The Effect of Rib Fracture Patterns in the Obese

Susumu Ejima, Sven A. Holcombe, Peng Zhang, Brian A. Derstine, Rebecca L. Goulson,
Carla Kohoyda-Inglis, Joel MacWilliams, Stewart C. Wang

Abstract In this study, analytic morphomics is applied to understand rib fractures in obese occupants in frontal and nearside crashes. Rib fracture patterns were examined in occupants involved in crashes from the International Center for Automotive Medicine database. Among these occupants, two BMI groups (nonobese and obese) with a maximum abbreviated injury scale in the chest region of $\geq$ 3 ($MAIS_{thx}$3+) were categorized and compared. Univariate analyses were conducted for the BMI groups to compare the rib fracture incidence ratio in each rib and occupant factors based on morphomics variables. In frontal crashes, rib fractures were mainly located under the path of shoulder belt. For the obese group, fracture patterns tended to be located on the lower ribs (#6-8). In the nearside crashes, rib fractures were located in the lateral and posterior regions. For the obese group, fracture patterns tended to be located more laterally rather than posteriorly. Morphomics related to rib angle, fat in the back, and subcutaneous fat are the major differences between the groups. The current results for rib orientation and fat distribution can highlight the importance of considering these morphomics characteristics when assessing chest injury and creating obese computer models.

Keywords analytic morphomics, automotive medicine, obese, frontal crashes, nearside crashes, rib fracture,

I. INTRODUCTION

The proportion of obese in the US population has been growing in the last two decades. The Centers for Disease Control announced that more than one-third (36.5%) of US adults are obese [1]. By 2030, approximately 42% of the population will be obese according to the estimation of demographic shifts in the US [2]. This shift in the population will likely increase the societal burden from Motor Vehicle Crashes (MVCs). Wang [3] remarks that obesity is highly associated with cardiovascular disease, hypertension, diabetes, and poor wound healing, and complicates post-injury treatment and rehabilitation. In addition, the increasing size of occupants increases their kinetic energy in crashes and may also degrade the effectiveness of occupant safety systems that have been tested and tuned for occupants of normal stature.

Several studies have examined the relationship between body habitus and injury rate and/or fatality based on the crash data. The consequence of obesity related to motor vehicle crashes is problematic [4-7]. These studies suggest that while the 50th percentile male is best protected in the current vehicle fleet, occupants whose bodies differ from that baseline are at greater risk for injury or death.

Obesity may also affect the distribution of body regions injured in MVCs. Boulanger et al. [8] reported that the obese were more likely to have pulmonary contusions and rib, pelvic and extremity fractures, and less likely to receive head trauma and liver injuries. Rupp et al. [9] found that increased BMI is associated with increased risks of lower-extremity, upper-extremity, and spine injuries in frontal crashes. Arabai et al. [10] and Wang et al. [11] also noted an increase in lower extremity injuries and fewer abdominal injuries for obese occupants when compared to their lean counterparts. Forman et al. [12] and Kent et al. [13] conducted laboratory tests that simulated frontal impact crashes with mid-sized and obese post-mortem human subjects (PMHS) to understand the potential injury mechanisms by studying the kinematics of the subjects. The authors documented that a reclined torso during belt loading in combination with large hip excursion may increase the risk of rib and pulmonary trauma. Shi et al. [14] developed whole-body human models with different obesity levels and predicted significantly higher risks of injuries to the thorax and lower extremity in frontal crashes based on a parametric analysis. These results led to the hypothesis that not all regions of the body

S. Ejima is a Research Associate Professor of the International Center for Automotive Medicine at the University of Michigan, USA (+1-734-763-1807 and sejima@umich.edu). SA. Holcombe is a Crash Research Engineer, P. Zhang is a Research Assistant Professor, BA. Derstine is a Data Scientist, RL. Goulson is a Research Assistant, J. MacWilliams is Crash Investigator, C. Kohoyda-Inglis is a Program Director and SC. Wang is Endowed Professor from the International Center for Automotive Medicine at the University of Michigan.

sustain severe injuries as a result of obesity and highlight the potential importance of body size and composition in influencing injury severity.

In previous work at ICAM, analytic morphomics was developed to objectively measure body geometry and composition data from computed tomography (CT) scans [15-17]. Holcombe et al. [18-20] used analytic morphomics to measure rib shape for all patients. That study showed that rib shape changes were associated with age, BMI, and gender. Ejima et al. [21] linked rib morphomic data with crash data to analyze rib fracture patterns in elderly occupants and found that rib shape change is important when predicting rib fracture. Based on these previous findings, rib geometry differences for obese occupants in frontal and nearside crashes are analyzed in this study. By using this data set with analyzed crash and medical data involving obese occupants, the characterization of rib fracture is compared in these patients. This methodology allows our analysis to estimate the features of obese rib fracture and provides robustness for targeting rib fracture in real-world crash cases.

