Analysis of Morphomics Parameters by Gender and BMI Groups: Thorax Shape and H-point Location

Chantal S. Parenteau, Peng Zhang, Sven Holcombe, Carla Kohoyda-Inglis, Stewart C. Wang

Abstract The automotive safety community is questioning the effect of obesity on the performance and assessment of occupant protection systems. This study analyzed CT scan measurements of 10,952 individuals older than 15 years by Body Mass Index (BMI) and gender, including the H-point location defined relative longitudinal distance between the centroid of the femoral head and the most posterior skin measurement, vertebra-to-front-skin distance, and spine-to-back-skin distance along the sagittal plane. The distance data was obtained at each vertebra level.

The average H-point location increased with BMI and varied with gender. A regression analysis was fitted on the data. For females, it was equal to 55.90 +2.47*BMI in the normal size group, 86.25+1.30*BMI in the obese group, and 116.25+0.55*BMI mm in the morbidly obese group ($p<0.01$). For males the corresponding H-point was 64.12+2.11*BMI, 77.28+1.62*BMI, and 95.13+1.17*BMI mm ($p<0.01$). The vertebra-to-front skin and spine-to-back skin distances also increased with BMI and differed with gender.

With the increasing worldwide concern for obese occupant protection, test devices representative of this segment of the population are necessary. Human math models provide the best option for a parametric analysis of protection systems designed and optimized for various BMI and gender groups. The morphomic data was analyzed to represent a 5th percentile female and 50th percentile male dummy. These results will be useful in the modifications of the current human mathematical models to represent obese occupants.

Keywords BMI, H-point, Injury, Obesity, Torso Depth.

I. INTRODUCTION

Concern for increasing obesity rates has gained international interest since obesity will soon become the world's biggest health problem. [1] In the United Sates, obesity is considered an epidemic. More than one-third of adults and about 17% of children and adolescents are obese. [2] Obesity is associated with higher health risks such as Type 2 diabetes, heart disease, and high blood pressure. Consequently, obesity-related medical costs are also increasing.

Obesity influences risks of serious and fatal injury in motor vehicle crashes. Various studies have found that obese occupants were more at risk of fatal injuries in vehicle crashes [3-5]. Viano, Parenteau [5] and Lichtenstein et al. [6] showed that morbidly obese occupants were less likely to wear their seatbelts. Reed et al. [7] reported an increase in seatbelt webbing length with BMI increase. They reported that lap belt webbing length increased by 13 cm for each 10 kg/m^2 increase in BMI. Lack of seatbelt use or increase in belt webbing may explain the higher injury risks in obese occupants. Forman et al. [8] tested belted obese and normal size post mortem human subjects (PHMS) in 48 km/h frontal sled tests. The authors reported an increase in forward excursion with the obese PMHS.

Wang et al. and Wang [9-10] found lower risk for abdominal injuries in obese occupants when compared to normal size occupants. Zhu et al. [11] reported that obese men had higher risk of serious injury to the upper body regions than normal size men. They attributed the differences in injury patterns to differences in body shape, fat distribution, and center of gravity between obese and normal size occupants.

In this study, selected morphomic variables obtained from imaging measurements were analyzed to help characterize changes associated with BMI. The morphomics variables included torso shape and hip-point location. These changes were believed to be associated with differences in injury loading patterns between normal size and obese occupants.

Chantal Parenteau, Ph.D, Peng Zhang Ph.D., Sven Holcombe, Carla Kohoyda-Inglis, Stewart Wang, MD, Ph.D.. International Center for Automotive Medicine, University of Michigan, USA, parentea@med.umich.edu, ph: (734) 764-4380, fax: (734) 764-7173,

II. METHODS

CT scans

Standard medical computed tomography (CT) scans were used. CTs were obtained from University of Michigan trauma department patients admitted between 1995 and 2012. Only patients 16 years or over were included. The study was approved by the Institutional Review Board (IRB) at the University of Michigan (HUM00041441).

Software

CT scans were processed semi-automatically using custom algorithms written in MATLAB (The Math Works, Natick, MA). The methodology was discussed in Parenteau et al. [12]

CT scan measurements

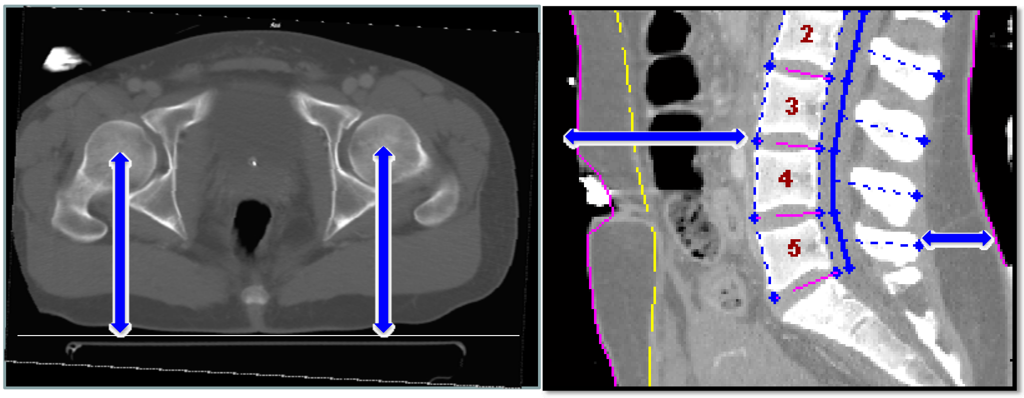


Fig 1. CT scan measurements including H-point (center of femoral head), vertebra-to-front skin and spine-to-back skin distance

CT measurements: Determined at each vertebra level using an automated process (see Parenteau et al. 2013 for methodology). The measurements consisted of:

- H-point: The H-point was determined as the relative longitudinal distance between the centroid of the femoral head and the most posterior skin measurement. The data was calculated for both left and right H-points. The H–point measurement provided herein is the average of the two measurements. Vertical distance was not assessed since there was no reference point.
- Depth measurements: Two body depth measurements were assessed and are shown in Figure 1:
  - o Vertebra-to-front skin: Distance between the front of vertebral body to front of the skin. Measurements are given in mm.
  - o Spine-to-back skin: Distance between the posterior tip of spine to the back skin. This measurement is representative of the fat and other tissues in the back area and is given in mm.

