

Thoracolumbar Spine Fracture occurring in Obese People involved in Motor Vehicle Crashes

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Abstract Crash data from the International Center of Automotive Medicine (ICAM) database, with analytic morphometrics, were used to evaluate thoracolumbar spine fractures for obese occupants in frontal crashes. Two BMI (Body Mass Index) groups (non-obese and obese) with a maximum abbreviated injury scale (MAIS) in the spine region of ≥ 2 (MAIS_6S 2+) were categorised and compared. The fracture types were assessed based on AIS for each occupant. Univariate analyses were conducted to investigate the association between analytic morphometrics measures and thoracolumbar spine fracture.

The results indicate that MAIS 2+ injury occurred mainly in severe crashes with high delta-V and large intrusion. Transverse process fractures were the most common AIS 2+ fractures, followed by minor compression type fractures ($\leq 20\%$ anterior height). Compared to the non-obese occupants, the majority of obese occupants sustained transverse process fractures at lumbar vertebra with a higher incidence ratio. A statistical analysis was conducted, using vehicle, demographic, and morphomic variables, to explain the difference between transverse process fractures and vertebra body compression fractures. Transverse process fractures were related to BMI and vehicle factors (intrusion) in the obese group. In addition, morphometrics related to fat distribution, muscle area, and cortical bone density are the major difference between non-obese and obese occupants.

Keywords Analytic morphometrics, Automotive medicine, Obese, Frontal crashes, Thoracolumbar spine fracture

I. INTRODUCTION

In 2016, the Centers for Disease Control (CDC) recorded that more than one-third (36.5%) of US adults were obese [1]. This trend in US adult obesity has increased every year from 1999 to 2014. One recent study [2] stated that while numbers do seem to be levelling off now, 42% of US adults could be obese by 2030. This shift in the population is occurring not only in the US but around the world, and will likely increase the societal burden of Motor Vehicle Crashes (MVCs).

Based on several studies that examined the relationship between body habitus and injury rate or fatality in crash data, the consequence of obesity with regard to MVCs is problematic [3-6]. Obesity affects the distribution of body regions injured in MVCs. Rupp *et al.* [7] found that increased BMI is associated with increased risks of lower-extremity, upper-extremity, and spine injuries in frontal crashes. Boulanger *et al.* [8] reported that obese occupants were more likely to sustain rib fractures, pulmonary contusions, pelvic fractures, and extremity fractures, but less likely to receive head trauma and liver injuries. Kent and Forman *et al.* [9-10] documented the different kinematics of mid-sized and obese post-mortem human subjects (PMHS) in order to understand the potential injury mechanisms, based on the laboratory test that simulates frontal impact crashes. These results led to the hypothesis that not all regions of the body sustain severe injuries as a result of obesity and highlight the potential importance of body size and composition in influencing injury severity.

According to several studies examining these injuries, thoracolumbar spine injuries occur mainly in severe crash cases and are often accompanied by abdominal injuries [11]. Furthermore, the occurrence of spine injury increased based on crash data [12-13] by year, and Pintar *et al.* [14] concluded that there was a significantly increasing trend in the incidence of thoracolumbar spine injuries in frontal crashes by vehicle model year. Most studies reported that thoracolumbar spine injuries typically occur in lumbar spine or transition between the thoracic and lumbar spine area [14-16]. The mechanism of injury was seen as a result of forward bending

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motion of the upper body during the impact, with debate as to the effect of crash factors (crash pulse, collision type) or vehicle factors (stiffness, belt usage). There are no studies to date, however, examining the thoracolumbar spine injury in obese occupants, and limited studies have been done with regard to age of occupants [17]. The purpose of this study was to use detailed medical injury information to evaluate thoracolumbar spine fractures sustained by obese patients in real-world frontal crashes.

