

Subcutaneous Fat Distribution in the Human Torso

Sven A. Holcombe, Stewart C. Wang

Abstract With obesity becoming a major health issue in recent years and a topic of interest in vehicle occupant safety, there is a need for detailed descriptions of body fat distribution in order to develop accurate models of the human body. In this study subcutaneous fat measurements were obtained from over 17,000 CT scans using planar distance maps from skin surface locations to the fascial envelope. Measures were taken as a map registered by vertebral level (from T6 down to L5, extended to the sacrum) and body location around the body perimeter. Multivariate regression maps were calculated showing the individual effect of demographics on the subcutaneous layer thickness. Regression coefficients were statistically significant, with results showing the progression of 20 years of age producing a migration of 3mm of fat from mid-abdominal to lower-abdominal regions and female occupants having thicker subcutaneous regions compared to males by between 6 and 24mm with accumulation peaks near the buttocks and breasts. Each 20kg of added body weight produce regional fat increases between 2 and 14mm across the torso, with a primary peak near the hips and secondary peak near the lower abdomen.

Keywords fat, human body, model, obesity, subcutaneous

I. INTRODUCTION

Concern for increasing obesity has gained international interest since obesity will soon become the world's biggest health problem (NIH 2003 [1]). In motor vehicle crashes, obesity has been shown to influence the risks of serious and fatal injury [2-4]. Jehle et al. [5] found that overweight occupants had the lowest risk of fatality while obese and morbidly obese occupants had the highest risks. The authors suggested that subcutaneous fat may provide a cushioning effect for overweight drivers involved in a vehicle crash. The authors also indicated that a large amount of subcutaneous fat may force drivers to sit in close proximity to the steering wheel increasing their injury risks. Parenteau et al. [6] found that the amount of subcutaneous fat differed based on location, vertebra level, BMI and gender.

Crash test dummies and post-mortem human subjects (PMHS) are generally used to assess occupant responses in a simulated crash environment. They are however representative of normal-sized occupants. Different methods have been used to assess the effect of weight on occupant response. For example, McGowan [7] ballasted the weight of a 95th percentile male Hybrid III dummy to 300 lb. to study the effect of seat back stiffness in rear impacts. Additional weights were added to the abdomen, thorax and extremities. Kent et al. [8] tested two obese and three normal weight, lap-shoulder belted PMHS to study the effect of obesity on the biomechanical responses in frontal crashes. The authors found increased excursion with the obese occupants in the test.

Zhu et al. [9] developed computer models of various sized male and female drivers. They varied the amount of torso subcutaneous fat in the form of elliptical masses added axially around the body based on limited MRI data. Other studies [10] have also used digital models to assess the role of obesity on occupant seated posture.

While considerable clinical research (see [11] for review) has gone into using medical imaging modalities to assess body fat content, published studies are generally focused on the association of fat content with particular clinical outcomes, rather than detailing the distribution of the fat itself.

This study aims to enhance the available data for human body modeling by providing 3-dimensional torso subcutaneous fat measures registered by underlying vertebral landmarks and skin perimeter locations. A large underlying population of CT scans drives regression analyses to highlight local changes in subcutaneous thickness by demographic factors of age, gender and weight.

II. METHODS

Scan population

Under IRB HUM00041441, 17080 scans from adults (16+ years) in the International Center for Automotive Medicine (ICAM) morphomics database were included in this study. Scans were from University of Michigan trauma patients who underwent abdomen and/or pelvis CT scanning as part of their normal course of treatment. Scan protocol was to have patients in the supine position with arms raised.

Study demographics are summarized in Table 1 below, with demographics for adults over 20 years in a 2008 CDC Health Statistics Report [12] in parentheses, showing strong similarity between the study demographics and the reported CDC demographics of North American adults.