Data analysis

The data was analyzed by gender groups (males, females) and by BMI groups. For each patient, the BMI was calculated by dividing their mass in kilograms by the square of their height in meters. Patients with normal BMI were in the range of BMI = 18.5–<25.0 kg/m^2, patients who were overweight had a BMI = 25.0–<30.0 kg/m^2, and patients who were obese had BMI 30-<40 kg/m^2 (CDC, 2012). Morbidly obese patients had a BMI 40-<60 kg/m^2 , and underweight patients, a BMI 13.5- <18.5 kg/m^2 .

Data at the L1 level was used to provide an overall comparison between various age groups. L1 was chosen as it appeared in the largest number of scans. Measurements taken at L1 are representative of an abdominal level. Regression analysis was carried out to assess the relationship between a CT scan measurements and BMI and gender. Box plots were also used to graphically represent the measurements as a function of BMI groups.

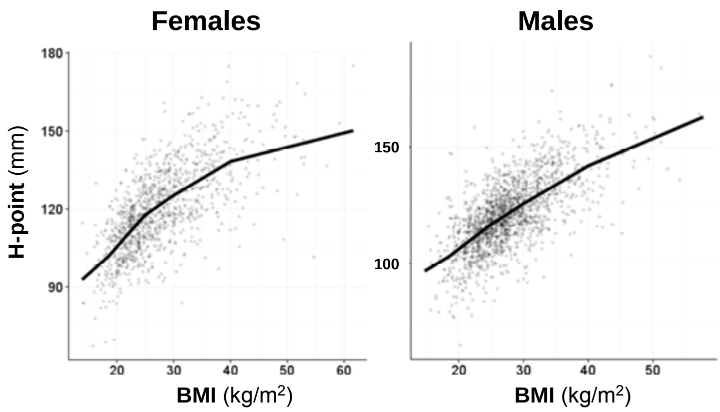
III. RESULTS

H-point

Table I summarizes the H-point location relative to the most posterior point in the sagittal plane. The data is tabulated by BMI and gender groups. There were 10,952 CT scans available for review, 2,919 had both H-point and BMI information available. The data indicated that H-point distance increased with BMI for all patients. The H-point was 101.8 ± 15.6 mm in underweight patients, 111.2 ± 10.9 in normal size patients, and 131.1 ± 12.9 in obese patients. Similar trends were observed in males and females. Except for the underweight and the morbidly obese group, males and females generally had similar H-point distances. A regression analysis was fitted through the data. Figure 2 shows the scatter plots with fitted regression lines for males and females. The results indicated that the H-point varied with BMI and gender. For females, the H-point was equal to 65.71+1.94*BMI in the underweight group, 55.90 +2.47*BMI in the normal size group, 79.65 +1.52*BMI in the overweight group, 86.25+ 1.30*BMI in the obese group, and 116.25 +0.55*BMI mm in the morbidly obese group (R^2 = 0.4794, p<0.01). For males the corresponding H-point was 72.28+1.67*BMI, 64.12+2.11*BMI, 71.94+1.79*BMI, 77.28+1.62*BMI, and 95.13+1.17*BMI mm (R^2 =0.4655, p<0.01).

Table I
H-point distance (mm) in the sagittal plane by BMI and gender.

BMI groups		All	Females	Males
		H-point distance (mm)		
Under	avg	101.8	100.5	103.9
	sd	15.6	15.8	15.3
	n	92	55	37
Normal	avg	111.2	110.9	111.4
	sd	10.9	10.6	11.2
	n	1016	449	567
Over	avg	121.2	121.3	121.2
	sd	10.3	11.3	9.9
	n	974	302	672
Obese	avg	131.1	130.3	131.5
	sd	12.9	13.6	12.5
	n	705	272	433
Morbid	avg	143.6	140.5	146.6
	sd	16.0	15.8	15.8
	n	132	65	67



	$H\text{-point}_{female}$ =	$H\text{-point}_{male}$ =
If 13.5 ≤BMI<18.5	65.79 + 1.94*BMI	72.28 + 1.67*BMI
If 18.5 ≤ BMI<25	55.99 + 2.47*BMI	64.12 + 2.11*BMI
If 25 ≤ BMI<30	79.55 + 1.52*BMI	71.94 + 1.79*BMI
If 30 ≤ BMI<40	86.26 + 1.30*BMI	77.29 + 1.62*BMI
If 40 ≤ BMI<65	116.21 + 0.55*BMI	95.13 + 1.17*BMI
	R^2: 0.4794	R^2: 0.4655
	P-value <0.0001	P-value <0.0001

Fig 2. Scatter plot of H-point location as a function of BMI in males and females with linear regression.

Vertebra-to-front-skin

Table II
Vertebra to front skin distance (mm) along the sagittal plane by vertebra level, BMI and gender.