In previous work at ICAM, Analytic Morphomics was developed to objectively measure body geometry and composition data from computed tomography (CT) scans [18-20]. The method of Analytic Morphomics includes techniques for the processing of CT data to collect geometry and tissue density information in a consistent manner. Using a chest/abdomen/spine CT scan, this process begins with segmentation, visual identification and tagging of anatomic landmarks. Using the spatial location of these landmarks as references, the process segments out soft tissues, visceral organs, and bony structures via a customised, semi-automated image-processing algorithm. Based on this processing, the features of body shape, such as skeletal geometry, fat distribution, spine curvature, and tissue density, are measured as morphomic variables in 3D space in relation to each other and to the body as a whole. Parenteau *et al.* [20] used analytic morphomics to measure body shape and size for all patients. That study showed that torso and abdominal body shape changes were associated with serious abdominal injury risk. Wang *et al.* [21] identified additional morphomic factors that were predictive of injury risk in MVCs. Based on these previous findings, this study used analytic morphomics to analyse potential mechanisms of thoracolumbar spine fracture for obese occupants in frontal crashes. By using this data set with analysed crash and medical data involving obese occupants, the characterisation of thoracolumbar spine fracture can be compared in these two BMI groups – obese and non-obese. This methodology allows our analysis to estimate the features of obese thoracolumbar spine fractures and provides the robustness for targeting fracture risk from real-world crash cases.

II. METHODS

Crash Injury Analysis

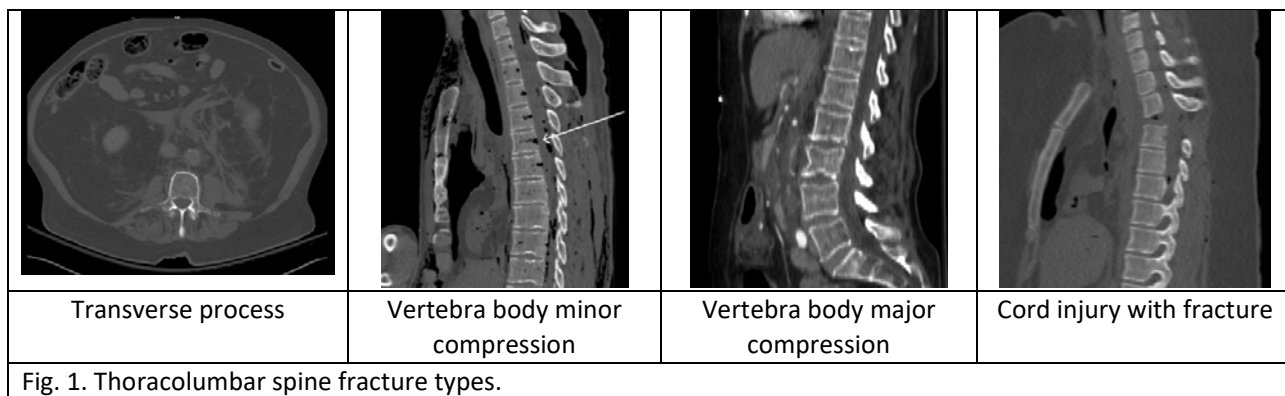
The crash data were obtained from the ICAM database at the University of Michigan for calendar years 1996–2017. The crash data are linked to medical data of the case occupant. In addition, analytic morphomics is utilised to quantify occupant characteristics based on the medical imaging data, in order to understand more about the sustained injury. Inclusion criteria for the current study were based on the following vehicle and crash parameters: vehicle model year 1990 or newer; the primary event was a frontal crash (Collision Deformation Classification (CDC) column 3=F); and the principal direction of force (PDOF) was between 11 and 1 o'clock. 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; had Abbreviated Injury Scale [22] (AIS) coding; and a CT scan was available. Only front-seat outboard occupants were included. The total number of case occupants fitting these inclusion criteria was 261 for frontal crashes. Occupants were categorised by BMI in either the under 30 (non-obese) group or 30+ (obese) group. In this study, the Maximum Abbreviated Injury Scale (MAIS) was assessed separately for each occupant with spine injuries (MAIS_6S). The data included:

- Model year: vehicle model year;
- Delta V: change in vehicle velocity, miles per hour;
- Intrusion count: the total number of intrusions to all vehicle compartments;
- Longitudinal intrusion sum: the sum of maximum resultant displacement of intrusions in the lower, mid- and upper instrument panel area from the longitudinal direction in centimetres;
- Height: the standing height of the occupants in centimetres;
- Body Mass Index (BMI): calculated by dividing the patient's mass in kilograms by the square of their height in metres;
- MAIS_6S: Maximum Abbreviated Injury Scale of spine region.