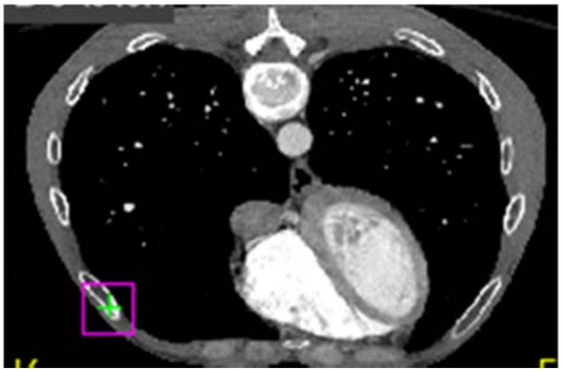
II. METHODS

Crash Injury Analysis

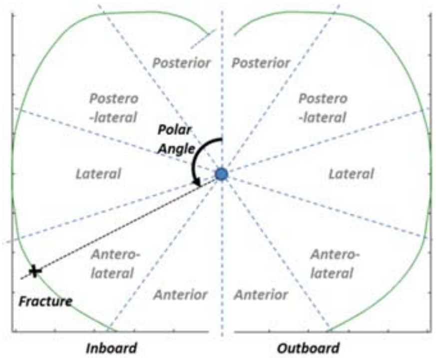
The crash data were obtained from the University of Michigan International Center for Automotive Medicine (ICAM) database for calendar years 1996-2016. The crash data are linked to the medical records of the case occupant. In addition, analytic morphomics is utilized to quantify occupant characteristics based on the medical imaging data to understand more about the injury. Inclusion criteria for the current study were based on the following vehicle and crash parameters: vehicle model year was 1990 or newer, the Collision Deformation Classification (CDC) of the impact was between 11 to 1 o'clock for the frontal and either 2-4 o'clock (passenger side) and 8-10 o'clock (driver side) for nearside. In cases with multiple impacts, only the primary impact was considered. Vehicles that sustained a non-horizontal event such as a rollover were excluded. The occupant and injury parameters were based on the following criteria: occupant was older than 15 years and an Abbreviated Injury Scale [22] (AIS) severity of 3+ injury involving rib fracture (AIS code prefix 45****), and an available thoracic CT scan. Occupants in frontal crashes were seated with 3-point belt in the front outboard seating positions. For the side impact crashes, only the nearside crash occupants seated in the vehicle with and without 3-point belt were included. The total number of case occupants fitting these inclusion criteria was 92 for frontal crash and 61 for nearside crashes. Occupants were categorized by BMI in either the under 30 (nonobese) group or 30 and over (obese) group. In this study, the Maximum Abbreviated Injury Scale (MAIS) was assessed separately for each occupant with thoracic injuries (MAIS$_{thx}$).

Rib fracture pattern

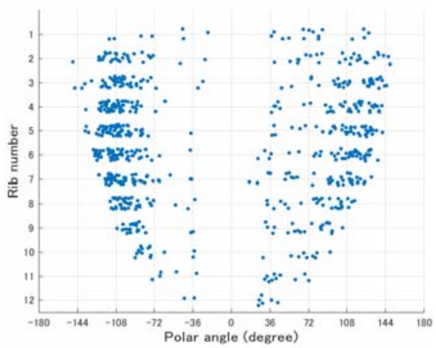
The location of rib fracture taken from medical imaging and in combination with morphomic variables is ideal to determine fracture patterns in the obese population. The 3-dimensional location of rib fractures present in CT scans from the ICAM population of car crash occupants is shown in Figure 1(a). Using this system, the fracture location is recoded as a point in the rib local coordinate system. It also records a polar angle relative to the origin, halfway between the spine and the sternum along the rib, shown in Figure 1(b). With this polar angle, the fracture locations are categorized into five segments (A: Anterior, AL: Antero-Lateral, L: Lateral, PL: Postero-Lateral, and P: Posterior) [23]. For the current study, the polar angle of each fracture point was utilized for quantifying locations of rib fractures, shown in Figure 1(c). Each segment has 36 degrees in the mid-sagittal plane. The location of rib fractures for the passenger side was mirrored to the opposite side, in order to combine driver and passenger data. For the purpose of comparison, rib fracture heat maps were constructed based on rib number and five segments along the rib (A, AL, L, PL, and P) on the inboard and outboard side of the thorax, shown in Figure 1(d). Each area shows the rib fracture incidence rate determined by dividing the number of rib fracturess by the number of occupants.