		Lower Thoracic Spine							**Lumbar Spine**				
		T6	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**	**L1**	**L2**	**L3**	**L4**	**L5**
		Vertebra-to-Front Skin Distance (mm)											
All	avg	147.3	154.3	158.8	161.3	162.0	160.4	156.1	148.9	139.4	129.3	124.9	132.0
	sd	26.7	27.8	28.8	30.0	30.9	31.6	32.9	34.8	36.5	38.0	37.2	36.3
	n	4,393	5,090	6,339	8,218	9,823	10,611	10,952	10,832	10,673	10,567	9,807	8,269
Under	avg	117.5	124.3	125.5	126.3	126.9	123.6	117.2	109.0	98.4	87.9	85.1	93.1
	sd	23.2	24.3	24.7	24.7	25.3	25.0	27.0	28.6	30.4	30.8	29.6	24.2
	n	57	61	66	83	103	117	126	126	124	123	120	102
Normal	avg	128.2	133.5	136.6	138.6	139.1	137.0	131.3	122.5	111.7	100.3	97.2	104.8
	sd	20.8	21.3	21.5	23.1	23.7	23.7	24.1	25.3	26.7	27.5	26.3	24.6
	n	693	729	822	1,026	1,251	1,371	1,431	1,430	1,410	1,405	1,357	1,156
Over	avg	145.9	152.8	156.4	159.9	161.6	160.3	155.3	147.4	137.5	126.7	122.2	128.5
	sd	22.0	22.5	23.2	23.7	24.2	24.9	25.9	27.5	29.0	30.0	28.6	27.0
	n	692	763	885	1,105	1,272	1,356	1,389	1,379	1,368	1,362	1,262	1,055
Obese	avg	163.2	169.9	173.8	178.0	180.1	179.7	176.6	170.6	162.3	153.4	148.8	156.1
	sd	23.1	23.6	24.9	25.7	26.3	27.1	28.5	30.1	31.4	32.5	31.5	30.2
	n	528	620	768	921	1,018	1,067	1,084	1,064	1,059	1,062	993	849
Morbid	avg	182.5	190.3	195.1	198.1	200.2	200.3	198.2	192.8	185.7	179.4	176.3	181.8
	sd	26.0	27.7	28.7	29.3	29.1	29.8	31.3	33.7	34.7	35.7	36.5	34.4
	n	131	151	187	206	223	230	232	225	224	226	218	190
		Vertebra-to-Front Skin Distance (mm) in Females											
All	avg	138.7	145.0	148.8	150.0	149.9	148.2	144.5	138.0	129.2	120.2	118.6	129.5
	sd	23.9	24.6	25.5	26.5	27.5	28.5	30.2	32.3	34.3	36.1	36.2	36.0
	n	1,757	2,052	2,623	3,391	4,077	4,437	4,590	4,552	4,487	4,457	4,236	3,589
Under	avg	110.1	116.2	117.7	118.6	119.4	115.6	108.5	100.1	89.9	80.8	80.8	92.0
	sd	22.3	23.1	23.4	22.6	23.8	21.9	23.3	24.4	26.0	26.4	25.9	24.5
	n	32	34	36	47	59	71	77	77	76	76	74	62
Normal	avg	120.2	125.1	128.2	129.0	128.6	126.8	121.5	113.6	103.7	93.4	92.5	104.1
	sd	17.3	17.3	17.5	18.2	18.5	18.8	19.5	21.0	22.6	23.9	24.2	24.1
	n	291	306	354	443	552	617	648	656	649	648	633	530
Over	avg	135.0	140.8	143.8	146.0	147.2	145.7	141.8	134.8	125.5	115.5	113.6	124.8
	sd	18.6	18.5	19.1	19.4	20.0	20.4	21.5	23.1	25.2	26.6	26.6	26.5
	n	205	224	267	337	407	441	462	462	457	456	417	337
Obese	avg	151.2	156.4	159.6	162.9	165.3	165.3	162.6	157.4	149.4	141.2	139.6	150.8
	sd	17.6	18.3	19.4	20.4	21.2	22.2	23.3	25.4	26.9	28.3	28.4	27.2
	n	179	216	285	350	396	422	431	427	424	426	399	336
Morbid	avg	169.6	176.7	181.1	184.1	187.1	188.2	186.9	182.0	176.3	171.6	169.9	178.0
	sd	19.4	21.9	23.1	23.5	24.2	25.5	27.9	31.0	32.7	34.4	36.3	33.4
	n	65	78	99	113	124	128	128	125	125	127	121	107
		Vertebra-to-Front Skin Distance (mm) in Males											
All	avg	153.0	160.6	165.9	169.2	170.7	169.2	164.5	156.7	146.8	136.0	129.8	133.9
	sd	27.0	28.0	28.9	29.8	30.3	30.8	32.3	34.4	36.3	37.9	37.2	36.5
	n	2,636	3,038	3,716	4,827	5,746	6,174	6,362	6,280	6,186	6,110	5,571	4,680
Under	avg	126.8	134.3	135.0	136.4	136.9	136.0	130.9	122.9	111.8	99.5	92.0	94.8
	sd	21.2	22.4	23.3	23.9	24.1	24.7	26.9	29.4	32.3	33.9	34.0	24.0
	n	25	27	30	36	44	46	49	49	48	47	46	40
Normal	avg	134.0	139.7	142.9	145.9	147.4	145.4	139.3	130.0	118.6	106.3	101.3	105.5
	sd	21.3	21.8	22.2	23.8	24.1	24.0	24.6	26.2	28.0	29.0	27.4	25.1
	n	402	423	468	583	699	754	783	774	761	757	724	626
Over	avg	150.4	157.7	161.9	166.0	168.4	167.3	162.1	153.8	143.5	132.3	126.4	130.2
	sd	21.7	22.1	22.7	22.8	23.0	23.8	25.3	27.4	28.9	30.0	28.6	27.1
	n	487	539	618	768	865	915	927	917	911	906	845	718
Obese	avg	169.4	177.0	182.2	187.2	189.5	189.1	185.9	179.4	170.8	161.5	154.9	159.6
	sd	23.2	23.0	23.9	24.3	24.8	26.0	27.8	29.7	31.3	32.5	32.0	31.5
	n	349	404	483	571	622	645	653	637	635	636	594	513
Morbid	avg	195.3	204.8	210.8	215.2	216.5	215.5	212.1	206.1	197.6	189.4	184.2	186.7
	sd	25.4	26.0	26.2	26.5	26.5	27.9	29.8	32.2	33.7	35.0	35.4	35.2
	n	66	73	88	93	99	102	104	100	99	99	97	83

Table II summarizes the vertebra-to-front skin distance by BMI group and gender. The distance increased with BMI groups. It was 109.0 ± 28.6 mm at L1 in the underweight group, 122.5 ± 25.3 mm in the normal size group, 147.4 ± 27.5 mm in the overweight group, 170.6 ± 30.1 mm in the obese group, and 192.8 ± 33.7 mm in the morbidly obese group.

Figure 3 shows the vertebra-to-front skin distance in females and males by BMI group. The distance was consistently larger in males than in females, irrespective of vertebra level and increased as BMI increased. In males, the ratio of obese and normal size distances increased continuously from T6 to L5 ranging from 1.26 at T6 to 1.53 at L5. Similarly, the ratio increased from 1.25 at T7 to 1.51 at L5 in females.