Thoracolumbar spine fracture

Severity of thoracolumbar spine fracture was assessed using AIS coding. In the ICAM data collection system, medical records are examined to find all thoracolumbar spine fractures, as well as location of fractures

(vertebral number) previously identified by a board-certified radiologist; all injuries were coded by the ICAM team using AIS2005 [22]. The Maximum Abbreviated Injury Score (MAIS) of thoracolumbar region (MAIS_6S) was assessed separately for each occupant. Thoracolumbar spine fractures in this analysis were categorised with AIS coding. Using this categorisation, transverse process fractures (AIS code 650420, 650620), vertebra body minor compression (AIS code 650432, 650632), vertebra body major compression (AIS code 650434, 650634), spinal cord injury with fracture (AIS code prefix 6306**, 6404**, 6406**), and other fractures involved the thoracic and lumbar spine (AIS code prefix 65041*, 65042*, 65061*, 65062*). Figure 1 shows the CT image of typical fracture in each categorisation.



Analytic morphomics

Analytic morphomics processing was performed according to the methods previously described [18-20] and the results from each individual were placed in the context of the Reference Analytic Morphomics Population (RAMP) [23]. The University of Michigan Internal Review Board approved the use of the standard CT scans available for each occupant for this study (HUM00043599 and HUM00041441). CT scans were obtained from the University of Michigan radiology archive. The scans were processed semi-automatically using custom algorithms written in MATLAB 2015a (The Mathworks Inc., Natick, MA, USA). By using semi-automated processing of CT scans, analytic morphomics measures detailed geometry and material characteristics for tissue, organ and bone. The following morphomic variables were assessed, based on the need to represent the shape and material characteristics of abdomen and spine components. Data at L1 were used for the subcutaneous fat area, fascia area, vertebra-to-front skin, spine-to-back skin, cross-sectional area of Dorsal Muscle Group (DMG) area, DMG muscle density, cortical bone density, and trabecular bone density. Measurements are illustrated in Fig. 2.

- Subcutaneous fat area: the cross-sectional area between skin and fascia at L1 meeting fat density thresholds -205 and -51 Hounsfield units (HU).
- Fascia area: the cross-sectional area within the fascia at L1; square millimetre.
- Vertebra-to-front skin: distance between front of vertebra body to skin at L1; millimetre.
- Spine-to-back skin: distance between the posterior tip of the spinous process to the back skin at L1; millimetre.
- DMG muscle area: cross-sectional area of the DMG (Dorsal Muscle Group) perimeter; square millimetre.
- DMG muscle density: the ratio of low density (HU) to high density (HU) dorsal muscle group.
- Cortical bone density: the maximum cortical bone signal peak at L1; Hounsfield units (HU).
- Trabecular bone density: average pixel intensity within a circular core sample at the mid-level of each vertebral at L1; Hounsfield units (HU).

