# Effects of High Levels of Obesity on Lap and Shoulder Belt Paths

Monica L. H. Jones, Sheila M. Ebert, Jingwen Hu, and Matthew P. Reed

***Abstract*** Obese occupants have higher risks of fatalities and injuries in frontal crashes than normal-weight individuals. In particular the chest and the lower extremities are the body regions that are more likely to be injured for obese than non-obese occupants. Previous studies demonstrated that obesity increases the amount of belt webbing used by drivers, and have shown that lap belt placement tends to be higher and further forward relative to the pelvis, but have not characterized the belt paths in detail with respect to skeletal landmarks. Moreover, previous studies have used data from only a few individuals with BMI>35 kg/m$^2$. Driving postures and belt fit of 52 men and women with BMI from 31 to 59 kg/m$^2$ (median 38 kg/m$^2$) were measured in laboratory mockup. The paths of the lap and shoulder portions of the belt were captured using a three-dimensional coordinate digitizer. The paths were fit using basis splines and a statistical analysis was conducted to examine the effects of overall body dimensions on belt paths. For both men and women, the torso portion of the belt routed further forward of the bony landmarks at the sternum and more laterally on the inboard (buckle) side, passing higher on the ribcage, but the effect was larger for women. The torso belt path was further forward, relative to the top of the sternum, for women than for men, reflecting greater thickness of breast tissue. For men, higher BMI was associated with a lower but more forward belt position relative to the pelvis. The effects of these differences in belt path with increased adiposity should be studied further using human body models.

***Keywords*** obesity***,*** safety belt fit, body shape

## I. INTRODUCTION

The proportion of adults who are obese has increased significantly worldwide since 1980s according to World Health Organization (WHO). In 2014, 39% of adults aged 18 years and over were overweight and 13% were obese around the world. In the United States, the prevalence of overweight and obesity were 68.8% and 35.7% in 2009-2010, compared with 55.9% and 22.9% in 1988-1994 [1]. A study by Finkelstein et al. [2] predicted that the prevalence of obesity could be up to 42% in the United States in 2030. Currently about 5% of US adults are “morbidly” obese, defined by the CDC [3] as a BMI ≥ 40 kg/m$^2$. In the United States, the growth rate in the prevalence of a BMI>40 kg/m$^2$ and a BMI>50 kg/m$^2$ has been found to be twice and three times, respectively, the growth rate of the prevalence of moderate obesity since 2000 [4]. The issue of disproportionate increases in the more extreme categories of BMI is important because the adverse health risks amplify as the level of obesity increases [5].

Increased numbers of obese occupants raises challenges for the occupant protection in MVC. Field data analyses have shown that the obese occupants had higher risks of fatalities and injuries in frontal crashes than normal-weight individuals [6-13]. Trends from several studies using fatality and medical injury data have shown that the effects of obesity on the risks of injury vary for different body regions. Modeling the relative effects of BMI on the number of occupants with serious-to-fatal injury has shown that the chest region [6,11,14-17] and lower extremities [6,14,18-21] are more likely to be injured for obese than non-obese occupants involved in crashes. These results demonstrate a need to improve understanding of the occupant protection needs of individuals with high BMI.

Obese occupants are at increased risk of injury due to anatomical and physiological variations that alter normal occupant and safety belt response during a crash [13,22-23]. Specifically, the higher risks of injuries for the obese

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occupants are believed to be caused primarily by the increased body mass exacerbated by poor belt fit resulting from corpulence [24,25]. Studies by the University of Virginia [26-29] compared the kinematics of five post-mortem human subjects (PMHSs) in frontal crash tests and found that the obese PMHS experienced greater body excursions that they attributed to higher kinetic energy. A modeling study by Turkovich et al. [22] also reported that the increased body mass was the most significant factor affecting the injury risks for obese occupants, followed by body shape. More recently, Shi et al. [30] and Wang et al. [31] used computational human models to quantify the effects of obesity on occupant kinematics and injury in severe frontal crashes.