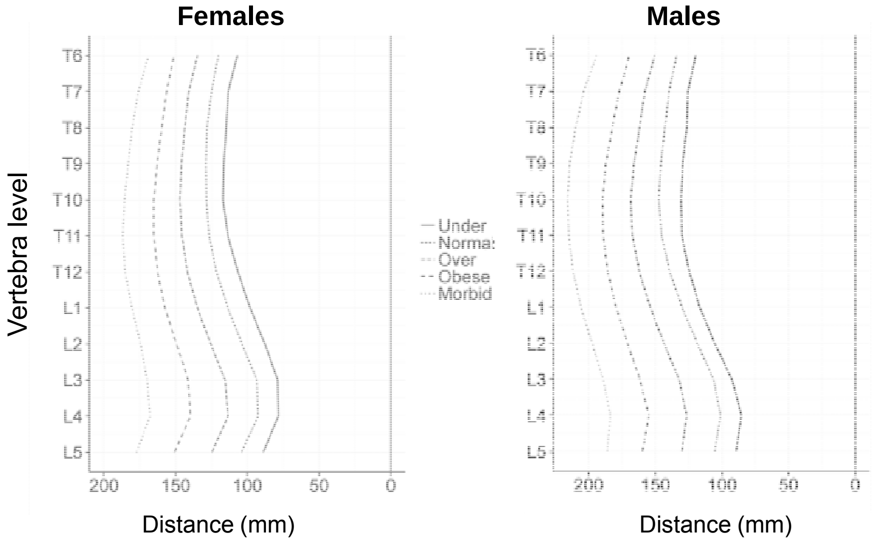
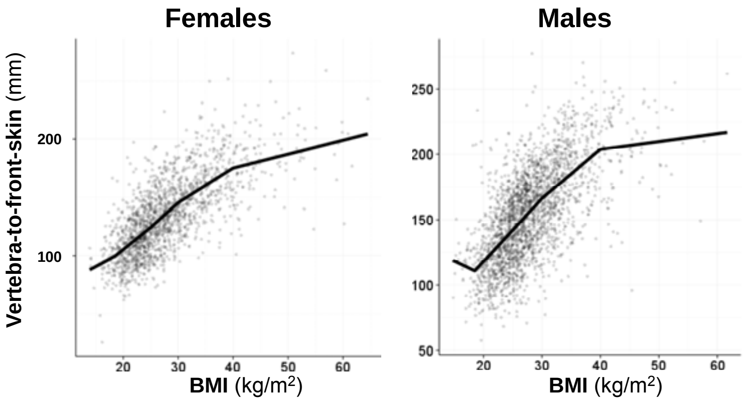


Fig. 3. Vertebra-to-front skin along the sagittal plane by gender and BMI groups.

Figure 4 shows the scatter plots of vertebra-to-front skin distance taken at L1 in female and male patients by BMI. It shows the consistent increase in distance with BMI in females. A regression analysis was conducted for each BMI group. The vertebra-to-front skin distance in females was 52.72.06+2.54*BMI in the underweight, 29.19+3.81*BMI in the normal size, 19.62+4.19*BMI in the overweight, 56.66+2.96*BMI in the obese, and 127.06+1.20*BMI mm in the morbidly obese group (R^2 = 0.5263, p<0.01). The corresponding distance for males was 150.23-2.31*BMI, 22.26+ 4.79*BMI, 18.94+4.92*BMI, 54.80+3.73*BMI, and 179.92+0.60*BMI mm in males (R^2 =0.438, p<0.01).



	$\text{VB-front-skin}_{female}$ =	$\text{VB-front-skin}_{male}$ =
If 13.5 ≤ BMI<18.5	52.72 + 2.54*BMI	150.23 – 2.13*BMI
If 18.5 ≤ BMI<25	29.19 + 3.81*BMI	22.26 + 4.79*BMI
If 25 ≤ BMI<30	19.62 + 4.19*BMI	18.94 + 4.92*BMI
If 30 ≤ BMI<40	56.66 + 2.96*BMI	54.90 + 3.73*BMI
If 40 ≤ BMI<65	127.06 + 1.20*BMI	179.92 + 0.60*BMI
	R^2: 0.5263	R^2: 0.438
	P-value <0.0001	P-value <0.0001

Fig 4. Scatter plot of vertebra-to-front skin at L1 as a function of BMI in females and males with linear regression.

Spine-to-back-skin

Table III
Spine to back skin distance along the sagittal plane by vertebra level, BMI and gender.

