Belly Fat Forces on the Spine: Finite Element Analysis of Belly Fat Forces by Waist Circumference

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ABSTRACT

Object: It has been well-established that obesity, or the fat content of the belly, is associated with diabetes, heart conditions, metabolic syndrome and back pain. With regard to back pain, this study aimed to assess the forces that incremental amounts of belly fat exert on the spine.

Methods: A finite element analysis (FEA) was performed with a 3D CAD model of the spine using data for various populations from the Dallas Heart Study.

Results: There were significant differences in the forces exerted on the spine by belly fat among ethnic groups.

Conclusions: These findings should help clarify the stress forces experienced by the spine in relation to waist circumference and could help to explain the association between obesity and back pain.

INTRODUCTION

It has been well-established that obesity, or the fat content of the belly, is associated with diabetes, [1] heart conditions,[2] metabolic syndrome,[3] and back pain.[4-7] This study sought to assess the forces that belly fat exerts on the spine with an increase in waist circumference.

Using data from the Dallas Heart Study, Grundy et al.[8] calculated belly fat mass according to waist circumference by both ethnicity and sex. Using a finite element analysis, our study specifically placed the abdominal fat masses into position in the abdomen, and calculated the levered forces seen by the spine. We transformed the measured abdominal fat masses into forces seen by the spine to obtain a better feel for the stress, strain and energy exerted on the spine by incremental changes in belly fat. Furthermore, these forces could be compared to identify differences based upon ethnicity and sex.

MATERIALS AND METHODS

This study used data from the Dallas Heart Study regarding the amount of fat in men and women in different ethnic populations.[8-10] Grundy et al.[8] used a single MRI slice at the L2-L3 level to quantify total abdominal fat (TAF), anterior subcutaneous fat (ASF), intraperitoneal fat (IPF), and retroperitoneal fat (RPF), as detailed by Abate et al.[10,11]

While visceral fat comprises a greater

percentage of total abdominal fat in men, women have a greater proportion of subcutaneous fat.[12,13] Since both types of fat are strongly correlated with the waist circumference; we used the waist circumference as a reference point. We defined "abdominal fat" as the sum of visceral fat and anterior subcutaneous fat. This fat content represented the weight on the spine and was the primary variable for our analysis.

Using a finite element analysis (FEA) with a 3D CAD model of the spine, we calculated the forces exerted by fat according to sex and ethnicity.

Development of the 3D Model

The model used for the FEA simulation was based on 'BodyParts3D/Anatomography' data (Database Center for Life Science, University of Tokyo, Tokyo, Japan),[14] as shown in Fig. 1. The model was imported into the FEA software (described below) and evaluated by scanning actual parts of the spine and collecting the data into a single 3D model (Figs. 1 and 2). A FEA requires a perfect fit of surfaces, and all of the measurements were made to fit the contact surfaces within an accuracy of 0.1 mm (Fig. 3). The spine model was physiologically accurate in accordance with the standards of the industry.[15-20]

Physics setup

Optistruct® software (Altair, Troy, MI) was used for the FEA analysis. According to the input conditions, it accounts for the deformations, stresses, and reaction forces at the boundary or volume level. A nonlinear structural scheme was used. This is important since material and geometric nonlinearities play essential roles in this analysis. Several boundary conditions were applied to the initial requirements:

- Fixed constraint, for the bottom part of the spine (coccyx region)
- Body load, on the areas where the forces are exerted (areas around the abdominal region)
- Contact, for the areas where the vertebrae come in contact

The solver was a stationary type to account for the required forces and stresses. The skeleton model was constrained at the pelvis, and the loads were applied in the vertical direction, with a respective offset. This offset was located at the L2-L3 level and varied based on the waist circumference (Fig. 4). The premise was that a greater weight of abdominal fat and a larger waist circumference would be associated with greater momentum and hence a greater force on the spine.