TABLE I
STUDY DEMOGRAPHICS MEAN AND PERCENTILES (CDC REFERENCE POPULATION IN PARENTHESES)

Males (N = 9587)	Mean	5 th	10 th	25 th	50 th	75 th	90 th	95 th
Weight, kg	87.6 (88.3)	60 (62.2)	66 (66.7)	75 (75.2)	84 (85.6)	99 (98.4)	113 (111.5)	123 (122.6)
Height, cm	178 (176.3)	165 (163.6)	168 (166.6)	173 (171.3)	178 (176.3)	183 (181.5)	188 (186)	190 (188.7)
Females (N = 7493)								
Weight, kg	74.5 (74.7)	49 (50.5)	52 (53.5)	60 (60.2)	70 (70.7)	84 (84.3)	100 (101.8)	113 (113.6)
Height, cm	163 (162.2)	152 (150.7)	155 (153.3)	158 (157.7)	162 (162.2)	168 (166.7)	173 (170.8)	175 (173.1)

Subcutaneous region segmentation

The subcutaneous fat region examined in this study is defined as the region deep to the patient's skin, and superficial to an envelope of fascial tissue separating visceral and subcutaneous regions. This fascial envelope is defined on any cross-sectional view of the body as the superficial boundary of abdominal (*rectus abdominis*, *transverse abdominis*, *external oblique*) and paraspinous musculature. In pelvic regions this envelope is superficial to the bony pelvis and gluteal musculature, and in chest regions the envelope is superficial to the chest wall including the bony ribcage, costal cartilage, intercostal musculature and sternum.

The skin segmentation was performed using thresholding and morphology operations, with a custom-built MATLAB editing software (The Mathworks Inc., Natick MA) to allow manual adjustment of the skin boundary.

The fascial envelope contour placement was performed on a subset of CT image slices of each scan, with slices selected to be spaced by half the average vertebral body height. Contour placement was performed with custom-built MATLAB software, in which users would place markers on the fascial envelope boundary. Between markers, an image edge detection algorithm tuned to maximize edges consistent with the magnitudes and gradient of the transition from muscle or bone (higher image intensity) to fat (lower image intensity) was used to find the fascial layer. When the edge detection between two markers failed to follow the fascial envelope, the final edge could be adjusted by additional marker placement reducing the distance needing to be traversed by edge detection. Figure 1 below shows the fascial boundary and markers for different regions of the torso.



Figure 1: Fascial envelope drawn at lower (left), mid (center) and upper (right) torso regions.

Subcutaneous thickness measurement

On any given axial slice with known skin and fascial envelope contours, the subcutaneous region thickness at any location along the skin contour is given by the distance to the nearest point on the fascial envelope. In image morphology terms, the subcutaneous thickness at the skin is equal to the geometric distance map from the fascial envelope. In the present study, only two dimensional distances in the axial plane were considered.

To register subcutaneous thickness measures taken around the circumference of the body, a medial plane at each slice in the scan was defined by a line through the spinal canal and the *linea alba* extending from the sternum to the pubic symphysis. Skin locations were then defined as their distance along the skin perimeter from the posterior medial point, normalized by the full distance from the posterior medial point to anterior medial point. One hundred equally spaced points were sampled on the left and right sides of the body perimeter. Figure 2 gives a visual representation of the subcutaneous region depth as a function of location around the body.

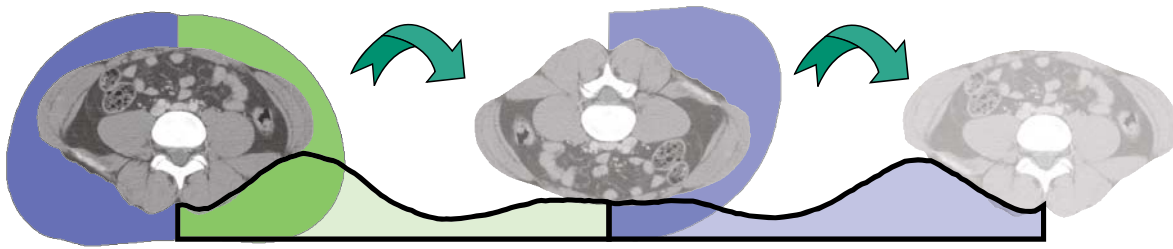


Figure 2: Subcutaneous fat thickness around the body perimeter at a given cross sectional region.