		Lower Thoracic Spine							Lumbar Spine				
		T6	T7	T8	T9	T10	T11	T12	L1	L2	L3	L4	L5
		Spine-to-Back Skin Distance (mm)											
All	avg	25.3	24.5	24.0	23.6	23.7	24.9	24.4	23.2	25.0	30.8	37.6	41.3
	sd	10.8	11.2	11.6	12.0	12.6	13.8	14.5	14.6	15.8	18.3	19.3	18.9
	n	1,613	1,866	2,219	2,542	2,644	2,664	2,663	2,632	2,609	2,601	2,563	2,438
Under	avg	14.5	13.5	13.4	12.4	11.5	11.7	11.6	11.6	12.6	15.4	19.7	23.4
	sd	8.3	7.8	7.5	8.6	9.2	9.7	10.0	10.1	10.9	12.6	13.1	13.1
	n	42	42	48	60	66	68	68	68	68	68	67	68
Normal	avg	19.5	18.3	17.7	17.4	17.2	17.7	16.9	16.0	17.2	21.4	27.4	31.5
	sd	7.0	6.3	6.5	6.4	6.7	7.5	8.2	8.4	9.1	10.4	11.6	12.1
	n	440	471	529	586	601	604	607	604	601	602	602	600
Over	avg	24.4	23.4	23.1	23.4	24.0	25.3	24.5	22.6	24.0	29.4	36.6	41.1
	sd	6.6	6.7	6.7	6.8	7.2	8.1	9.2	9.6	10.6	12.2	13.2	13.3
	n	410	450	498	524	527	526	528	528	527	529	528	513
Obese	avg	32.0	30.9	31.7	32.7	33.9	36.3	35.9	33.7	35.7	43.6	51.8	55.6
	sd	9.7	9.7	10.6	10.5	10.6	11.8	12.7	13.1	14.3	16.6	16.9	15.4
	n	320	348	369	380	379	380	377	377	376	376	376	371
Morbid	avg	45.9	45.8	47.3	49.9	52.3	55.8	57.5	56.4	60.6	73.6	81.6	82.8
	sd	14.5	15.1	16.0	15.9	16.7	18.3	19.5	19.2	18.5	20.7	20.4	21.3
	n	74	83	85	86	86	87	84	82	82	82	82	82
		Spine-to-Back Skin Distance (mm) in Females											
All	avg	24.276	23.947	23.856	23.615	23.889	25.169	24.968	24.183	27.083	34.505	41.912	45.337
	sd	11.867	12.331	13.105	13.468	14.069	15.218	15.917	15.804	17.335	19.947	20.283	19.332
	n	615	724	872	1,024	1,065	1,074	1,070	1,062	1,058	1,058	1,054	1,030
Under	avg	11.9	11.2	11.6	11.7	11.1	11.4	11.4	11.6	12.3	15.2	19.6	23.3
	sd	5.0	4.7	4.9	8.0	8.9	9.2	9.8	10.0	10.2	11.4	11.7	10.6
	n	25	25	28	36	39	41	41	41	41	41	40	41
Normal	avg	18.2	17.4	16.9	16.8	17.1	17.7	17.1	16.6	18.4	23.9	30.9	35.7
	sd	6.5	6.2	6.4	6.6	7.2	8.0	8.8	8.9	9.5	11.1	12.6	12.8
	n	190	206	239	275	278	278	280	278	277	277	278	278
Over	avg	7.4	7.6	7.4	7.4	8.1	8.8	10.4	11.1	12.2	13.9	13.8	12.9
	sd	23.5	22.6	22.6	22.8	23.5	25.1	25.3	24.4	27.3	35.3	44.4	48.8
	n	115	129	146	157	160	161	161	161	161	161	161	154
Obese	avg	30.6	30.0	32.1	33.3	34.3	36.9	36.9	34.3	37.3	48.2	57.3	59.6
	sd	11.7	11.3	12.6	12.0	11.7	12.5	13.1	13.6	15.1	17.8	16.9	15.0
	n	113	131	143	150	150	150	150	150	150	150	149	147
Morbid	avg	43.8	43.1	45.1	48.0	50.4	53.3	54.3	53.2	60.0	73.1	79.9	80.4
	sd	15.2	15.0	16.1	16.1	17.0	19.0	20.8	20.9	20.1	20.4	19.7	21.3
	n	44	51	52	53	52	53	50	48	48	48	48	48
		Spine-to-Back Skin Distance (mm) in Males											
All	avg	25.9	24.8	24.1	23.7	23.6	24.7	24.0	22.5	23.7	28.3	34.5	38.4
	sd	10.1	10.4	10.5	10.9	11.5	12.7	13.4	13.7	14.4	16.7	17.9	18.0
	n	998	1,142	1,347	1,518	1,579	1,590	1,593	1,570	1,551	1,543	1,509	1,408
Under	avg	18.3	16.9	15.9	13.6	12.1	12.1	12.0	11.5	13.0	15.7	19.9	23.6
	sd	10.7	10.1	9.7	9.5	9.8	10.6	10.6	10.4	12.1	14.5	15.2	16.5
	n	17	17	20	24	27	27	27	27	27	27	27	27
Normal	avg	20.5	19.0	18.4	17.9	17.3	17.6	16.8	15.4	16.2	19.2	24.4	27.9
	sd	7.2	6.4	6.4	6.2	6.2	7.0	7.5	8.0	8.6	9.3	9.7	10.2
	n	250	265	290	311	323	326	327	326	324	325	324	322
Over	avg	24.8	23.8	23.3	23.7	24.2	25.3	24.2	21.8	22.5	26.8	33.2	37.8
	sd	6.2	6.3	6.3	6.6	6.7	7.8	8.6	8.8	9.4	10.5	11.4	12.0
	n	295	321	352	367	367	365	367	367	366	368	367	359
Obese	avg	32.7	31.5	31.5	32.4	33.7	35.9	35.2	33.4	34.6	40.6	48.3	53.0
	sd	8.4	8.5	9.1	9.5	9.9	11.2	12.3	12.8	13.7	15.1	15.9	15.2
	n	207	217	226	230	229	230	227	227	226	226	227	224
Morbid	avg	49.0	49.9	50.8	52.9	55.2	59.8	62.2	61.0	61.3	74.3	84.0	86.1
	sd	12.9	14.6	15.5	15.3	16.1	16.6	16.7	15.8	16.3	21.3	21.3	21.3
	n	30	32	33	33	34	34	34	34	34	34	34	34

Table III shows the results for the spine to back skin measurements from T6 to L5 by BMI groups and gender. The spine to back skin distance was largest at L5 at 41.3 ± 18.9 mm. The distances increased with BMI groups. It was 11.6. ± 10.1 mm at L1 in the underweight group, 16.0 ± 8.4 mm in the normal size group, 22.6 ± 9.6 mm in the overweight group, 33.7 ± 13.1 mm in the obese group, and 56.4 ± 19.2 mm in the morbidly obese group.

Figure 5 shows a breakdown of spine to back skin distance by vertebral levels and gender in the normal and obese groups. The figure shows a significant (p<0.01) increase in distance at all vertebral levels (T6 to L5) for both males and females in the obese group compared to the normal group. Normal size females had a larger distance at L1 than normal size males. The L1 distance was however similar in the obese male and female group. The increase in L1 distance from the normal to the obese group was thus more significant in males than in females.

Figure 6 shows the scatter plots of spine-to-back skin distance taken at L1 by gender and BMI. There was an increase in distance with BMI in females and in male. The regression analysis shows that the increase was most significant in the overweight and obese groups for both genders. The increase was more significant in males than in females. The regression analysis is shown in Figure 6.