Lap belt fit is strongly affected by obesity. Reed et al. [32], Reed et al. [33] and Jones et al. [34] demonstrated that higher BMI is associated with poor lap belt fit, with the lap portion of the belt riding higher and more forward relative to the pelvis and an associated increase in lap belt webbing length. Increases in BMI are associated with approximately linear increases in both the fore-aft and vertical distance between the lap portion of the belt and the bony pelvis. Reed et al. [35] also showed that lower-abdomen body contours accounted for larger lap belt webbing lengths among individuals with high BMI. Both of these factors potentially diminish the effectiveness of the belt restraint. Sub-optimal belt fit adversely affects occupant kinematics in frontal impacts and increases injury risk.

These studies have also quantified shoulder belt fit by the lateral location of the inboard edge of the shoulder portion of the belt relative to the body midline at the height of the suprasternale landmarks. This measure of belt fit has not been shown to be strongly affected by obesity. Reed et al. [33] did not show any meaningful interactions between shoulder belt routing and participant characteristics after taking into account the geometric effects of shoulder height (expressed as stature). Jones et al. [34] extended previous findings with data for individuals with high levels of obesity (BMI ≥ 40 kg/m$^2$). A significant effect of gender nested within stature beyond the effects of overall body size was found for the high-BMI cohort. A significant interaction between the upper D-ring location and gender was also observed. Only at the smallest YZ angle did female participants show a larger shoulder belt score compared with male occupants. After accounting for stature and BMI, belt webbing length was longer for women than for men.

The current study extends current knowledge of belt fit [32-35] by quantifying the patterns of belt routing with respect to the torso for a cohort of obese drivers using a coordinate system defined by key skeletal landmarks. A functional statistical analysis methodology is used to examine the effects of gender, BMI, and stature on belt routing relative to the skeleton.

## II. METHODS

### *Participants*

Fifty-two participants (26 women and 26 men) were tested in this study. Participants are stratified based on BMI classification (Obesity Class I, II, and III) (CDC, 1998). The male study population averaged 48 (SD=13) years of age, stature of 1762 (312) mm, body weight of 126 (32) kg, and BMI of 41 (13) kg/m$^2$. Female participants averaged 46 (16) years, stature of 1623 (97) mm, body weight of 103 (19) kg, and BMI of 39 (6) kg/m$^2$ for BMI. Participants were stratified based on body mass index (BMI) classification, stature, and age. Tables A.1 and A.2 illustrate the distributions of selected anthropometric variables. The study protocol was approved by the University of Michigan Institutional Review Board (IRB) for Health Behavior and Health Sciences (IRB #HUM00102426). Participants were recruited through online postings and through healthcare providers at the University of Michigan Adult Bariatric Surgery program.

### *Vehicle Mockup*

Testing was conducted in a driver workstation mockup used in a previous study of posture and belt fit [33]. The driver mockup included a steering wheel, instrument panel, brake and accelerator pedals, six-way power seat, and seat belt. The package was set to dimensions of a typical midsized sedan [36]. The steering-wheel fore-aft position relative to the pedal reference point (SAE L6) was set to 550 mm, the steering wheel height above the heel surface (H17) was set to 646 mm, and the steering wheel angle (A18) was fixed at an angle of 25° relative to vertical. Seat height (H30) was set to 270 mm at mid vertical travel. The starting position of the seat H-point aft of AHP was initially set to 850 mm for women and 905 for men. Seat back and cushion angles were initially set to 23˚ relative to vertical and 14.5˚ relative to horizontal respectively (SAE J826).

The vehicle mockup was equipped with a six-way power seat with a power recline adjuster and a large range of vertical adjustment. The seat was mounted on a motorized platform that could be moved fore-aft so that all participants were able to select a comfortable seat position without being censored by the available seat track adjustment range.