To account for differences in patient height, measures were registered in the inferior-superior direction by a vertebral level coordinate system aligned at the inferior aspect of each vertebral body [13]. Ten equally spaced axial slices were sampled between each successive vertebra, and 20 slices taken between the L5 vertebra and the tip of the sacrum. To avoid complications in the definition of a fascial envelope for upper chest regions (where the arms connect), subcutaneous measures were only taken from the 11 vertebrae extending from the inferior aspect of T6 through L5, with an additional pelvis region extended inferiorly from L5 to the tip of the sacrum.

III. RESULTS

17,000 scans were analyzed, with the extraction of a subcutaneous thickness map for each individual in the form of a 150-by-200 matrix (150 locations between T6 and the sacrum, 100 locations around the left and right of the body.) To illustrate this mapping, Figure 3 shows the average thickness as a distribution by vertebral level and body perimeter location for all males and females, alongside a projection of that map onto representative torso geometry.

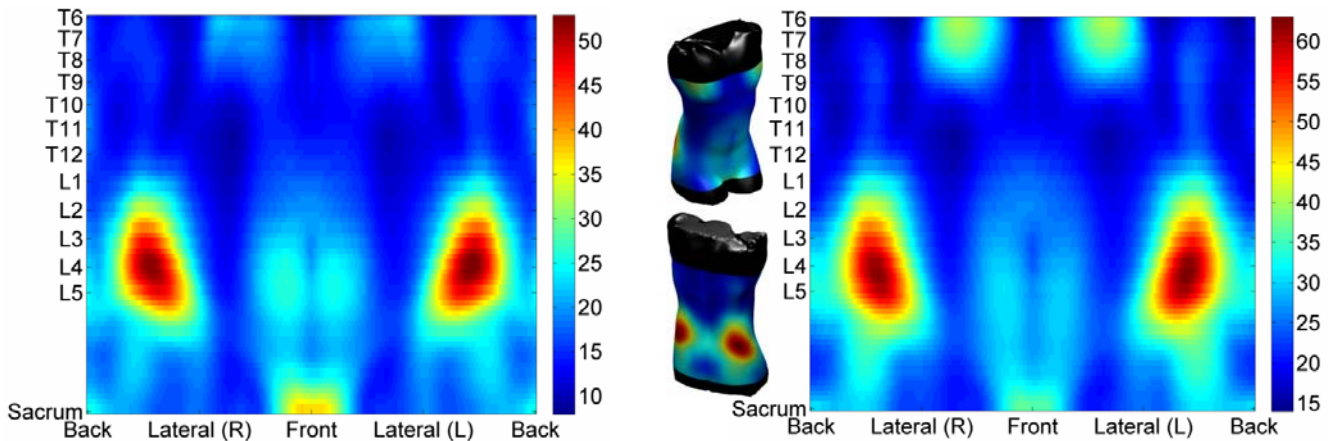


Figure 3: Average subcutaneous thickness map (color units in mm) for males (left) and females (right), with icons showing the body region registration between maps and an example 3D torso model.

At every regional location, linear regression was performed using predictors of age (years), weight (kg) and gender (0/1 for males/females), regressing to the subcutaneous thickness measurements at that specific location. Regression coefficients for age, weight and gender can therefore be collected into maps across the torso describing the local change in subcutaneous thickness, registered by vertebral level and body perimeter location. These data maps are available from <http://automotivemedicine.org/research/subcutaneous.shtml> and illustrated below, with Figure 4 showing the fat accumulation pattern resulting from an increase of 20kg while age and gender are both unchanged. Figure 5 shows the migration of subcutaneous fat with each 20 years increase if weight and gender are held constant, and Figure 6 shows the fat distribution difference between females and males of equivalent age and weight.