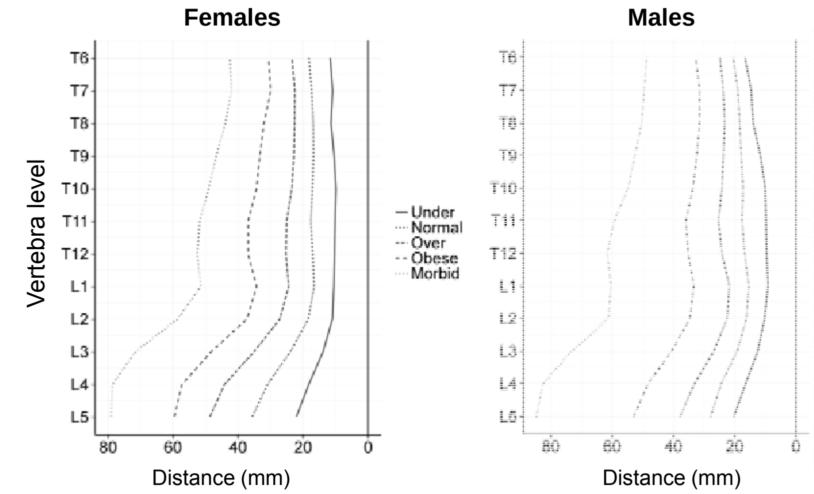
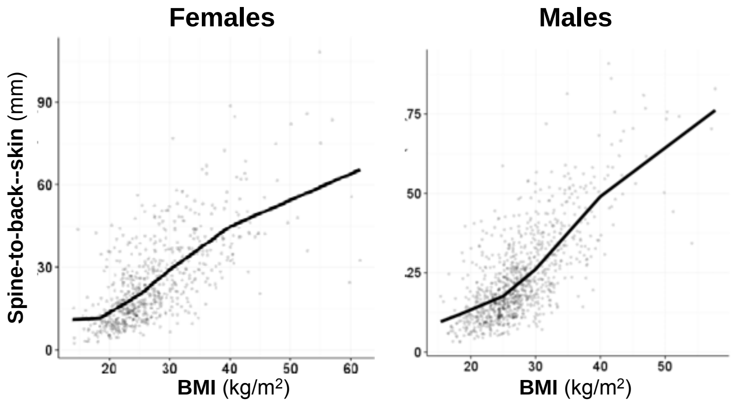


Fig. 5. Spine-to-back skin along the sagittal plane by gender and BMI groups.



	Spine-back-skin$_{female}$ =	Spine-back-skin$_{male}$ =
If 13.5≤BMI<18.5	9.57 + 0.11*BMI	-2.51 + 0.79*BMI
If 18.5≤ BMI<25	-12.77 + 1.31*BMI	-3.82 + 0.86*BMI
If 25 ≤BMI<30	-24.99 + 1.80*BMI	-24.73 + 1.69*BMI
If 30 ≤BMI<40	6.44 + 1.57*BMI	-42.70 + 2.29*BMI
If 40 ≤BMI<65	-2.51 + 0.79*BMI	-12.29 + 1.53*BMI
	R^2: 0.5263	R^2: 0.5373
	P-value <0.0001	P-value <0.0001

Fig 6. Scatter plot of spine-to-back skin as a function of BMI in males and females with linear regression.

Overall Analysis

Figure 7 shows the box plots for the vertebra-to-front-skin distance, spine to back-skin distance, and H-point distance at L1 as a function of BMI groups in females and Figure 8, in males. The band in the middle of the box represents the median (50th percentile). There was a steady increase in the all three distances from the underweight group to the morbidly obese group. BMI was a bigger moderator in the spine to back skin distance.

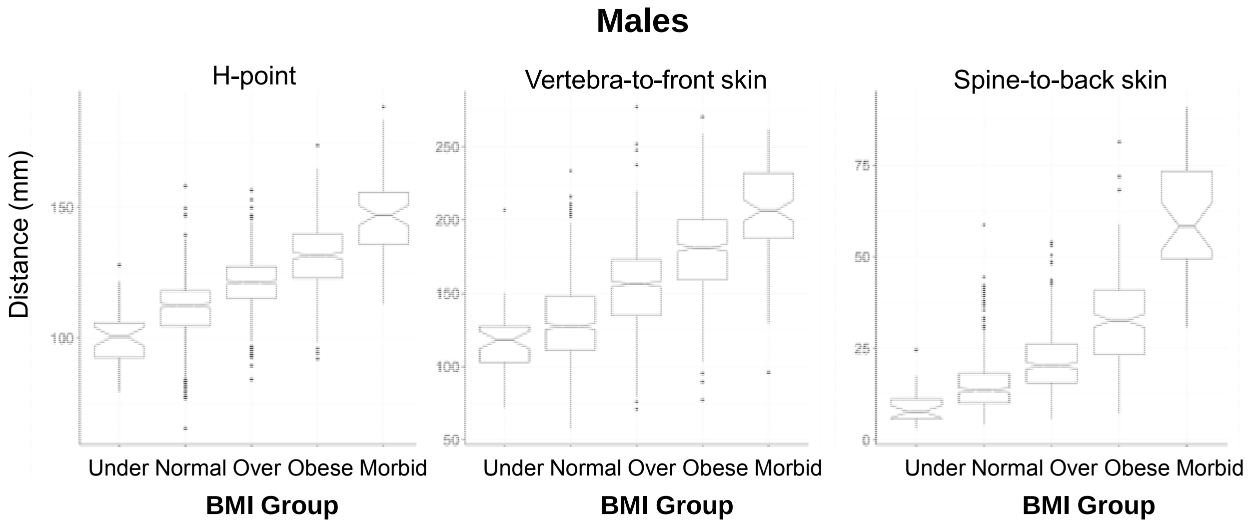


Fig. 7. Boxplots of H-point, vertebra-to-front skin, and spine-to-back skin at L1 as a function of BMI groups in males.