The mockup was also equipped with a three-point seatbelt with a sliding latch plate and a nominal belt webbing width of 45 mm. The lap belt angles were set relative to seating reference point (SgRP) and were equivalent on the inboard (buckle) and outboard sides. The retractor and D-ring were mounted on customized fixtures designed to permit location adjustment. The D-ring (upper belt routing point) and lower anchorages were measured relative to the seating reference point as described by U.S. Federal Motor Vehicle Safety Standard (FMVSS) 210. The lower anchorages were set to an angle of 52˚ relative to horizontal, which is in the middle of the allowable range of 30˚ to 75˚ defined in FMVSS 210. The D-ring was set such that the front-plane angle of the vector from the SgRP on seat centerline to the D-ring was 21˚ relative to vertical (see Reed et al. [33]).

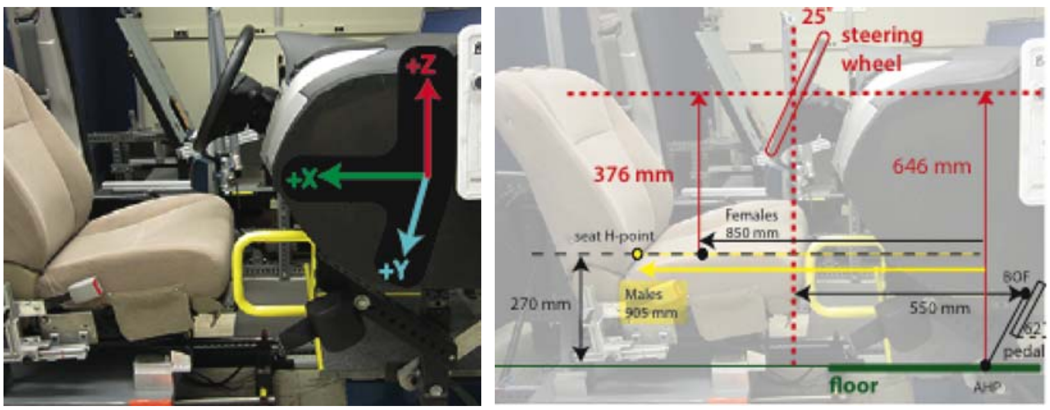



Figure 1. Vehicle mockup and package dimensions for midsized sedan condition.

***Protocol***

On arriving for testing, participants were briefed on the purposes and methods of the study and written consent was obtained. Participants changed into test garments made of thin material that provided good access to body landmarks. Standard anthropometric measures were taken on each participant to characterize overall body size and shape. A three-dimensional coordinate measuring machine (FARO Arm®, FARO Technology, USA) was used to record surface landmarks to document skeletal posture. The landmark set and measurement methods were derived from those used in previous studies of automotive posture for both adults and children [37-38]. This procedure involved the participants sitting in a specially designed laboratory hardseat that provides access to the posterior spine and pelvis landmarks. The hardseat has a 14.5° fixed cushion angle and a 23° fixed seatback angle, designed to produce postures similar to those in an automotive seat.

Participant entered the mockup and adjusted the seat (fore-aft position, vertical position, cushion angle, backrest angle) to obtain a comfortable driving posture. The participant then donned the belt and assumed a normal driving posture. The investigator used the FARO arm coordinate digitizer to record the participant's posture, vehicle mockup, seat and belt components. A stream of points with approximately 5-mm spacing was also recorded along the edges of lap and torso portions of the belt between the anchorages and latch plate. The current analysis is based on the upper edges of both portions of the belt.

***Driving Posture and Torso Coordinate System***

The body surface landmarks were used to compute estimates of internal joint center locations to quantify the driving posture [37]. Pelvis landmark locations (L5/S1, anterior iliac spine (ASIS), posterior iliac spine (PSIS) and hip joints) were initially calculated from the hardseat data, and then repositioned in the vehicle-seat data using an optimization algorithm [39].