(a) Rib fracture in CT scan



(b) 3-dimensional location of rib fractures with ribcage coordinate system [23]



(c) Polar angle to identify the rib fracture location in five area by using published method

Inboard						Outboard				
P	PL	L	AL	A	Rib No.	A	AL	L	PL	P
0.0	0.0	0.0	0.0	0.0	1	0.0	0.0	0.1	0.1	0.0
0.0	0.0	0.2	0.1	0.0	2	0.0	0.2	0.1	0.1	0.0
0.0	0.0	0.3	0.2	0.0	3	0.0	0.2	0.1	0.0	0.0
0.0	0.0	0.2	0.3	0.0	4	0.0	0.2	0.1	0.1	0.0
0.0	0.0	0.3	0.3	0.0	5	0.0	0.2	0.1	0.1	0.0
0.0	0.0	0.3	0.3	0.0	6	0.0	0.3	0.1	0.0	0.0
0.0	0.1	0.3	0.2	0.0	7	0.0	0.1	0.1	0.1	0.0
0.0	0.0	0.3	0.1	0.0	8	0.0	0.0	0.2	0.1	0.0
0.0	0.0	0.2	0.0	0.0	9	0.0	0.0	0.1	0.1	0.0
0.0	0.0	0.1	0.0	0.0	10	0.0	0.0	0.0	0.0	0.0
0.0	0.0	0.0	0.0	0.0	11	0.0	0.0	0.0	0.1	0.0
0.0	0.0	0.0	0.0	0.0	12	0.0	0.0	0.0	0.0	0.0

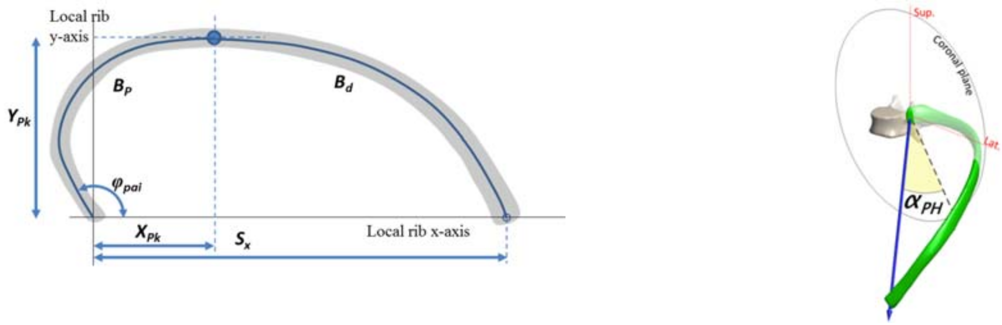
(d) Rib fracture heat map based on rib number and circumferential location categorized into five segments.

Fig. 1. Rib fracture heat map based on crash cases

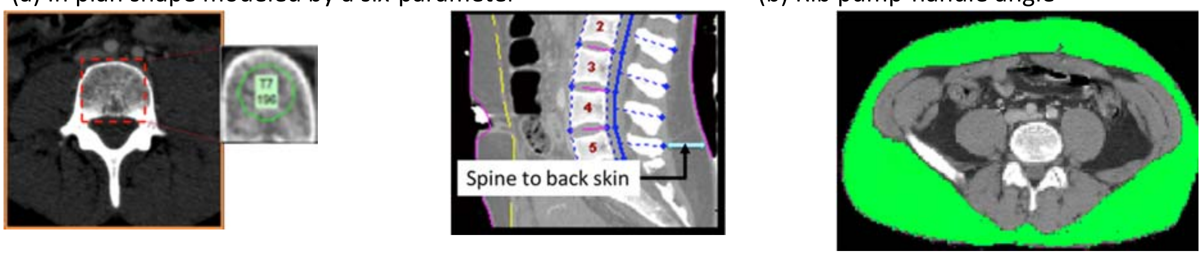
Analytic morphomics

Analytic morphomics processing was performed according to the method previously described [15-17]. The University of Michigan Review Board approved the use of the standard CT scans available for each occupant for this study (HUM00043599 and HUM00041441). CTs were obtained from the University of Michigan radiology archive. By using semi-automated processing of CT scans, analytic morphomic measures detailed geometry and material characteristic for tissue and bone. The morphomic variables used in this study were selected based on the potential importance of body size and composition in influencing rib fracture during the impact. In addition to the orientation of each rib with respect to a fixed body coordinate system [18], the rib in-plane shape was represented using the six-parameter shape model [19-20]. Measuring a fractured rib could confound the normal, appropriate, value. To avoid this variation, the nonfractured rib is applied for a given rib of an occupant. Measurement items are illustrated in Figure 2.