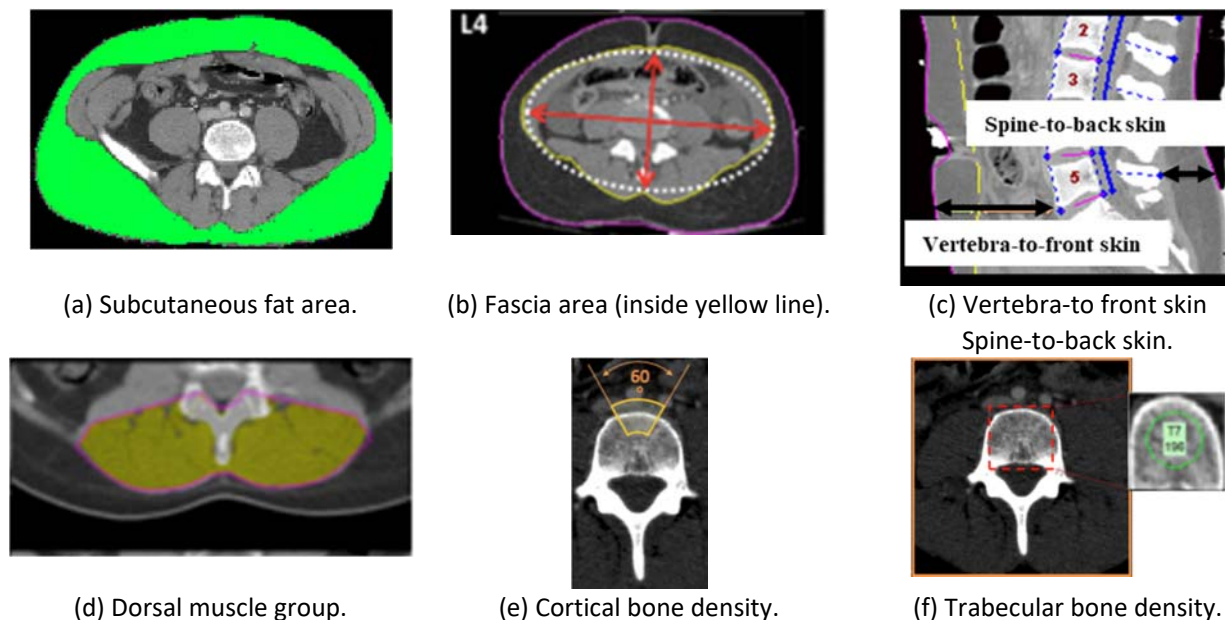


Fig. 2. Morphomic measurement obtained from CT scans [18-20].

Statistics with crash and analytic morphomics data

Utilising the occupants with moderate/severe spine injury data (MAIS_6S 2+) and thoracolumbar spine fracture distribution due to frontal crashes in each BMI group, two-sample *t* tests were conducted to investigate the association between vehicle, demographic and morphomics variables and the spine injury (MAIS_6S 2+).

There are 78 cases available with MAIS_6S 2+ injured occupants involved in frontal crashes. Among these are 72 frontal cases with completely processed *Subcutaneous fat area*, *Fascia area*, *Vertebra-to front skin*, *Spine-to-back skin*, *Dorsal muscle group*, *Cortical bone density*, and *Trabecular bone density* at L1. The morphomics variables related to L1, selected in this analysis, show a high transverse process fracture incidence ratio for the obese group compared to the non-obese. Group means of these morphomic variables were compared between the non-obese and obese groups. The data were separated into two groups, non-obese and obese group, and analysis was conducted using MATLAB2015a statistical toolbox.

III. RESULTS

Spine injuries were first examined with occupants involved in frontal crashes from the ICAM database. There were 261 occupants who met the inclusion criteria of this study. Among 261 occupants, there were 183 occupants MAIS_6S 0-1 and 78 occupants MAIS_6S 2+. By using vehicle and demographic data, spine injuries were compared between the two groups. Table I shows the result of the univariate analysis for the vehicle and demographic variables used in this analysis. 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 percentages for categorical variables (Belt and Gender) of each group, and the *P* value from the Fisher's exact tests.

While the MAIS_6S 2+ group had a higher *Delta-V*, *Intrusion_Count* and *Longitudinal intrusion sum* compared to the MAIS_6S 0-1 group, there are no significant differences in the demographic variables (*Age*, *Height*, *Weight*, *BMI*, *Gender*) between the two groups.