Transformation of the joint center locations into a local torso coordinate system enabled the belt fit data to be evaluated consistently across participants in terms of the bony anatomical landmarks on the thorax and pelvis. The origin of the torso coordinate system was placed at the midpoint between the estimated anterior-superior iliac spine landmarks on the bony pelvis. The Z axis was defined from this origin through the suprasternale landmark at the top of the chest. The X axis was obtained from the cross product of the vector passing through the ASIS landmarks and the Z axis and the Y axis was defined orthogonal to X and Z. All data were scaled by the length of the vector from mid-ASIS to surprasternale to normalize for differences in torso length.

***Basis Spline Modeling of Belt Stream Data***

To facilitate analysis of the belt paths, basis splines were fitted to the 3D curves of the torso and lap belt stream data. Torso and lap streams were fit separately. A basis spline of order *k* (degree $k-1$) is a piecewise polynomial function composed of a linear combination of $n+1$ control points and basis function $N_i^k(u)$:

$$S(u) = \sum_{i=0}^{n} P_i N_i^k(u), where\ 0 \le u\ \le 1$$

where $n - k + 2 > 0$. The b-spline curve is evaluated along the ascending input parameter u ∈ $[0,1]\ and\ \boldsymbol{f}(u) \in \mathbb{R}^3$, or a position vector of any point of the belt stream data. The position vector $\boldsymbol{f}$ consists of three components $x(u), y(u), and\ z(u)$ which may be considered as the Cartesian coordinates (e.g. $\boldsymbol{f}(u) = [x(u)\ \ y(u)\ \ z(u)]^T$). The $\boldsymbol{f}$ vector consists of $n+k+1$ *knots* that locally control the shape of the b-spline curve. For the current work, five uniformly spaced knots were used.

The b-spline basis function is defined recursively as follows:

$$N_i^1 = \begin{cases} 1, & F_i \le f\ F_{i+1}, \\ 0, & \text{otherwise} \end{cases}$$

$$N_i^k(u) = \frac{u - F^i}{F_{i+k-1} - F_i} \cdot N_i^{k-1}(u) + \frac{F_{i+k} - u}{F_{i+k} - F_{i+1}} \cdot N_{i+1}^{k-1}(u)$$

where the fraction is set to 0 if the numerator and denominator both equal 0. For the current application, the Cartesian coordinates of the points on the belt path expressed in the local torso coordinate system ($T$) are approximated by finding the set of $n+1$ spline coefficients P using linear least squares regression:

$$P = (N^T N)^{-1}(N^T T)$$

Prior to fitting, the belt streams were truncated to lie within the normalized Y- and Z-axis ranges of {-0.5, 0.5} and {-0.1, 1.1}, respectively. Following the fitting process, each torso or lap belt path was represented by five sets of 3D spline coefficients (15 values), which can be interpreted as 3D spline control points.

***Statistical Analysis***

A regression analysis was conducted to assess the effects of gender, stature, the ratio of erect sitting height to stature (SH/S), and BMI on the spline coefficients. The goal was not to assess statistical significance but rather to demonstrate and to compare the magnitudes of the effects over ranges relevant for occupant safety. Least-squares models were created to predict each spline coefficient, with the predictors including first-order interactions of gender with the other predictors. These models were exercised over ranges of the predictors spanning approximately the ranges of stature and BMI by gender within the sample. To provide a visual reference for evaluating factor effects, a rendering of the torso skeleton from the THUMS 4 midsize-male human body model was scaled and aligned to the data based on the ASIS and suprasternale landmarks.