- Rib size S_x : Linear distance between rib ends
- Spiral peak location X_{Pk}, Y_{Pk} : Rib's spiral peak location along the local rib X-axis and Y-axis normalized by S_x is given for characterizing "aspect ratio" and "skewness" of rib.
- Prox. end inner angle φ_{pia} : Inner angle of the origin of the rib and the local rib x-axis
- Spiral curvature B_p , B_d : "Curvature" at the proximal and distal end of the rib specified by logarithmic spiral.
- Pump-handle angle α_{PH} : Orientation of rib specified as the angle between the rib local x-axis and coronal plane.
- Trabecular bone density BMD: Trabecular bone density, which was measured with average pixel intensity within a circular core sample at the mid-level of each vertebral.
- Spine-to-back skin: Distance between the posterior tip of the spinous process to the back skin, which represent the fat tissue in the back.
- Subcutaneous fat area: The cross-sectional area inside between skin and fascia meeting fat density thresholds (-205 to -51 Hounsfield units: HU) [17].



(a) In plan shape modeled by a six-parameter (b) Rib pump-handle angle



(c) Trabecular bone density (d) Spine-to-back skin (e) Subcutaneous fat area

Fig. 2. Morphomic measurement obtained from CT scans [15-20]

Statistics with crash and analytic morphomics data

Utilizing the serious injury data ($MAIS_{thx}$3+) and rib fracture pattern due to frontal and nearside crashes in the ICAM database, 2-sample *t* tests were conducted to compare the group means for each crash condition. There are 92 and 61 cases available with $MAIS_{thx}$3+ occupants involved in frontal and nearside crashes respectively. Among which 71 are frontal and 46 are nearside cases with complete processed rib seven, trabecular bone, skin-to-back, and subcutaneous fat area at T7. Group means of these morphomic variables were also compared between the nonobese and obese groups. The data was separated into two groups: nonobese and obese group and analysis was conducted using MATLAB2015a statistical toolbox.

III. RESULTS

Chest injury rates and patterns were first examined with occupants involved in frontal and nearside crashes from the ICAM database. Among these occupants, two BMI groups (nonobese and obese) with a MAIS in the chest region of $\geq$3 ($MAIS_{thx}$ 3+) were categorized. There were 92 frontal and 61 nearside occupants who met the inclusion criteria of this study. Table I and II shows the severity, demographics, and number of rib fractures used in the current analysis. The total number of fractures was 700 for frontal and 559 for nearside occupants. By using these data, obese occupants were compared with nonobese occupants who sustained $MAIS_{thx}$3+ injuries.

Among the 92 occupants in frontal crashes, there were 57 nonobese occupants with 409 rib fractures, which was a mean of 7.2 fractures per occupant, and 35 obese occupants with 291 rib fractures, which was a mean of 8.3 fractures per occupant. Figure 3 shows rib fracture patterns along the rib, categorized into five segments (A, AL, L, PL, and P). Figure 3(a) is the nonobese group and Figure 3(b) is the obese group. The left side indicates inboard (driver's right side) and right side indicates the outboard (driver's left side). The rib fractures of belted occupants were mainly located under the path of the shoulder belt and locations of rib fracture are concentrated inboard in both groups. For the obese group, fracture patterns tended to be located on the lower ribs (#6-8) in the anterior-lateral region compared to the nonbese group.

Among 61 occupants in nearside crashes, there were 46 nonobese occupants with 447 rib fractures, which was a mean of 9.7 fractures per occupant, and 15 obese occupants with 112 rib fractures, which was a mean of 7.5 fractures per occupant. Figure 4 shows rib fracture patterns in the same manner as frontal crashes. The rib fractures of nearside occupants were mainly located on the outboard side and distributed over a wide area. For the obese group, fractures tended to be located more laterally, rather than posteriorly, in the lower outboard ribs (#6-8).

TABLE I

SUMMARY OF STATISTIC BETWEEN THE GROUPS OF NONOBESE AND OBESE OCCUPANTS IN FRONTAL CRASHES ($MAIS_{THX}$ 3+)

Variables	Nonobese (n=57)		Obese (n=35)		*P* value
	Mean or count	Std error or percent	Mean or count	Std error or percent	
Severity	36.23	15.89	33.88	13.29	0.527
Age	58.44	17.57	55.76	20.07	0.483
Height (cm)	170.84	9.74	172.85	9.95	0.358
Weight (kg)	73.33	13.68	109.29	27.88	0.000 **
BMI	24.95	2.98	36.25	6.82	0.000 **
Male	28	49%	20	57%	0.551
Num. Rib Fx.	7.18	5.83	8.38	4.11	0.167

* p<0.05 ** p<0.01

TABLE II

SUMMARY OF STATISTIC BETWEEN THE GROUPS OF NONOBESE AND OBSE OCCUPANTS IN NEARSIDE CRASHES ($MAIS_{THX}$ 3+)