TABLE I
SUMMARY OF STATISTICS BETWEEN THE GROUPS OF MAIS_6S 0-1 AND MAIS_6S 2+ IN FRONTAL CRASHES

Variables	MAIS_6S (0-1) (n=183)		MAIS_6S (2+) (n=78)		P value
	Mean or count	Std error or percent	Mean or count	Std error or percent	
Vehicle					
Model year	2001.73	5.32	2002.28	5.26	0.442
Delta_V	28.45	11.04	34.10	13.72	0.002 **
Intrusion count	2.11	1.86	2.79	1.93	0.009 **
Longitudinal intrusion sum	24.55	29.39	36.76	38.43	0.013 *
Belted	76.0%	0.43	75.6%	0.43	0.957
Demographic					
Age	46.55	20.05	49.38	20.28	0.302
Height	170.69	10.54	170.05	9.80	0.640
Weight	86.91	25.05	83.03	26.35	0.270
BMI	29.73	7.79	28.55	8.14	0.282
Gender _{male}	46.4%	0.50	46.2%	0.50	0.965

* $p < 0.05$ ** $p < 0.01$

The total number of thoracolumbar spine fractures was 158 among 78 occupants who sustained MAIS_6S 2+ in frontal crashes. Among these 78 occupants, 62 had thoracolumbar spine fractures; the distribution of fracture types are shown in Fig. 3. The X-axis shows the fracture types and the Y-axis shows the number of fractures. The transverse process fracture accounts for 60%, followed by the *Vertebra body minor compress* and *Other* at 16%.

By using these data, obese occupants were compared with non-obese occupants who sustained MAIS_6S 2+ injuries. Among the 62 occupants in frontal crashes, there were 38 non-obese occupants with 92 thoracolumbar spine fractures, which was a mean of 2.4 fractures per occupant, and 24 obese occupants with 66 thoracolumbar spine fractures, which was a mean of 2.8 fractures per occupant. Figure 4 shows the thoracolumbar fracture incidence rate along the spine vertebra in each type of fracture, categorised into 17 segments (T1-12, L1-L5). Fig. 3(a) is the non-obese group and Fig. 3(b) is the obese group. The X-axis shows the thoracolumbar spine fracture incidence rates, which are determined by dividing the number of thoracolumbar spine fractures at each vertebra by the number of occupants, and the Y-axis shows the spine vertebra number.

The thoracolumbar spine fractures of occupants were mainly located at the lumbar spine vertebra in both groups. However, the different types of fracture show different distribution from each other. The non-obese group shows transverse process fractures as well as vertebra body fractures (minor and major) and other fractures. For the obese group, the transverse process fractures are predominantly at the lumbar spine vertebra and show high incidence ratio compared to the non-obese group. In addition, the cord injury with fracture tended to be located at thoracic spine, and this type of fracture was not seen in the non-obese group.

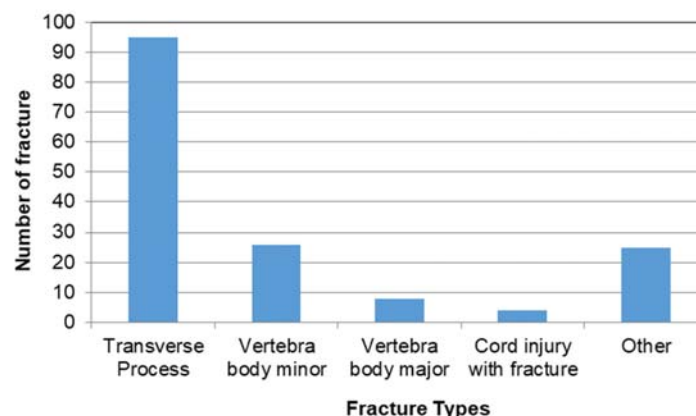


Fig. 3. The thoracolumbar spine fracture for occupants in frontal crashes (N=62).