## III. Results

Figure 2 shows images of six participants with a range of BMI. Figure 3 shows the effects of gender (holding stature and BMI at mean values). As expected, the torso belt path is further forward relative to the skeleton for women, due to breast tissue. The lap belt placement is also higher for women. Figure 4 shows the effects of stature for men and women while holding BMI at mean values for the sample. Because BMI is held constant, body weight varies with stature. Shorter stature, at the same BMI, is associated with more torso adiposity and belt routing farther from the skeleton for both men and women. As expected, BMI is associated with torso belt routing further forward relative to the skeleton, but different patterns are observed for men and women (Figure 5). For women, increased BMI not only shifts the belt forward, but also results in the torso portion of the belt routing higher relative to the ribcage. For men, increased BMI results in a small shift upward in the torso belt, but a larger shift downward in the lap belt routing. Table A.1 and A.2 illustrates the distribution of the lap and shoulder belt scores for women and men. Lap belt fit was quantified by the fore-aft and vertical location (X, and Z, respectively) of the upper/rearward margin of the lap portion of the belt at the lateral location of the anterior-superior iliac spine (ASIS) landmarks on the left and right sides of the pelvis (LapBeltX and LapBeltZ). Shoulder belt fit was quantified by the lateral location of the inboard edge of the shoulder portion of the belt relative to the body midline at the height of the suprasternale landmarks. The Y-axis (lateral) distance between the body midline and belt is termed shoulder belt score. These measures were defined in accordance with previous belt fit studies [32-35].