Variables	Nonobese (n=46)		Obese (n=15)		*P* value
	Mean or count	Std error or percent	Mean or count	Std error or percent	
Severity	27.41	10.82	28.53	10.91	0.805
Age	38.50	18.87	46.40	18.98	0.195
Height (cm)	173.41	10.65	169.93	12.12	0.352
Weight (kg)	72.39	12.13	99.60	16.95	0.000 **
BMI	24.04	3.17	34.36	3.86	0.000 **
Male	23	50%	10	67%	0.194
Num. Rib Fx.	9.72	9.15	7.47	6.84	0.230

* p<0.05 ** p<0.01

Inboard						Outboard				
P	PL	L	AL	A	Rib No.	A	AL	L	PL	P
0.0	0.0	0.0	0.0	0.0	1	0.0	0.1	0.1	0.1	0.0
0.0	0.0	0.2	0.1	0.0	2	0.0	0.2	0.1	0.1	0.0
0.0	0.0	0.2	0.2	0.0	3	0.0	0.3	0.1	0.0	0.0
0.0	0.0	0.3	0.4	0.0	4	0.0	0.2	0.1	0.1	0.0
0.0	0.0	0.3	0.3	0.0	5	0.0	0.2	0.1	0.1	0.0
0.0	0.0	0.3	0.2	0.0	6	0.0	0.2	0.1	0.0	0.1
0.0	0.0	0.2	0.2	0.0	7	0.0	0.1	0.1	0.1	0.0
0.0	0.0	0.3	0.1	0.0	8	0.0	0.0	0.1	0.1	0.0
0.0	0.0	0.2	0.0	0.0	9	0.0	0.0	0.1	0.1	0.0
0.0	0.0	0.1	0.0	0.0	10	0.0	0.0	0.0	0.0	0.0
0.0	0.1	0.0	0.0	0.0	11	0.0	0.0	0.0	0.1	0.0
0.0	0.0	0.0	0.0	0.0	12	0.0	0.0	0.0	0.0	0.0

Nonobese (n=57)

Inboard						Outboard				
P	PL	L	AL	A	Rib No.	A	AL	L	PL	P
0.0	0.1	0.0	0.0	0.0	1	0.0	0.0	0.0	0.1	0.0
0.0	0.0	0.2	0.1	0.0	2	0.0	0.1	0.1	0.1	0.0
0.1	0.0	0.3	0.1	0.0	3	0.0	0.1	0.2	0.0	0.0
0.0	0.1	0.2	0.3	0.0	4	0.0	0.3	0.1	0.1	0.0
0.0	0.0	0.3	0.4	0.0	5	0.0	0.4	0.1	0.1	0.0
0.0	0.0	0.3	0.4	0.0	6	0.0	0.4	0.2	0.0	0.0
0.0	0.1	0.4	0.3	0.0	7	0.0	0.1	0.2	0.1	0.0
0.0	0.1	0.3	0.1	0.0	8	0.0	0.1	0.2	0.1	0.0
0.0	0.0	0.2	0.0	0.0	9	0.0	0.0	0.1	0.1	0.0
0.0	0.0	0.1	0.0	0.0	10	0.0	0.0	0.1	0.1	0.0
0.0	0.0	0.0	0.0	0.0	11	0.0	0.0	0.0	0.0	0.1
0.0	0.0	0.0	0.0	0.0	12	0.0	0.0	0.0	0.0	0.1

Obese (n=35)

Fig .3 The rib fracture pattern for belted occupants in frontal crashes

Inboard						Outboard				
P	PL	L	AL	A	Rib No.	A	AL	L	PL	P
0.0	0.2	0.1	0.0	0.0	1	0.0	0.1	0.1	0.2	0.0
0.0	0.1	0.1	0.1	0.0	2	0.0	0.2	0.2	0.2	0.1
0.0	0.1	0.1	0.1	0.0	3	0.0	0.2	0.2	0.2	0.1
0.0	0.1	0.1	0.1	0.0	4	0.0	0.2	0.2	0.4	0.1
0.0	0.0	0.1	0.1	0.0	5	0.0	0.2	0.4	0.3	0.2
0.0	0.1	0.1	0.1	0.0	6	0.0	0.1	0.4	0.2	0.2
0.1	0.0	0.1	0.0	0.0	7	0.0	0.1	0.3	0.2	0.2
0.0	0.0	0.1	0.0	0.0	8	0.0	0.0	0.3	0.2	0.2
0.0	0.0	0.1	0.0	0.0	9	0.0	0.0	0.2	0.2	0.2
0.0	0.1	0.0	0.0	0.0	10	0.0	0.0	0.0	0.2	0.2
0.0	0.0	0.0	0.0	0.0	11	0.0	0.0	0.0	0.1	0.2
0.0	0.0	0.0	0.0	0.0	12	0.0	0.0	0.0	0.1	0.1