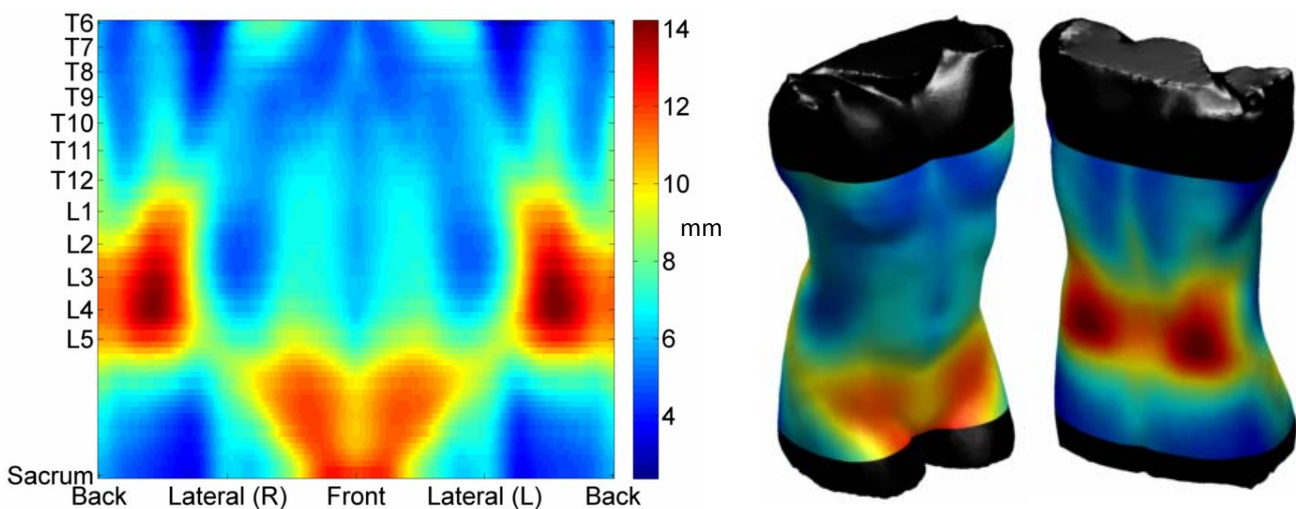


Figure 4: Regional effect of weight showing subcutaneous thickness change (mm) with each increase of 20kg.

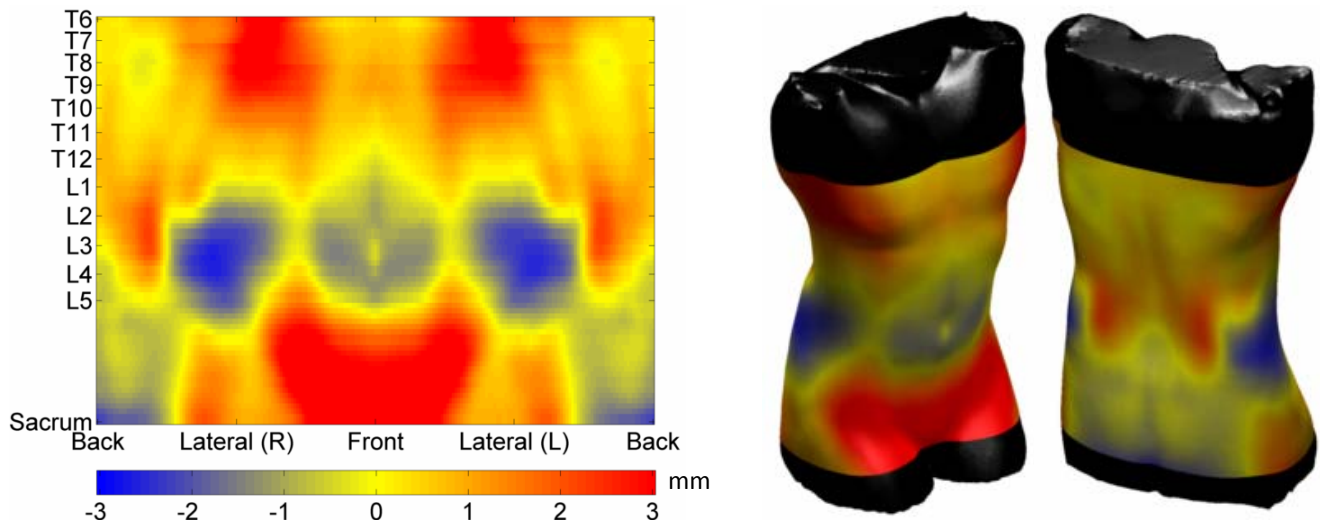


Figure 5: Individual regional effect of age showing subcutaneous thickness change (mm) with each added 20 years. The color scale is centered at zero change (yellow).