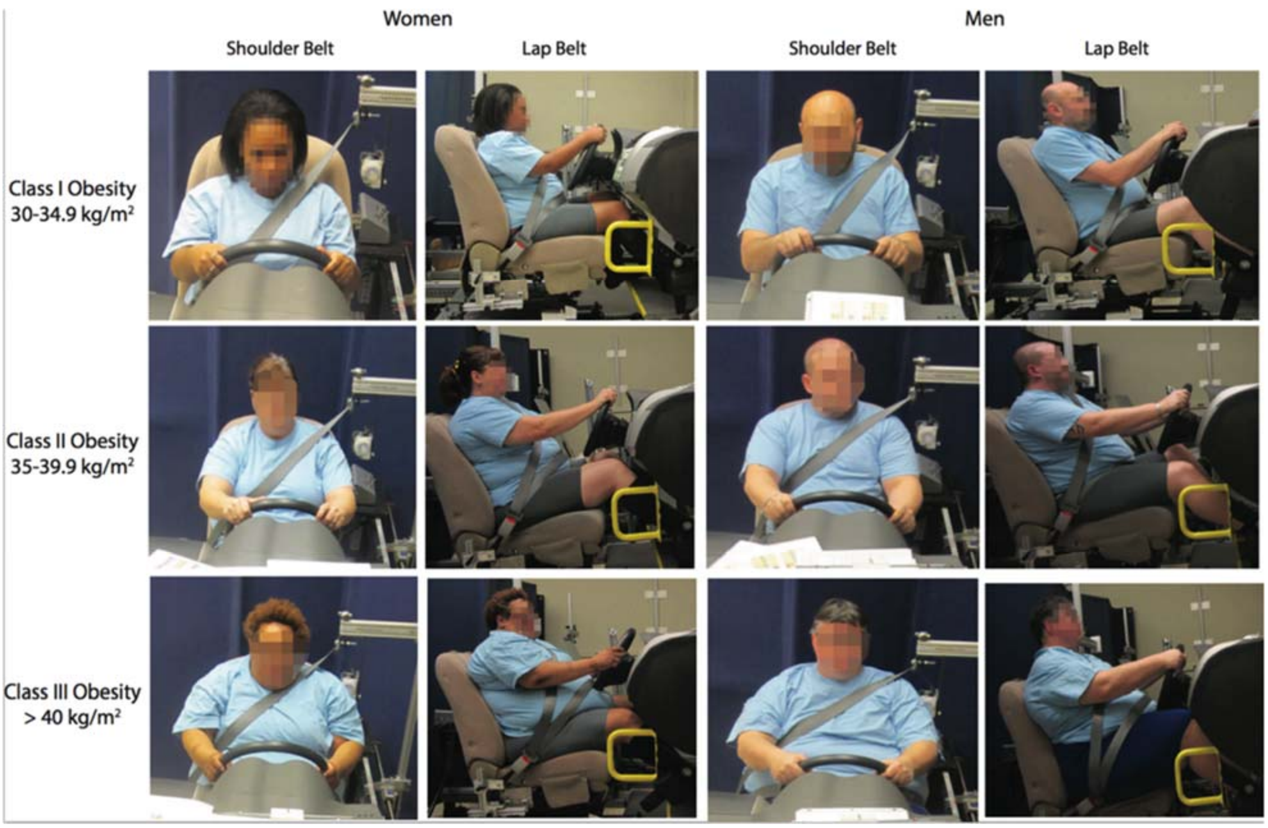



Figure 2. Photos showing torso and lap belt fit for a range of occupant sizes (stratified by BMI classification).

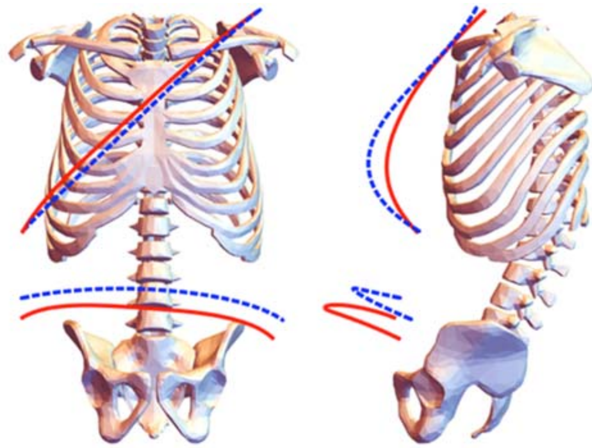
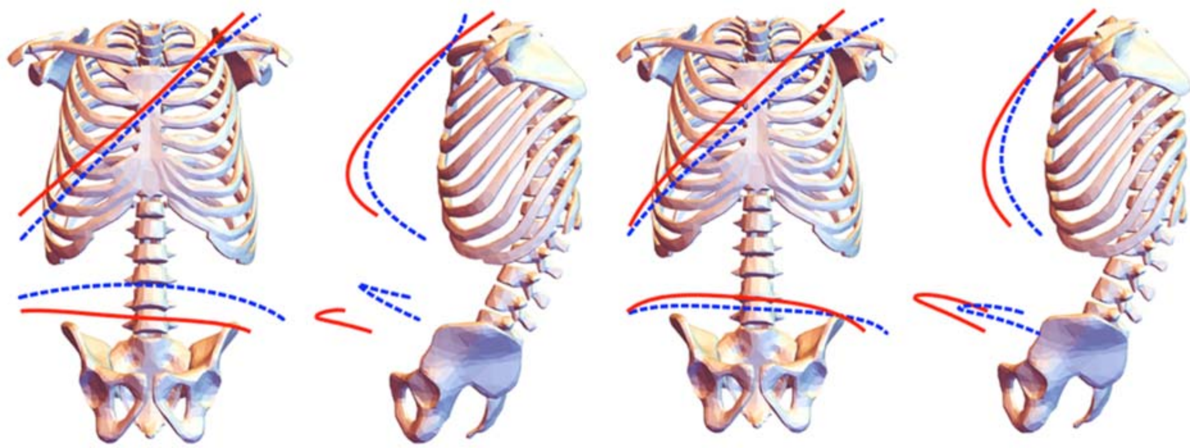
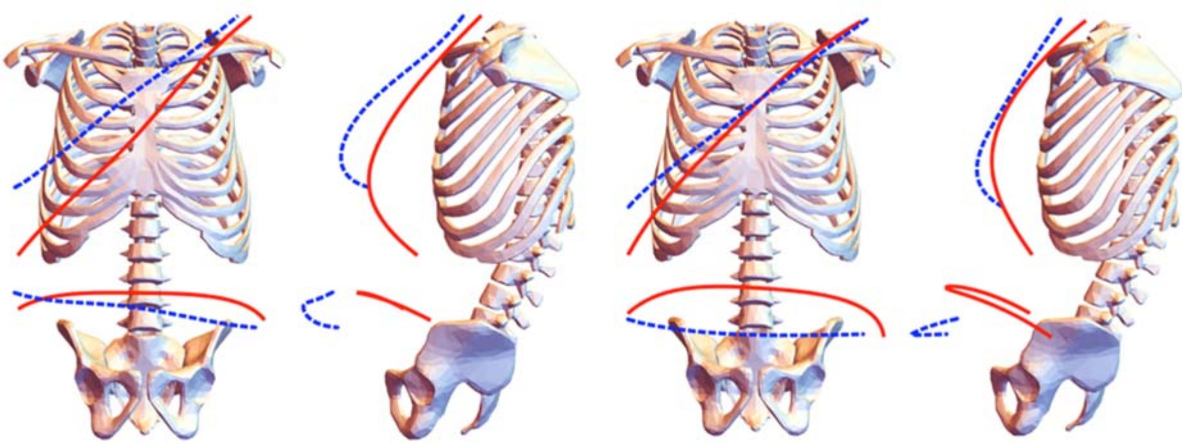