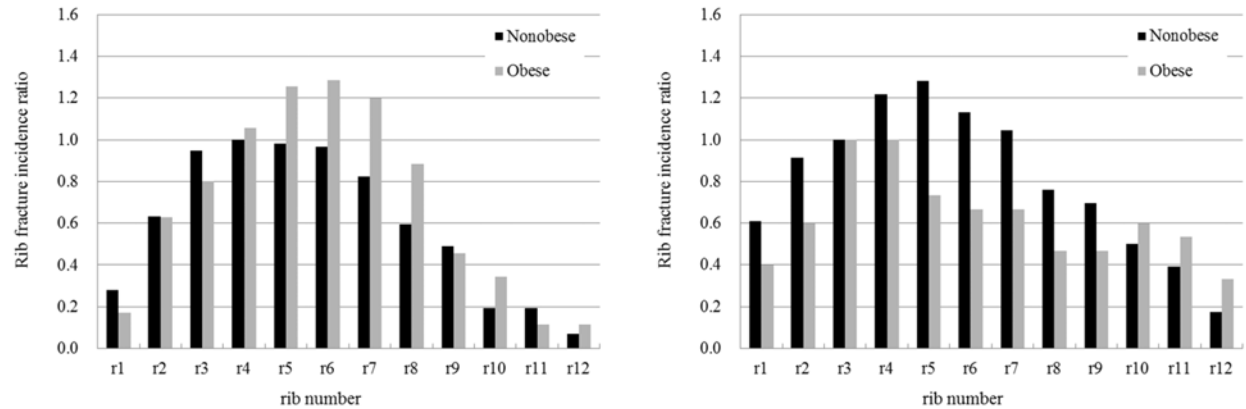
Nonobese (n=46)

Inboard						Outboard				
P	PL	L	AL	A	Rib No.	A	AL	L	PL	P
0.0	0.1	0.1	0.0	0.0	1	0.0	0.0	0.1	0.2	0.0
0.1	0.0	0.0	0.0	0.0	2	0.0	0.1	0.1	0.3	0.1
0.1	0.0	0.1	0.1	0.0	3	0.0	0.1	0.3	0.2	0.1
0.1	0.0	0.1	0.1	0.0	4	0.0	0.1	0.3	0.2	0.1
0.1	0.0	0.1	0.1	0.0	5	0.0	0.1	0.3	0.0	0.1
0.0	0.1	0.1	0.1	0.0	6	0.0	0.1	0.3	0.1	0.0
0.0	0.1	0.1	0.1	0.0	7	0.0	0.1	0.3	0.0	0.0
0.0	0.1	0.1	0.0	0.0	8	0.0	0.1	0.1	0.1	0.0
0.1	0.0	0.0	0.0	0.0	9	0.0	0.1	0.1	0.2	0.1
0.0	0.1	0.0	0.0	0.0	10	0.0	0.0	0.1	0.3	0.1
0.0	0.1	0.0	0.0	0.0	11	0.0	0.0	0.1	0.2	0.2
0.0	0.1	0.0	0.0	0.0	12	0.0	0.0	0.0	0.1	0.1

Obese (n=15)

Fig. 4 The rib fracture pattern for occupants in nearside crashes

Figure 5 shows the distribution of where these fractures occurred with respect to subject rib number between the nonobese and obese groups. The X-axis shows the rib number and the Y-axis shows the rib fracture incidence rate determined by dividing the number of rib fractures s at each rib by the number of occupants. Compared to the nonobese occupants, higher rib fracture incidence in the obese is distributed in ribs #5-8, and these occupants had significantly more rib fractures s than the nonobese at rib 7 ($p< 0.05$) in frontal crashes. For the nearside impact, there is no statistically significant difference in each rib between nonobese and obese occupants, however, there is a higher incidence ratio in ribs #4-9 for nonobese occupants.