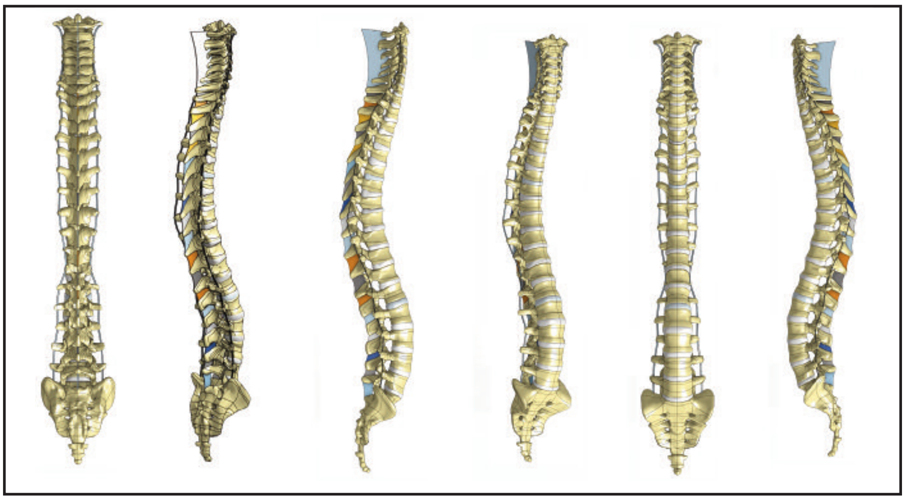

Figure 1. 3D model of the spine. Source Optistruct software (Altair, Troy, MI) used for the FEA analysis.

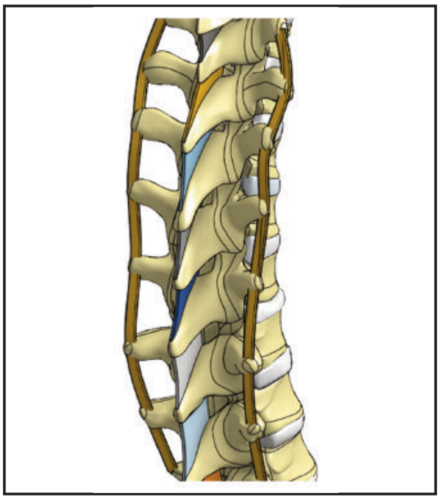

Figure 2. 3D model of the thoracic spine

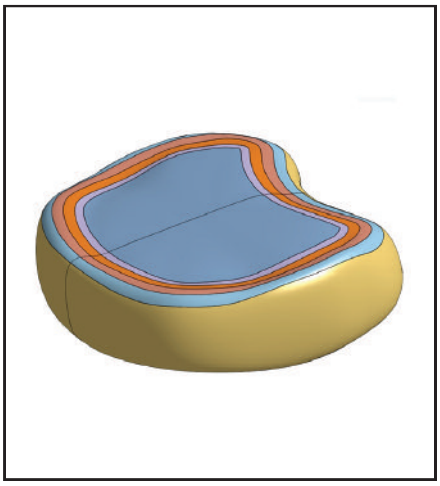

Figure 3. 3D model of annulus fibrosus and nucleus pulposus of the disc.

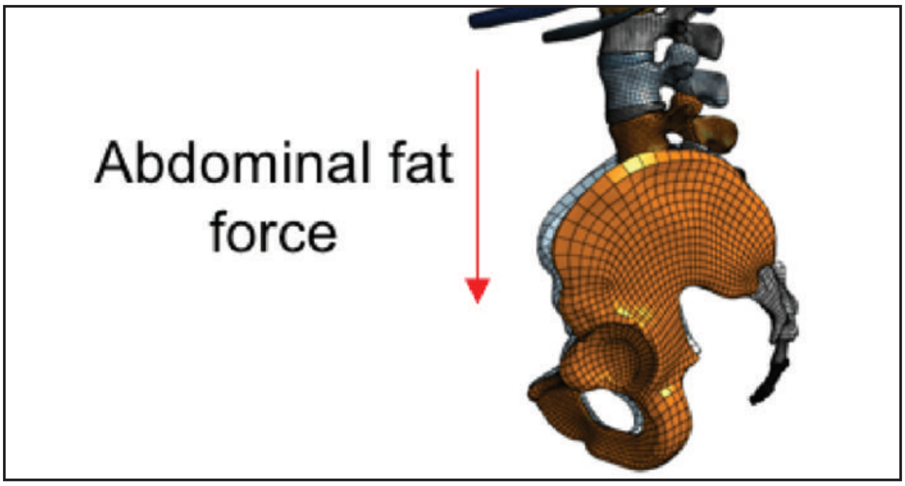

Figure 4. Loads were applied vertically, with a respective offset.

Mesh

Fine meshing of all vital spine components is the key to obtaining a realistic representation of the biomechanical conditions. Because of the complexity of the shapes used in the model, tetrahedral mesh with proximity refinement and aspect ratio control was used. As shown in Fig. 5, bones and ligaments of the spine were meshed with very dense finite elements.

To obtain realistic stresses and strains in the disc, this area was modelled using hexahedral FEA (Fig. 6); fewer elements were used, and the stress and strain resolution and convergence were much better in these parts. The entire model contained 13 thousand elements (Figs. 7-9).