Figure 3. Mean belt paths for men (—) and women (--) with stature = 1700 mm and BMI= 40.5 kg/m$^2$ relative to scaled midsize-male skeleton.



Women Men

Figure 4. Mean belt paths for short (—, M=1600 mm, F=1500 mm) and tall (--, M=1870 mm, F=1750 mm) stature for men and women with BMI=40.5 kg/m$^2$ relative to scaled midsize-male skeleton.



Women Men

Figure 5. Mean belt paths for low (—, 30 kg/m$^2$) and high (--, 55 kg/m$^2$) BMI for men and women with mean stature (M=1630 mm, F=1750 mm) relative to scaled midsize-male skeleton.

## IV. Discussion

This paper is the first to conduct a parametric, 3D analysis of seat belt routing, and the first to address belt routing for individuals with high BMI. The mean BMI in this sample (40 kg/m$^2$) is approximately 95$^{th}$ percentile BMI for U.S. adults. The analysis methodology allows the 3D effects of driver attributes to be visualized relative to the skeleton. As expected, higher BMI was associated with belt routing further forward, relative to the skeleton, but the analysis showed different patterns for men and women. Of particular concern, the torso belt routing for women was elevated relative to the lateral ribcage and the lap belt moved higher into the abdomen region with increased BMI.

The results are broadly consistent with previous analyses of BMI effects on belt fit that used scalar measures [32-34], but this is the first to document the potentially large fore-aft gap between the belt and the sternum, and the extent to which breast tissue increases this gap for women.

The result of increased torso adiposity associated with high BMI is an increase in the offset between the belt and sternum, which effectively introduces slack into the restraint. This suggests considerable challenges for improving belt performance for drivers with high BMI. Pretensioners will reduce the flesh margins, but the lap belt placement may not enable the lap belt to engage with the bony pelvis, resulting in higher levels of lower-extremity and abdomen injuries. Similarly the torso belt routing along the lateral rib cage may also attribute to the increased chest injuries for individuals with high BMI.

This study is limited in a number of ways. The data were gathered in a laboratory setting following a short duration of sitting. Belt fit in a real vehicle could differ and belt donning behaviors in drivers' own vehicles might differ. A different vehicle seat could also have produced different postures and slightly different belt routing. Heavier clothing than the light garments used for testing might alter belt fit. Locating the pelvis is very challenging with this population. The current methods are an extension of the measurements and computation reported by Reed et al. [33]. In particular, the distance between the estimated hip and knee joint locations are evaluated to ensure that the estimated pelvis location is realistic. Although the pelvis flesh margin estimates may consequently have some unknown bias, the relative positions of the belt paths produced by the statistical modeling are likely to be accurate. The pelvis and rib cage representations in Figures 3-5 are based on a single midsize male, although they have been normalized in the same manner as the data. Consequently, the offsets from the belt paths to the ribcage should be viewed as approximate visualizations rather than necessarily quantitatively accurate.