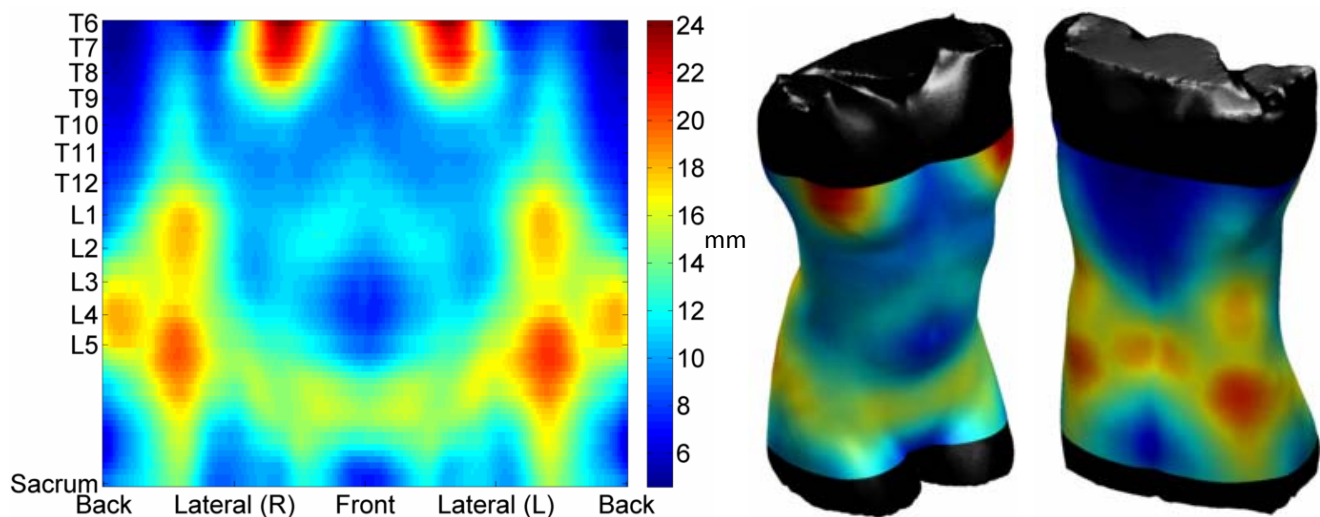


Figure 6: Individual regional effect of gender showing subcutaneous thickness difference (mm) from male to female.

Results show that if an individual were to maintain a constant weight, during the progress of 20 years, there would be a migration of around 1.5mm in subcutaneous thickness from antero-lateral regions near the L4 vertebral level (mid-abdomen) with a corresponding increase accumulated lower in the abdomen towards the level of the sacrum.

For individuals with equivalent age and weight, a female occupant will have approximately 22mm of additional subcutaneous fat at locations of peak difference (postero-lateral to the L5 vertebra and at the breasts). Across the torso, the female subcutaneous region is thicker than a male of equivalent age and weight, with the regional distribution ranging from 6 to 24mm.

For any individual with a known age and gender, the addition of 20kg to their weight corresponds to a peak increase of approximately 14mm in subcutaneous thickness located postero-laterally at the L4 vertebral level. Results show regional accumulation of fat with weight, with a second local peak near the lower abdomen at the front of the body.

IV. DISCUSSION

The CT analysis technique described has been applied over a large population. To the authors' knowledge no other study has attempted to characterize fat deposition patterns from such a large data source. As a result of the number of observations, statistical power is increased such that regressions to age, weight and gender were statistically significant ($p < 0.05$) for all predictors in practically all body regions of the maps provided above. Only regions with a regression coefficient very close to zero (less than 2% of all sampled locations) remained insignificant.