Grundy et al. [8] reported abdominal fat weight as a function of the waist circumference in men (Fig. 10) and women (Fig. 11):

- ◆ Low waist circumference (under 90 cm in men, under 80 cm in women); equivalent BMI less than 25;
- ◆ Medium waist circumference (90-101 cm in men, 80-89 cm in women); equivalent BMI 25 – 29.9;
- ◆ High waist circumference (more than 102 cm in men, more than 90 cm in women); equivalent BMI greater than 30.

The values for the waist circumference were chosen as equally distributed in the range of interest. These values were later used as the loading in our FEA analysis.

Effects of belly fat weight and waist circumference on the spine

We sought to analyze the impact of belly fat weight, which was directly correlated with the waist circumference, on spine stresses. We studied different ranges of waist circumference to properly classify the forces.

The reaction force values in this report represent the added forces and stress due to abdominal fat. All other effects (e.g., body weight) are not considered.

We used a FEA for the human spine simulation as a function of

Figure 5. 3D Finite Element Mesh.

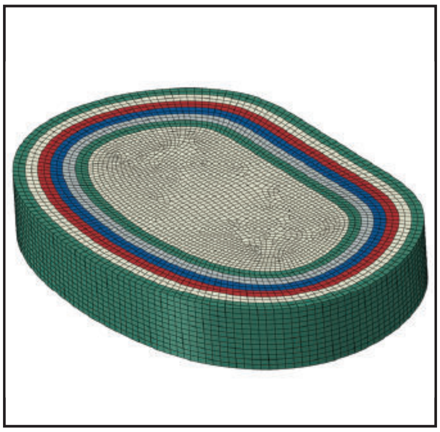

Figure 6. 3D model of the disc.

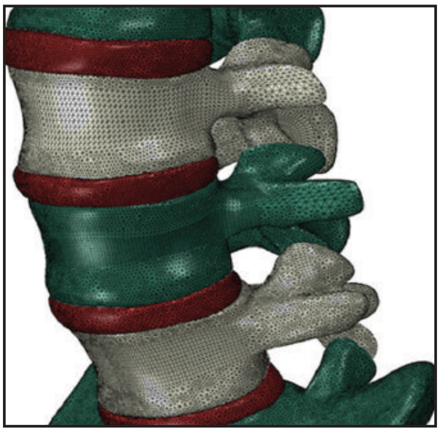

Figure 7. 3D model of the lumbar spine.

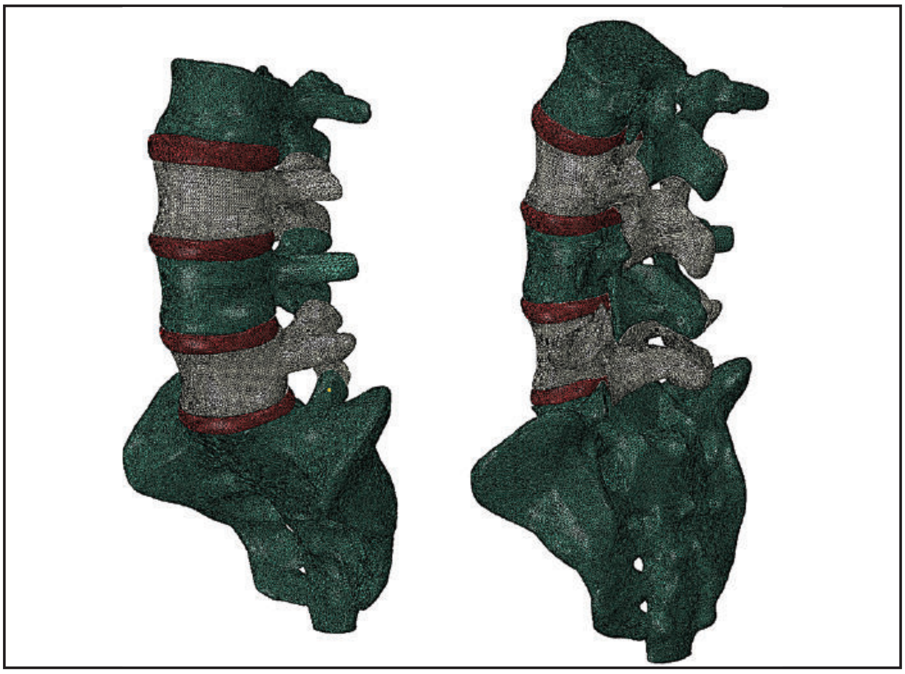

Figure 8. 3D model of the lumbar spine and sacrum.

