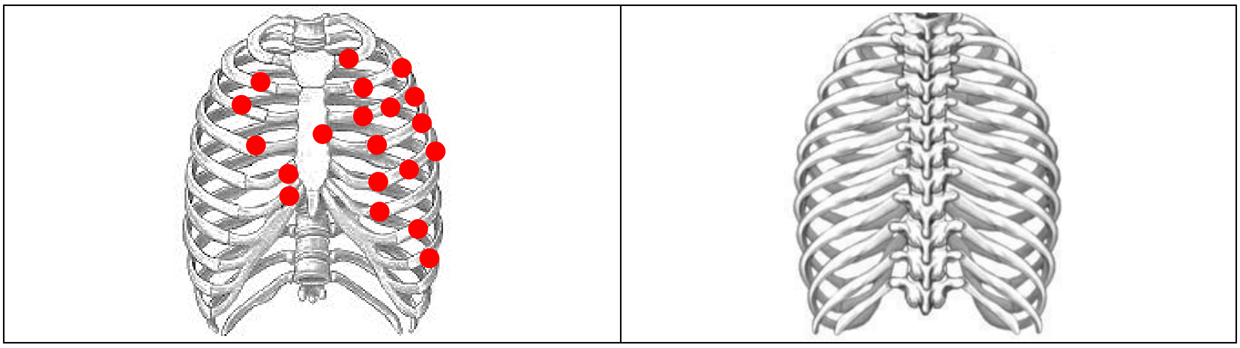
(G) Anterior and posterior views of the ribcage, illustrating fractures revealed upon autopsy of PMHS No. OSU 6696



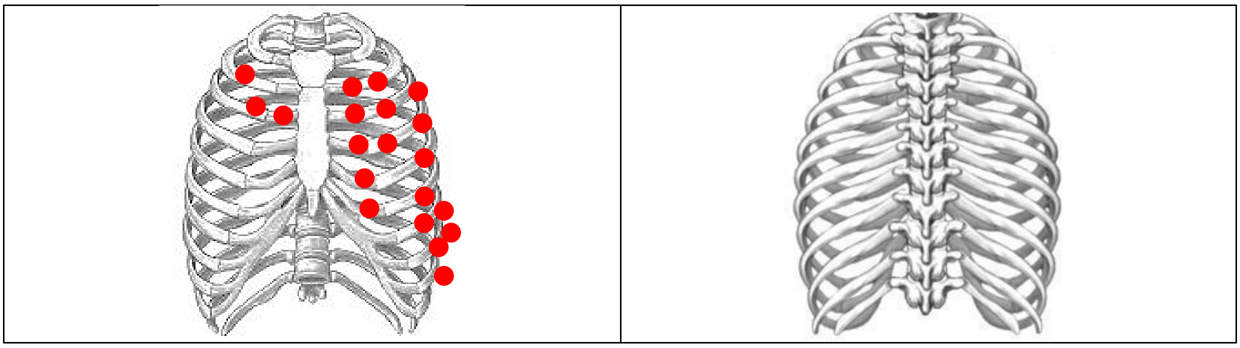
(H) Anterior and posterior views of the ribcage, illustrating fractures revealed upon autopsy of PMHS No. OSU 6721



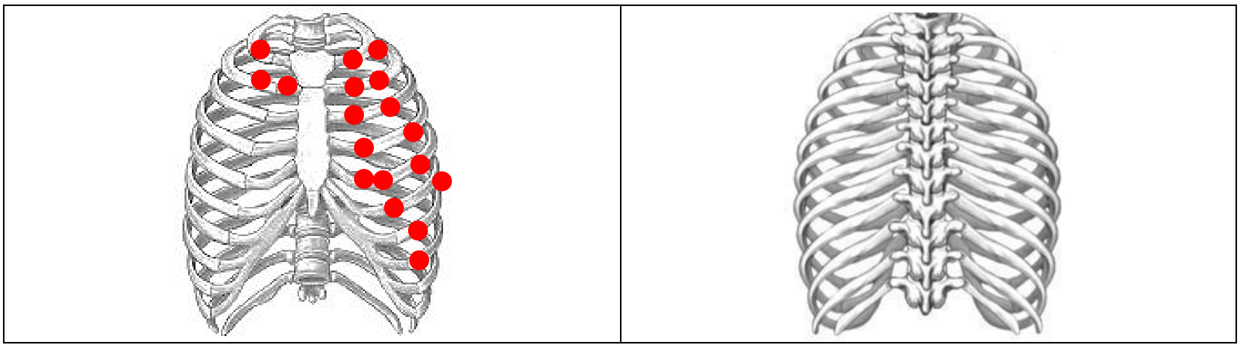
(I) Anterior and posterior views of the ribcage, illustrating fractures revealed upon autopsy of PMHS No. UM34931



(J) Anterior and posterior views of the ribcage, illustrating fractures revealed upon autopsy of PMHS No. WSU 625



(K) Anterior and posterior views of the ribcage, illustrating fractures revealed upon autopsy of PMHS No. WSU 660



(L) Anterior and posterior views of the ribcage, illustrating fractures revealed upon autopsy of PMHS No. WSU 719