The multivariate regression results themselves describe deposition patterns in the subcutaneous fat layer as age, weight or gender is changed while all other variables are held constant. It is therefore possible to use these maps to artificially age or increase the weight (or age) of a given human body model, and have the subcutaneous layer of that model change in a physiologically realistic way. In order to make such changes to model geometry, each torso surface point should be assigned a vertebral level coordinate and body perimeter coordinate pair, which can be used to look up the regression coefficient in the maps of Figure 4, Figure 5 and Figure 6, available from <http://automotivemedicine.org/research/subcutaneous.shtml>. These coefficients can be scaled by the desired changes in demographics, with the result being the distance offset to apply to the torso surface point in question and morph it to meet the given demographic.

This study has placed an emphasis on registration or alignment of the measures as they are taken spatially around the body. A vertebral level coordinate was chosen to register measures in the inferior-superior dimension due to the spinal column being a relatively stable and unmoving landmark that can be reproduced between individuals. The body-perimeter dimension of the registration is also guided by the spine along with the *linea alba* in order to retain consistency between individuals of body-anterior and body-posterior locations, with lateral locations distributed evenly around the left and right sides of the body perimeter from these fixed anchor locations. It is recognized that grossly differing body shapes may result in slight misalignment of the most lateral of these registration locations. Nevertheless, regression maps show symmetric and detailed patterns across the body including these lateral regions, providing confidence in these results and the underlying spatial alignment between observations.

To understand the intra-scan repeatability of the method used, 10 scans were randomly selected and each processed by different operators using the semi-automatic methods described above. Due to the automated portions of the method, thickness measures from 48% of all locations were identical between operators. Manual editing left 46% of all locations differing by less than 1mm, with the remaining 6% of locations varying by between 1mm and 5mm.

To understand the inter-scan repeatability, a sub-population of 250 individuals who received two separate scans within a 24 hour period was examined. These scan pairs were processed independently of each other and the absolute difference in subcutaneous thickness at each torso location was recorded with the expectation that any change within a 24 hour period should be minimal. The mean and median difference across all locations was 2.7mm and 1.29mm respectively, with more error seen towards the hips and breasts (~4mm median error) compared to the posterior and abdominal regions having median error below 1mm. Visual inspection of the 20 scan pairs exhibiting the largest error (35mm or more) each showed this error focused at locations of scan windowing, discussed further below.

In this study, all patients were scanned in a supine orientation. It is expected that subcutaneous fat directly under gravitational load (e.g., behind the spine and buttocks) will tend to compress, resulting in thinner fat layers immediately between the body and the scanning bed. Furthermore for larger patients, gravitational effects on fat around the abdomen or breasts can produce asymmetrical fat thicknesses if the subject is rotated towards their left or right sides. Such cases would result in a migration of the subcutaneous fat distributions when compared to vehicle occupants in a seated orientation, or pedestrians in a standing position. These orientations themselves would exhibit their own gravitational effects, and future work should be directed at either defining similar fat distributions in each target orientation or the development of transfer functions from supine to other postures.

Limitations

The approach used in this study is essentially to treat the subcutaneous region of the body as a cylinder with variable local thickness. This simple approach is valid in the abdominal and lower chest regions of the thorax

where such topology is present, but breaks down when considering the thorax subcutaneous layer superior to the armpits. In this upper chest region the arms and shoulders protrude laterally, changing the orientation of the boundary between deep and subcutaneous layers. For this reason, results have been limited to the inferior aspect of the T6 vertebral body.

A limitation of using CT scans originally taken for diagnostic purposes is that the subcutaneous region of the body is often of lower clinical importance than the visceral region containing organs and bony skeleton. Consequently, operator focusing of the scan window on visceral regions sometimes occurs with very large patients, particularly in the lateral aspects of the pelvis as illustrated in Figure 7. In this study, the edge of the scan window has been applied as the upper limit to the skin boundary. This constraint has the effect of suppressing high-end lateral thicknesses. Follow-up studies will be aimed at compensating for this by identifying and accounting for these truncated regions based on the presence of “in-window” body regions.