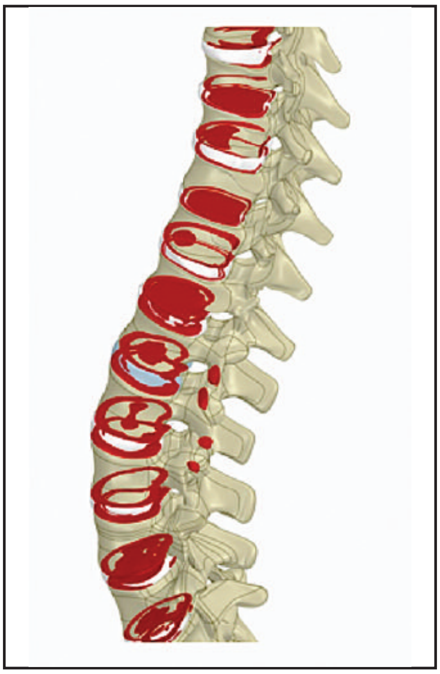

Figure 9. Contact between the discs and bones in the spine is defined.

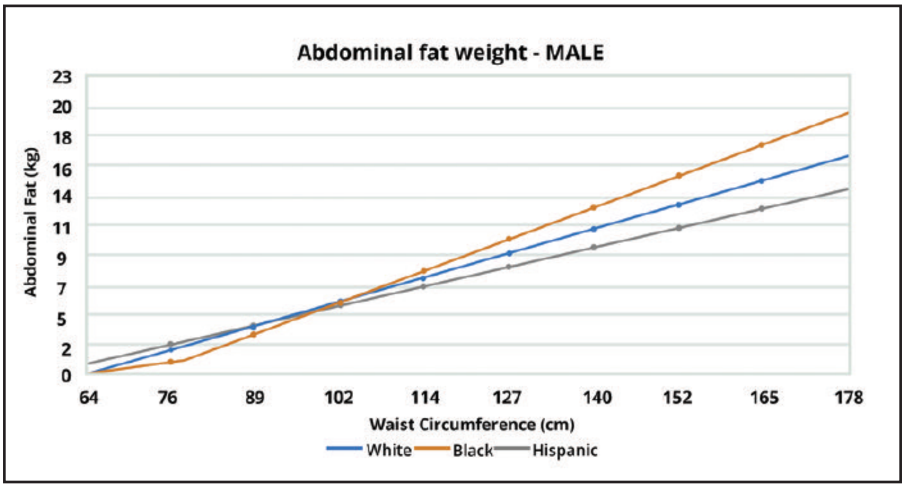

Figure 10. Waist circumference in male patients plotted against measured abdominal fat. Data from Grundy et al.[8]

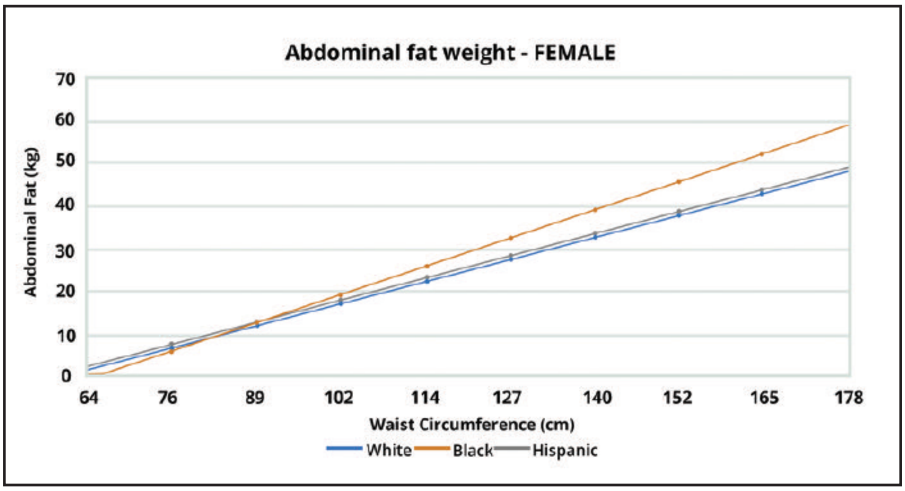

Figure 11. Waist circumference in female patients plotted against measured abdominal fat. Data from Grundy et al.[8]