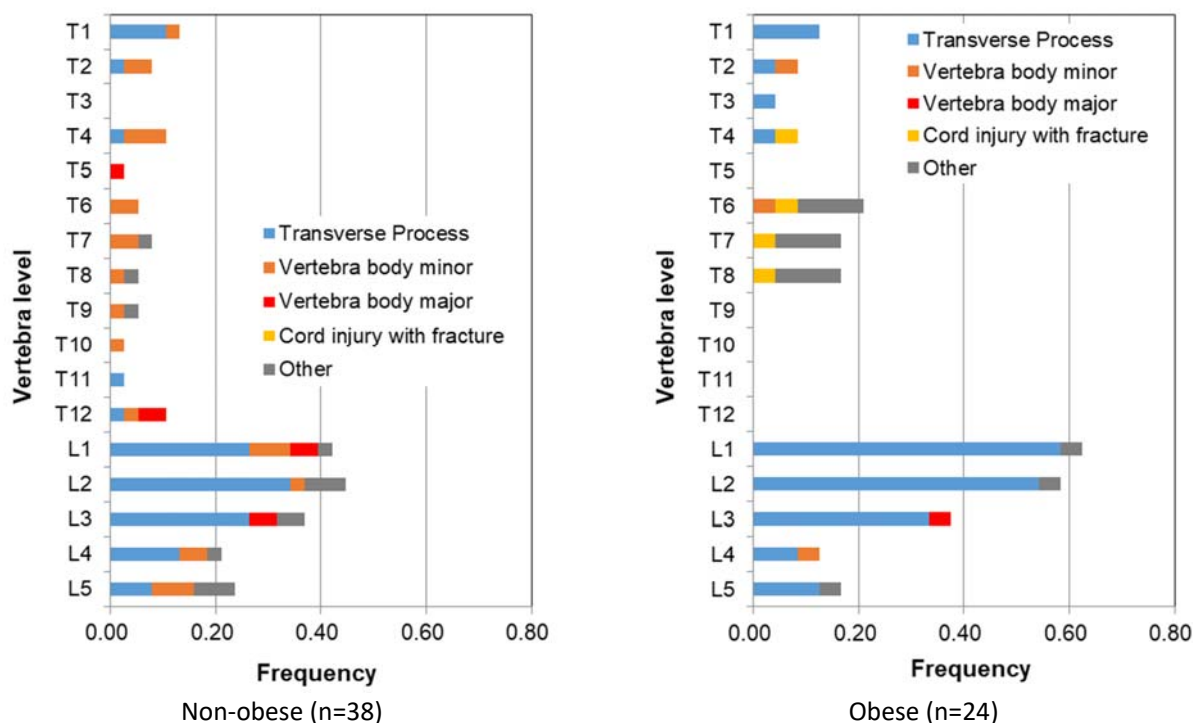


Fig. 4. Thoracolumbar spine fractures incidence ratio by spine level in frontal crashes (MAIS_6S 2+).

According to the distribution of thoracolumbar spine fractures and the fracture incidence ratio using MAIS_6S 2+ criteria, the obese group sustained more transverse process fractures in the lumbar spine in frontal crashes. On the other hand, the non-obese group sustained vertebral body fractures with transverse process fractures, and these tended to be located more in the lumbar spine than in the thoracic spine. From this result, L1, which indicates the differences in the obese group, was chosen as a representative value for comparing morphomics variables. For the 239 occupants with available L1 morphomics variables, statistical analysis was applied to quantify the contribution of abdominal and spine components by linking the morphomic database with the crash database.

Table II presents a univariate analysis of the vehicle, demographics, and morphomics variables used in the current analysis. There were 146 non-obese occupants and 93 obese occupants who met the inclusion criteria of this study. By using these data, obese occupants and non-obese occupants who sustained MAIS_6S 2+ injuries with thoracolumbar spine fracture could be compared. Among the non-obese group, there were 34 occupants with MAIS_6S 2+ with thoracolumbar spine fracture. There were 22 occupants with MAIS_6S 2+ with thoracolumbar spine fracture in the obese group. Table II includes mean, standard errors, and *P* values obtained from two-sample *t* tests for continuous variables. It also provides the counts and the percentages for categorical variables (*Gender_{male}*) in each group, and the *P* value from the Fisher's exact tests. Various features were compared between the groups of occupants with MAIS_6S 2+.