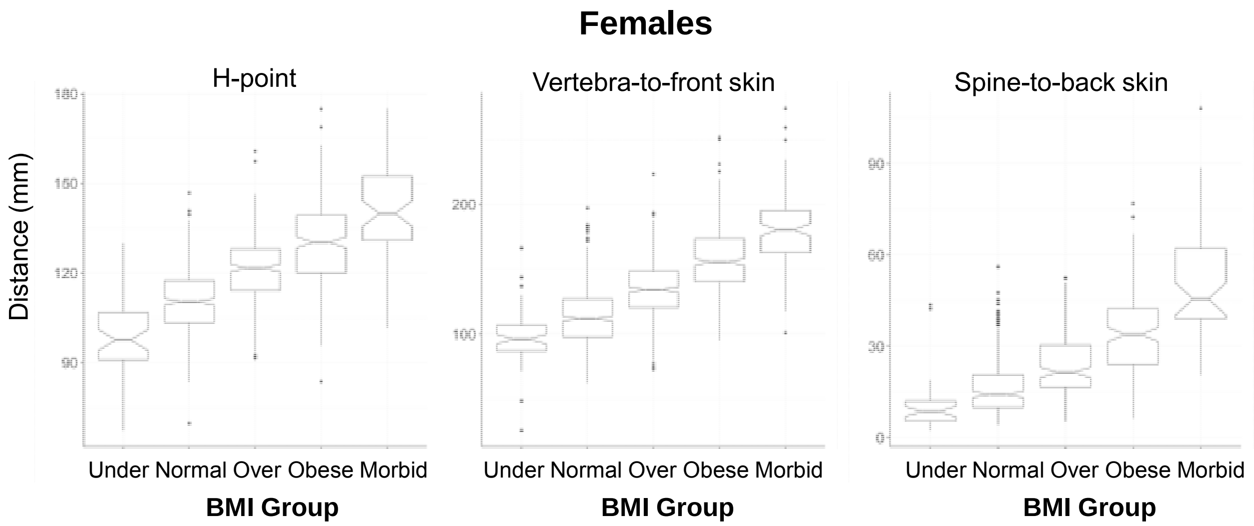


Fig. 8. Boxplots of H-point, vertebra-to-front skin, and spine-to-back skin at L1 as a function of BMI groups in females.

IV. DISCUSSION

There is considerable literature on increased injury risks to obese occupants. Most papers have focused on assessing obese occupant injury risk by body regions [10-11], kinematics in frontal sled tests, [8, 11] and posture. [7] In this study, the effect of obese occupant shape was addressed with respect to anatomical landmarks and torso shape.

The H-point was defined as the distance between the most posterior point on the patient's back and the center of the femoral head. The data was obtained on patients scanned in a supine position and not in a seated posture. As a result, the H-point results assessed in this study are only representative of the longitudinal distance. The effect of posture and H-point location merit additional research. For automotive engineers, the H-point is a reference measurement with respect to a vehicle seat. It is representative of the hip joint of an occupant and is usually measured with the SAE J826 H-point manikin. The H-point can vary depending on the seat longitudinal (for/aft) and vertical (up/down) positions. It also varies with cushion and seatback angles. The H-points generally differ by vehicle make and model and are representative of one particular seat configuration.

The results from Forman et al. [8] indicated a more forward H-point location in obese PMHS than in normal size PMHS. These results are consistent with those obtained in this study. The H-point was 18% greater in the obese group than in normal size group and 29% greater in the morbidly obese group. The spine-to-back-skin distance also increased with BMI. Compared to the normal size group, the distance at L1 was 2.11-times greater in the obese group and 3.54-times in the morbidly obese group. The increase in H-point and spine-to-back-skin distances with BMI is concerning, since it will lead to decrease ride-down distance on the seat cushion in frontal impacts. In rear impacts, it can lead to increase gap between the seatback and boney structure engagement.

The vertebra-to-front skin distance increased with BMI. It was 39% greater in the obese group and 57% larger in the morbidly obese group than in normal size group at L1. The increase in frontal torso shape can lead to increases in webbing length and to decrease gap for airbag deployment in frontal impacts. For example, the deployment logic for driver frontal airbag deployment is based on multiple factors including the crash severity and on the estimated distance between the occupant and the steering wheel. The timing must be fast enough to allow sufficient distance for airbag deployment. The increase in torso depth may hinder the airbag inflation performance.

Crash testing of safety systems has historically used the 50th percentile male Hybrid III dummy. In recent years, crash testing has included the 5th percentile female dummy in various test programs such as FMVSS 208 and frontal NCAP. Figure 9 shows vertebra-to-front-skin and spine-to-back-skin distances taken at L1 as a function of BMI for males with a height similar to a 50th percentile Hybrid III dummy (1.64-1.84 m based 5% of Mertz et al. [2001] standing height results). Figure 10 shows females with height similar to that of a 5th percentile female Hybrid III dummy (1.44-1.59 m). Since age has been shown to influence body depth results, the results were assessed for patients between 30 to 60 years old.

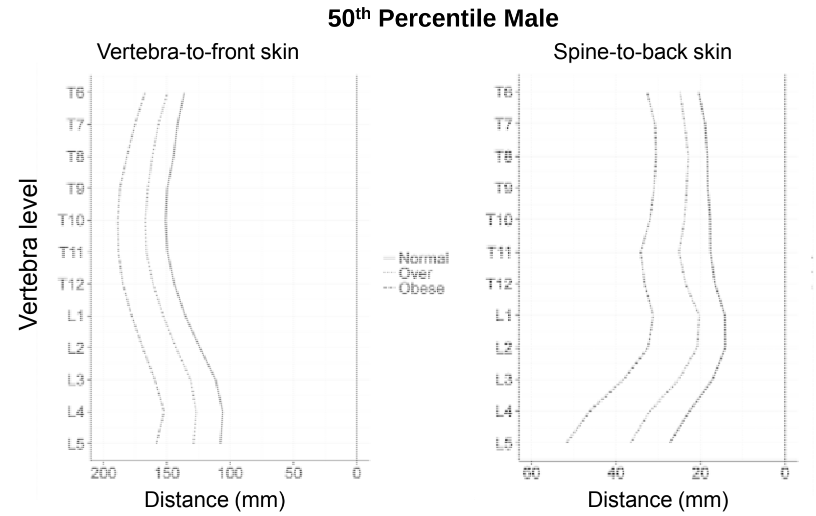


Fig.9. Body depth for a 50th percentile male for 3 different BMI groups (1.64<height<1.84; 30<age<60).