(a) Frontal (b) Nearside

Fig. 5. Rib fracture incidence ratio between nonobese and obese groups

According to the rib fracture heat map and rib fracture incidence ratio using $MAIS_{thx}$ 3+ criteria, the obese group had more fractures at lower ribs and shifted more toward the lower rib region in frontal crashes. On the other hand, the obese group had fewer fractures in nearside crashes and these tended to be located more laterally rather than posteriorly. From this result, rib 7, which indicates the difference in the obese group, was chosen as a representative value for comparing morphomics variables. For the 71 occupants in frontal and 46 occupants in nearside crash with available rib morphomics variables, a univariate analysis was applied to quantify the difference of rib parameter, bone density, and fat distribution by linking the morphomic database. Table III and IV show the result of the univariate analysis for the selected morphomics variables in each crash condition respectively. The table includes mean, standard errors, and P values obtained from two-sample t tests for continuous variables. It also provides the counts and the percentage for categorical variables (Gender) of each group, the P value from the Fisher's exact tests. Various features were compared between the groups. While the obese group had a similar bone density compared to the nonobese group, there are no significant differences in in-plane geometrical variables in either group, except proximal end inner angle: φ_{pia}. Among the various morphomics variables, rib pump-handle angle α_{PH}, Spine-to-back skin (T7), and Subcutaneous fat area (T7) were significantly different between the two groups in frontal crashes. In the nearside crashes, there are no significant differences in in-plane geometrical variables in either group. Rib pump-handle angle α_{PH}, Spine-to-back skin (T7), and Subcutaneous fat area (T7) were the most significant among the morphomics variables.

TABLE III

COMPARISON OF MORPHOMICS VARIABLES BETWEEN NONOBESE AND OBESE OCCUPANTS IN FRONTAL CRASHES ($MAIS_{THX}$ 3+)

Morphomics variables	Nonobese (n=46)		Obese (n=25)		P value	
	Mean or count	Std error or percent	Mean or count	Std error or percent		
S_x_r7 (mm)	210.21	18.62	213.70	19.51	0.529	
X_{Pk}_r7 (mm/S_x)	0.28	0.04	0.29	0.05	0.219	
Y_{Pk}_r7 (mm/Sx)	0.37	0.04	0.38	0.05	0.453	
ϕ_{pia}_r7 (deg)	112.61	11.83	106.52	9.47	0.025	*
B_p _r7	1.50	0.75	1.94	0.99	0.053	
B_d_r7	3.90	0.48	3.85	0.50	0.670	
α_{PH}_r7 (deg)	51.63	7.66	63.97	6.65	0.000	**
BMD_T7 (HU)	188.07	56.19	194.95	52.46	0.605	
Subcutanous fat area_T7 (mm^2)	11844.25	7458.20	21186.05	6928.20	0.000	**
Spin-to-back skin_T7 (mm)	17.83	6.39	36.77	16.99	0.000	**

* p<0.05 ** p<0.01

TABLE IV

COMPARISON OF MORPHOMICS VARIABLES BETWEEN NONOBESE AND OBSE OCCUPANTS IN NEARSIDE CRASHES ($MAIS_{THX}$ 3+)

Morphomics variables	Nonobese (n=34)		Obese (n=12)		P value	
	Mean or count	Std error or percent	Mean or count	Std error or percent		
S_x_r7 (mm)	210.30	16.69	205.35	16.67	0.388	
X_{Pk}_r7 (mm/S_x)	0.29	0.04	0.29	0.03	0.916	
Y_{Pk}_r7 (mm/Sx)	0.39	0.04	0.41	0.04	0.096	
ϕ_{pia}_r7 (deg)	110.64	11.03	110.23	10.78	0.911	
B_p _r7	1.41	0.58	1.66	0.46	0.150	
B_d_r7	3.69	0.47	3.57	0.29	0.318	
α_{PH}_r7 (deg)	47.90	7.15	57.65	7.71	0.001	**
BMD_T7 (HU)	222.09	54.94	225.63	46.37	0.830	
Subcutanous fat area (mm^2)	8721.12	6466.21	23735.74	11914.57	0.001	**
Spin-to-back skin_T7 (mm)	16.92	6.82	30.87	10.16	0.001	**

* p<0.05 ** p<0.01

IV. Discussion

Using integrated crash and medical data that includes analytic morphomics, the variables involved in crashes and causation of rib fracture in the obese group are validated by using real-world crash cases. The ICAM database captures the location of rib fractures with much more detail and precision than previously available. Utilizing this system to analyze the rib cages of ICAM study subjects who have sustained chest wall injures shows clear variation in the pattern of rib fractures observed in nonobese versus obese occupants. The pattern of rib fracture based on the location of the fracture instead of counting the number of fractured ribs can contribute to understand injury mechanisms during crashes.

In the frontal crashes, there were 92 occupants with 700 rib fractures, which was a mean of 7.6 fractures per occupant. This number is close to a prior study, [23] which had a mean of 6.5 (±3.4) fractures per occupant. The rib fractures of belted occupants were mainly located under the path of the shoulder belt and locations of rib fracture are concentrated inboard in both groups. This result indicates that the seat belt is the main involved physical component (IPC) of $MAIS_{thx}$ 3+ occupants and also shows a similar trend along with rib fracture patterns in various restraint statuses, when compared to the CIREN database [23].