The obese occupants who sustained MAIS_6S 2+ with thoracolumbar spine fracture have a significantly larger *Longitudinal intrusion sum*. Apart from BMI, the demographic variables, such as *Age*, *Height*, and *Gender*, were not significantly different between the non-obese and obese groups. On the other hand, there are significant differences in the BMI-related morphomic variables, such as *Subcutaneous fat*, *Fascia area*, *Vertebra-to-Front skin*, *Spine-to-back skin*, and *DMG muscle area*. The density of cortical bone, which represents material characteristics of the vertebra, was also significantly different between the non-obese and obese groups. The results suggest that transverse process fractures are significantly associated with vehicle and morphomics variables and that these variables present a major candidate for predicting the MAIS_6S 2+ with thoracolumbar spine fracture of obese occupants.

TABLE II
COMPARISON OF MORPHOMICS VARIABLES BETWEEN NONOBESE AND OBESE OCCUPANTS IN FRONTAL
CRASHES

(MAIS_6S 2+ WITH THORACOLUMBAR SPINE FRACTURE)					
Variables	Nonobese (n=34)		Obese (n=22)		p-Value
	Mean or count	Std error or percent	Mean or count	Std error or percent	
Vehicle					
Model year	2003.15	5.12	2002.00	5.37	0.431
Delta_v	34.15	15.21	35.50	11.50	0.707
Intrusion count	2.65	1.92	3.45	1.68	0.104
Longitudinal intrusion sum	26.79	32.45	51.86	39.16	0.017 *
Belt	73.5%	0.45	86.4%	0.35	0.237
Demographic					
Age	46.26	22.33	47.68	15.96	0.783
Height	171.41	9.60	169.36	9.16	0.427
BMI	24.23	3.58	37.61	8.87	0.000 **
Gender	41.2%	0.50	50.0%	0.51	0.528
Morphomics					
Subcutfatarea	9452.80	6407.67	26581.20	10291.31	0.000 **
Fascia area	46441.90	13957.87	62873.39	17114.49	0.001 **
Vertebra-to-front skin	122.71	33.20	165.49	31.58	0.000 **
Spine-to-back skin	15.06	8.21	41.87	19.79	0.000 **
DMG muscle area	5323.77	1497.73	6740.63	1554.27	0.002 **
DMG muscle density	0.22	0.37	0.33	0.23	0.158
Cortical bone density	310.02	82.72	241.53	66.54	0.001 **
Trabecular bone density	218.59	58.48	182.36	75.78	0.065

* 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 thoracolumbar spine fractures were validated by using real-world crash cases. The ICAM database captures the feature of thoracolumbar spine fractures with much more detail and precision than previously available. Utilising this system to analyse the ICAM study subjects who have sustained spine injuries shows clear variation in the distribution of thoracolumbar spine fractures observed in non-obese versus obese occupants. The distribution of thoracolumbar spine fracture types based on the location of the fracture can contribute to an understanding of injury mechanisms during MVCs.

In the frontal crashes, 78 occupants, of a total 261 occupants, sustained MAIS_6s 2+, as shown in Table I. Average *Delta-V* for the MAIS_6s 0-1 and MAIS_6s 2+ group is 28.5 (mph) and 34.1 (mph), respectively. According to earlier studies [11-12] [14], thoracolumbar spine fracture occurs at high crash severity; this is similar to the findings of current study, although the present analysis included unbelted occupants. Overall intrusion and *Intrusion_count* were among the significant variables. It has shown that the occupants who sustained MAIS_6s 2+ were involved in crashes with more occupant compartment intrusion and multiple components of intrusion with high crash severity, as noted by others [17].

The majority of the occupants who received thoracolumbar spine fractures in frontal crashes sustained transverse process fractures. The distribution of fracture type shows a different trend compared to the earlier study [16]. The most common fracture locations were the lateral edge of the vertebral body and the tip of the transverse process, where the fascia layer is attached. This layer surrounds the abdominal cavity, forming a strong aponeurotic attachment between transverse abdominis and spine vertebra, and can transmit tension from the lateral abdominal muscle [24]. The mechanism of fracture at this tiny space could be a tensile load rather than direct impact to the bone in the frontal crash. One possible explanation for this, is that the fascia

layer can transmit load by compressing the incompressible abdominal cavity by belt or steering wheel, the fascia membrane is under tension, and the tip of the transverse process is avulsed off.