## V. Conclusions

This study confirmed and extended previous findings regarding belt fit for individuals with high BMI. The data suggest a continued focus on improving restraint systems for individuals with high BMI is needed. The belt path models presented in this work will provide useful input for crash simulations using parametric finite-element human body models that can represent individuals with high BMI.

## VI. Acknowledgement

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## VIII. ANNEX

Table A.1. Distribution of the anthropometric dimensions, LapBelt X, LapBelt Z and Shoulder Belt scores for **women** (N=26).

| | | | | Percentiles | | | | |
|---|---|---|---|---|---|---|---|---|
| **Measurements** (mm unless noted) | **Min** | **Max** | **Mean** | **5th** | **25th** | **50th** | **75th** | **95th** |
| Age [years] | 21.5 | 68.5 | 47.4 | 22.1 | 33.0 | 49.0 | 62.6 | 68.4 |
| Stature | 1489.0 | 1781.0 | 1632.1 | 1497.8 | 1570.0 | 1630.5 | 1690.0 | 1773.3 |
| Erect Sitting Height | 794.0 | 923.0 | 857.8 | 794.5 | 823.8 | 861.0 | 892.0 | 920.8 |
| Weight | 72.1 | 147.6 | 104.0 | 73.7 | 88.0 | 99.0 | 119.2 | 144.5 |
| BMI [kg/m$^2$] | 31.3 | 55.3 | 38.9 | 31.5 | 32.9 | 38.2 | 42.8 | 53.6 |
| Lap Belt X | -153.9 | -14.4 | -75.7 | -152.0 | -102.0 | -78.0 | -41.9 | -15.5 |
| Lap Belt Z | 0.9 | 122.9 | 67.1 | 4.3 | 53.4 | 68.5 | 84.4 | 120.6 |
| Shoulder Belt Score (Y) | -111.8 | 0.5 | -57.6 | -108.3 | -74.4 | -57.2 | -33.9 | -4.8 |

Table A.2. Distribution of the anthropometric dimensions, LapBelt X, LapBelt Z and Shoulder Belt scores for **men** (N=26).

| | | | | Percentiles | | | | |
|---|---|---|---|---|---|---|---|---|
| **Measurements** (mm unless noted) | **Min** | **Max** | **Mean** | **5th** | **25th** | **50th** | **75th** | **95th** |
| Age [years] | 21.8 | 72.8 | 48.3 | 23.5 | 39.2 | 47.7 | 60.6 | 72.2 |
| Stature | 1558.0 | 1890.0 | 1759.3 | 1590.4 | 1711.0 | 1736.0 | 1826.0 | 1882.0 |
| Erect Sitting Height | 789.0 | 992.0 | 918.4 | 812.6 | 883.0 | 922.0 | 960.0 | 987.2 |
| Weight | 91.3 | 198.0 | 124.4 | 91.4 | 108.0 | 112.6 | 150.8 | 186.4 |
| BMI [kg/m$^2$] | 31.5 | 58.6 | 40.1 | 31.8 | 33.1 | 37.4 | 46.6 | 58.5 |
| Lap Belt X | -273.4 | -18.4 | -104.2 | -263.4 | -119.0 | -92.3 | -71.5 | -20.5 |
| Lap Belt Z | 19.0 | 106.4 | 54.5 | 22.8 | 40.5 | 51.0 | 66.4 | 96.0 |
| Shoulder Belt Score (Y) | -130.5 | -18.9 | -62.4 | -127.1 | -85.6 | -56.1 | -36.7 | -21.2 |