According to the univariate analysis with $MAIS_{thx}$ 3+ and rib fracture incidence ratio, obese occupants sustained more rib fractures s at lower crash severities compared to nonobese occupants in frontal crashes. This is consistent with a prior study that found an increase in the number of rib fractures with occupant BMI [8]. Although obese occupants having a nonsignificantly higher mean rib fractures than the nonobese occupants considering overall ribs ($p=0.167$), the lower rib (#7) shows significantly higher rib fracture incidence ratio ($p<0.05$) individually, compared with each rib level. The distribution of rib fracture incidence ratio at the lower ribs of obese occupants is the major difference compare to the nonobese occupants. This result demonstrates the current restraint systems are challenged in trying to arrest forward motion of obese occupants with larger mass around the chest region.

The BMI related changes increase the rib fracture incidence ratio due to the geometry or material changes along the ribs. According to the study of analytic morphomics with ribs [21], rib shape change has a potential to affect fracture location and loading path from seatbelts in frontal crashes. For this reason, the statistical analysis is applied to clarify the effect of rib shape by using morphomics variables linked to the crash case. According to the univariate analysis from two BMI groups, rib angle (α_{PH}), fat in the back (spine-to-back skin), and subcutaneous fat area (T7) were among the most significant morphomics variables in frontal impact. While most of the rib in-plane shape and bone density were not significantly different. Rib angle could change the boundary conditions with respect to frontal load with a belt as well as change the rib fracture location as described in a prior study [24]. These results suggest the rib angle is as important as boundary conditions when discussing rib fracture.

In the current study, obese occupants' rib fractures in frontal crashes tend to occur in lower ribs (#6-8) while nonobese occupants' fractures occur in higher ribs (#4-6). This phenomenon of lower rib fracture of the obese is supported by prior studies by Kent et al. [13]. The authors indicated that the obese subjects increased hip excursion and decreased torso pitch during the frontal impact. In addition to the large hip excursion, the primary difference was the reclined torso attitude during belt loading in the obese subject, which may subsequently show an increase in risk of lower rib fracture. This crash mechanism helps to predict the possibility of lower rib fracture due to greater interaction between compliant and vulnerable lower thorax and shoulder belt.

In nearside crashes, although the sample number is limited, obese occupant sustained less rib fracture incidence ratio at ribs #5-9 and had a higher mean crash severity compared to nonobese occupants. In addition, obese occupants' rib fractures in nearside crashes tended to be located more laterally rather than posteriorly in the outboard ribs #5-8 compared to nonobese occupants. According to the univariate analysis from the two BMI groups, rib angle (α_{PH}), fat in the back (spine-to-back skin), and subcutaneous fat area were among the most significant morphomics variables in frontal crashes.

In a prior study [11], subcutaneous fat thickness, which has strong correlation with fat in the back (spine-to-back skin), is important to determine injury severity and this fat distribution of the obese may contribute to reduce thorax injury "cushion effect" during the impact. Therefore, the role of fat in the back potentially has a protective effect for the obese occupant. On the other hand, increased fat mass increases the occupant's kinetic energy as well as load forces against the thorax in nearside crashes. Therefore, further study in this area with computer models would be beneficial. Fat distribution change appears to be an important factor when we consider rib fractures in real-world crashes. These results suggest utilizing the finite element model to understand the effect of fat distribution around the ribcage region. The next step of this study with finite element models clarifies these effects when compared to other properties.

Limitation

The ICAM database involves vehicle crashes where the occupants have been treated at University of Michigan, a Level-1 trauma center and is therefore the cohort used in this study is not representative of national sample or occupant exposure. Gender difference is not discussed due to the limited sample size. However, female body composition differs from that of males and these appear to be gender related variations with regard to the protective effect of fat. Rib angle and fat in back which tends to change the rib fracture pattern is obviously a BMI-related shape change, but also appears to be related to gender.

V. CONCLUSIONS

This study used detailed injury and crash data in conjunction with medical imaging from the ICAM and morphomics databases to evaluate the effect of rib fracture pattern in frontal and nearside crashes. Results, confirmed with real-world crash cases, demonstrated that BMI was associated with rib fracture incidence ratio and obese occupants sustained more fractures at lower ribs at lower crash severity compared to the nonobese occupants in frontal crashes. In contrast to frontal crashes, the obese occupants in nearside crashes had fewer rib fractures s at higher crash severities and fractures were located more laterally rather than posteriorly in the lower outboard rib. The primary differences in morphomics variables between the two groups are rib angle, fat in the back, and subcutaneous fat. The characterization of the obese rib fracture can then be used as a data source to provide relevant geometric data to inform tailored human finite element ribcage models.

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VII. REFERENCES

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