The location of fractures along the spine are distributed in lumbar vertebra in both groups. The obese occupant shows a higher ratio of transverse process fracture incidences compared to the non-obese occupant. In addition to the transverse process fractures, the cord injury with fractures is distributed in the thoracic spine; this type of fracture was not seen in non-obese occupants. For the non-obese occupants, the vertebra body minor/major compression are distributed along the spine, compared to the obese occupants. These results indicate that the mechanism of thoracolumbar spine fractures between non-obese and obese occupants is different. According to laboratory tests [9-10] that simulate frontal impact crashes with mid-sized and obese PMHS, the obese subjects had increased hip excursion and decreased torso pitch during the frontal impact. The primary difference was the reclined torso attitude during thorax and abdominal loading in the obese subject, which may subsequently show a decrease of bending motion at the lumbar spine vertebra. Therefore, the frequency of the vertebra body minor/major compression fractures was low in obese occupants. On the other hand, the increased fat mass increases the occupant's kinetic energy due to inertia as well as load forces from lap belt or steering components against the abdomen in frontal crashes. These kinematic differences, along with the inertia effect, provide the tensile force to the transverse process and therefore the frequency of transverse process fracture was increased. For the non-obese occupants, the compression-related mechanisms of fracture induced by the inclined torso during the frontal impact have already been discussed by others [11] [14-15]. These differences between fracture types promote understanding of the mechanisms of MAIS_6S 2+ injury due to greater interaction between the compliant and vulnerable abdominal region and the restraint components.

The BMI-related changes increase the thoracolumbar spine fracture incidence ratio due to the geometry or material changes along the spine. According to the study of analytic morphomics [20], abdominal shape change has the potential to affect injury type sustained in frontal crashes. For this reason, the statistical analysis is applied to clarify the effect of abdominal and spine geometry by using morphomics variables linked to the crash case. Results from the univariate analysis from two BMI groups, as shown in Table II, show that BMI-related variables were significant morphomic variables in frontal impact. *Subcutaneous fat*, which has strong correlation with fat in the back and front of the body, is important to determine injury severity. This fat distribution in the obese may contribute to reducing extensive forward bending of the upper body during a severe crash. Therefore, the role of fat potentially has a protective effect in the vertebral body fracture for the obese occupant. On the other hand, increased fat mass increases the occupant's kinetic energy to cause the transverse process fractures, as previously described. Therefore, further study in this area, computer human body models morphed with related analytic morphomics variables, would be beneficial to evaluate the contribution of these factors.

In addition, reduction of cortical bone density, which represents the biomechanical properties of the bone structures of the spine region, were seen between non-obese and obese who sustained MAIS_6S 2+ with thoracolumbar spine fracture. Reduction in cortical bone density as well as trabecular bone density, which are well known age-related factors, are found to increase the risk of transverse process fractures for obese occupants in this study. These morphomic variables also illustrate the differences in fracture types in thoracolumbar spine vertebra and are a major candidate for consideration as parameters in human body models.

Limitations

The ICAM database comprises vehicle crashes in which the occupants were treated at University of Michigan, a Level-1 trauma centre, therefore the cohort used in this study is not representative of national sample or occupant exposure. Gender differences were not discussed in this study because of the limited sample size. However, female body composition differs from that of males and there do appear to be gender-related variations with regard to the protective effect of fat in MVCs.

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 thoracolumbar spine fracture in frontal crashes. Results, confirmed with real-world crash cases, demonstrated that BMI was associated with transverse process fracture incidence ratio and that obese occupants sustained more fractures in the lumbar spine compared to the non-obese occupants in frontal crashes. Morphomic variables showed that fat distribution and material characteristics of bone and muscle were important in assessing the thoracolumbar spine fractures of obese occupants. The characterisation of the obese derived from analytic morphomics can then be used as a data source to provide relevant geometric data to inform human finite element models.

VI. ACKNOWLEDGEMENT

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