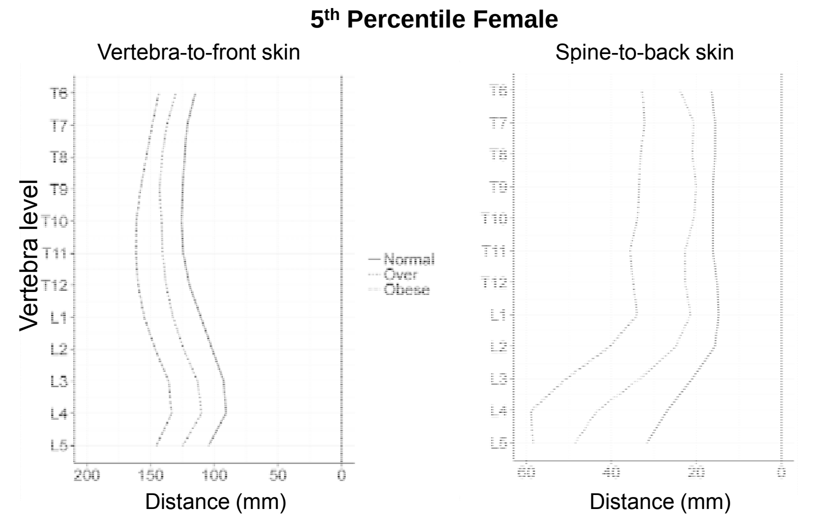


Fig.10. Body depth for a 5th female for 3 different BMI groups

(1.44<height<1.59; 35<age<60).

Table IV shows the weight, weight, and BMI for the dummies based on the data by Mertz et al. [13]. The calculated BMI is 25.5 kg/m^2 for a 50th percentile male Hybrid III dummy and 20.4 kg/m^2 for the 5th percentile female Hybrid III dummy. The 5th percentile female dummy has a BMI about 10 kg/m^2 smaller than an obese female occupant with the same height.

A recent CDC study [14] reported that the average weight and height of a 5th percentile female is 50.2 kg and 1.51m, respectively as tabulated in Table IV. The corresponding BMI is approximately 22.1 kg/m^2. Similarly, the data for a 50th percentile male is 86.1 kg, 1.76 m, and 27.8 kg/m^2. These results indicate that the 5th percentile female and the 50th percentile male have a BMI about 2 kg/m^2 (8%) larger than their related dummy sizes. These results imply greater vertebra-to-front-skin, spine-to-back-skin, and H-point distances as well as an increase in seatbelt webbing length according to Reed et al. [7]. This may potentially influence occupant performance.

Table IV. Height, weight and BMI summary for the 5th percentile female and the 50th percentile male.

	Weight (kg)	**Height** (m)	**BMI** (kg/m^2)
Dummy data			
5th F	46.7	1.51	20.4
50th M	78.2	1.75	25.5
CDC data			
5th F	50.2	1.51	22.1
50th M	86.1	1.76	27.8
% diff			
5th F	6.9%	-0.40%	7.7%
50th M	9.2%	0.57%	8.1%

5th F: 5th percentile female dummy, 50th M: 50th percentile male dummy

With the increasing worldwide concern for obese occupant protection, test devices representative of this segment of the population are needed. Human math models provide the best option for a parametric analysis of protection systems designed and optimized for various BMI and gender groupings. The morphomic data provided in this study will be useful in the modifications of human mathematical models designed to represent obese occupants. Morphomic data such as H-point, vertebra-to front skin, and spine to back skin distances are tangible measurements that characterize occupant shape. They are easily obtained from imaging reports and are representative of occupant diversity.

V. CONCLUSIONS

To the authors' knowledge, this study is the first to quantify abdomen and torso shape and H-point location as a function of BMI and gender. Information was also provided for the 5th percentile female and 50th percentile male dummy size so automotive engineers can use the data in mathematical parametric simulation and assess the effect of BMI of occupant responses.

VI. ACKNOWLEDGEMENT

The authors thank June Sullivan and Lucy Hully for their assistance in data collection.

VII. REFERENCES

[1] NIH, National Institutes of Health, National Heart, Lung, and Blood Institute. Psychosocial "Aspects of Overweight and Obese", http://www.nhlbi.gov/guidelines/obesity/e_txtbk/ratnl/22112/htm,2003.

[2] Ogden CL, Carroll MD, Kit BK, Flegal KM. Prevalence of Obesity in the United States, 2009–2010, NCHS Data Brief No. 82, January 2012.

[3] Mock CN, Grossman DC, Kaufman RP, Mack CD, Rivara FP. The relationship between body weight and risk of death and serious injury in motor vehicle crashes. Accid Anal Prev.; 34(2): 221-8, 2002.

[4] Viano DC, Parenteau CS, Edwards ML. Crash Injury risks for obese occupants using a matched-pair analysis. Traffic Injury Prevention; 9(1): 59-64, 2008.

[5] Viano DC, Parenteau, CS, Crash injury risks for obese occupants, SAE 2008-01-0528, Society of Automotive Engineers, Warrendale, PA, 2008.

[6] Lichtenstein MJ, Bolton A, Wade G. Body mass as a determinant of seat belt use. Am J Med Sci. 297(4):233-7, 1989.

[7] Reed MP, Ebert-Hamilton SM, Rupp JD. Effects of obesity on seat belt fit. Traffic Injury Prevention; 13(4):364-72, 2012.

[8] Forman J, Lopez-Valdes FJ, Lessley D, Kindig M, Kent R, Bostrom O. The effect of obesity on the restraint of automobile occupants. Ann Adv Automot Med; 53:25-40, 2009.

[9] Wang SC, Bednarski B, Patel S. Increased depth of subcutaneous fat is protective against abdominal injuries in motor vehicle collisions. Annu Proc Assoc Adv Automot Med.; 47:545–559, 2003.

[10]Wang, SC. Growing Obesity: Concerning Implications for the Burden from Crash Injury. Proceedings of the Japan Society of Automotive Engineers 60th Annual Meeting. Technical Paper 148-20075201, 2007.

[11]Zhu S, Layde PM, Guse CE, Laud PW, Pintar F, Nirula R, Hargarten S. obesity and risk for death due to motor vehicle crashes. Am J Public Health; 96:734-739, 2006.

[12]Parenteau CS, Holcombe S, Zhang P, Kohoyda-Inglis C, Wang SC. The effect of age on fat and bone properties along the vertebral spine, SAE paper #2013-01-1244, Society of Automotive Engineers, Warrendale, PA, 2013a.

[13]Mertz HJ, Jarrett K, Moss S, Salloum M, Zhao Y. The Hybrid III 10-Year-Old Dummy. Stapp Car Crash Journal; 45:319-28, 2001

[14]CDC, Anthropometric Reference Data for Children and Adults: United States, 2007–2010, Vital and Health Statistics, Series 11, Number 252, 2012.