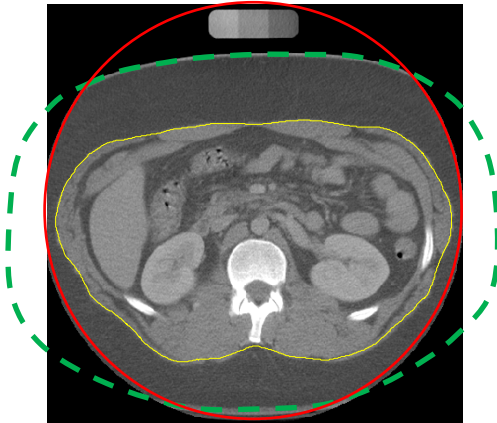


Figure 7 Example of CT scan windowing effect of larger patients. (Circular line: Scan window; Dashed line: True subcutaneous region).

V. CONCLUSIONS

A novel method for representing the subcutaneous fat layer of the human torso has been presented and applied to a large and representative cross section of the adult population. Measures of subcutaneous fat layer thickness have been taken across the torso, registered by vertebral level and body perimeter. Statistically significant multivariate regression maps of the changes in fat thickness with age, weight and gender have been presented showing patterns of fat deposition with changing demographic. Such maps can aid in the artificial modification of human body models to meet a given demographic by retaining regionally accurate subcutaneous fat thickness.

VI. ACKNOWLEDGEMENT

The authors would like to thank Chantal Parenteau, Patrick Rabban, Lucy Hully and Binu Enchakalody for their contributions to this research.

VII. REFERENCES

- [1] Reilly J, Methven E, et al. Health consequences of obesity, *Archives of Diseases in Childhood*, 2003, 88:748-52.
- [2] Mock C, Grossman D, Kaufman R, Mack C, Rivara F. The relationship between body weight and risk of death and serious injury in motor vehicle crashes, *Accident Analysis & Prevention*, 2002, 34(2):221-228.
- [3] Wang S, Bednarski B, Patel S, et al. Increased depth of subcutaneous fat is protective against abdominal injuries in motor vehicle collisions, *Annu Proc Assoc Adv Automot Med*, 2003, 47:545-559.
- [4] Viano D, Parenteau C, Edwards M. Crash injury risks for obese occupants using a matched pair analysis, *Traffic inj prev*, 2008, 9(1):59-64.
- [5] Jehle D, Gemme S, Jehle C. Influence of obesity on mortality of drivers in severe motor vehicle crashes, *Am J Emerg Med.*, 2012, 30(1):191-5.
- [6] Parenteau C, Zhang P, Holcombe S, Kohoyda-Inglis C, Wang SC. Analysis of morphomics parameters by

gender and BMI groups: thorax shape and H-point location, *Proceedings of the International IRCOBI Conference on the Biomechanics of Injury*, 2013, Gothenburg, Sweden.

- [7] McGowan J, Levitt A, Corrigan C, Burnett B, et al. Seatback strength and occupant response in rear impact crash: observations with respect to large occupant size and position, *SAE Technical Paper*, pp. 01-1029, 2010.
- [8] Kent R, Forman J, Bostrom O. Is there really a “cushion effect”? A biomechanical investigation of crash injury mechanisms in the obese, *Obesity*, 2010, 18(4):749-53.
- [9] Zhu S, Kim JE, Ma X, Shih A, Laud P, et al. BMI and risk of serious upper body Injury following motor vehicle crashes: concordance of real-world and computer-simulated observations, *PLoS Med*, 2010, 7(3): e1000250.10.1371/journal.pmed.1000250, 2010.
- [10] Gragg J, Yang J. Effect of obesity on seated posture inside a vehicle based on digital human models, *SAE Int. J. Mater. Manuf.*, 2011, 4(1):516-526.
- [11] Goodpaster B. Measuring body fat distribution and content in humans, *Curr Opin Clin Nutr Metab Care*, 2002, 5(5):481-7.
- [12] McDowell MA, Fryar CD, Ogden CL, Flegal KM, Anthropometric Reference Data for Children and Adults: United States, 2003–2006, *CDC National Health Statistics Reports*, vol. 10, 2008.
- [13] Wang SC, Holcombe S, Huhdanpaa H, Kohoyda-Inglis C, Sullivan J. Analytic morphomics: High speed medical image automated analysis method. US 14 Patent 014,485, 6 Mar 2014.