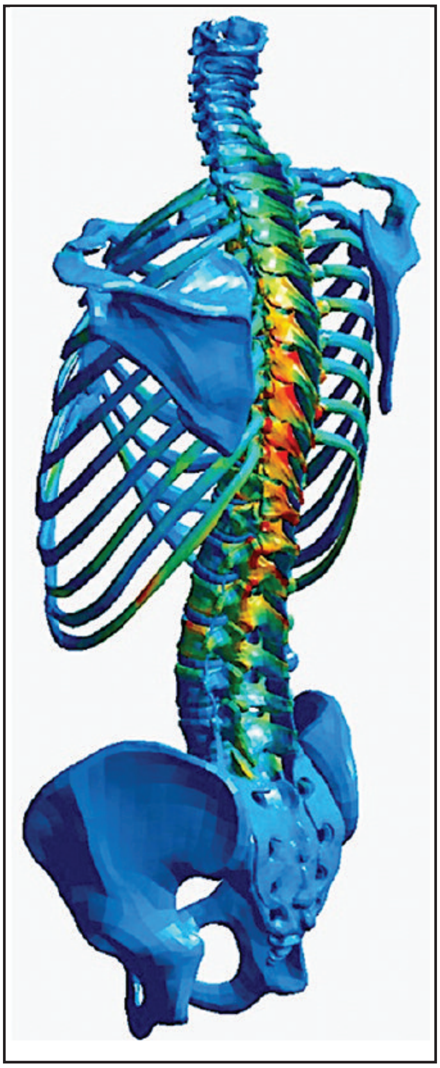

Figure 12. Stress within the spine. Example calculations for a waist circumference of 50 inches. Abdominal fat exerts stress in the lower thoracic spine and the upper lumbar spine.

- Waist circumference (26 categories)
- Ethnicity (3 categories)
- Sex (2 categories)

for a total of 156 different combinations (Fig. 12, Table I).

STATISTICAL ANALYSIS

Linear descriptive statistics were prepared for assessments. We assessed data points for Blacks, Hispanics and Whites in male and female categories. The belly fat data were normally distributed across all the groups. To visualize the data points before setting the hypothesis, we created box plots for both sexes, using 10%, 25%, 50%, 75% and 90% quantiles. For each ethnicity we had enough data points and applied the Z-test to establish the hypothesis for different ethnicities. We applied the Z-Normal Test and calculated p-values. All calculations were performed using Excel 2021 (Microsoft Corp., Redmond, WA).

RESULTS

The stationary solver computed the stress and forces outcomes (Table I). The main plots show that abdominal fat induces spine stress in the lower thoracic spine and the upper lumbar spine (Fig. 12).

In White women, abdominal fat exerted between 23 and 688 Newton-Meters of force on the lumbar spine for waist circumferences of 64 to 178 cm. For Black and Hispanic women, this range was 5 to 851 N.m and 38 to 713 N.m , respectively. Black women had significantly greater belly fat forces than White ($P < 0.004$) and Hispanic women ($P < 0.02$), while there was no significant difference between White and Hispanic women ($P < 0.9$) (Fig. 13).

In White men, abdominal fat exerted between 3 and 523 N.m of force on the lumbar spine for waist circumferences of 64 to 178 cm. For Black and Hispanic men, this range was 5 to 631 N.m and 29 to 450 N.m , respectively. Black men had significantly greater belly fat forces than White ($P < 0.009$) and Hispanic men ($P < 0.007$), while there was no significant difference between White and Hispanic men ($P < 0.17$) (Fig. 14).

The forces exerted on the spine varied by ethnicity when the waist circumference was held stable. If we considered a 127 cm waist circumference, the average belly fat mass was 13 kg in Hispanic females, 12.7 in White females, and 15 in Black females, which exerted 413, 392 and 468 N.m of force on the lumbar spine, respectively.

Table I

Waist circumference (cm)	Force exerted on thoracic and lumbar spine (Newton-Meter)					
	Women			Men		
	White	Black	Hispanic	White	Black	Hispanic
64	23.1	4.6	38.1	2.6	5.3	29.4
66	37.9	9.4	53.1	3.6	7.8	38.7
69	52.6	28.6	68.1	15.3	10.1	48.1
71	67.4	47.7	83.1	27.1	17.1	57.4
74	82.2	66.8	98.1	38.9	23.4	66.8
76	97.0	85.9	113.1	50.8	29.1	76.2
79	111.7	105.0	128.1	62.6	38.0	85.5
81	126.5	121.1	143.1	74.4	53.2	94.8
84	141.3	143.3	158.0	86.2	68.3	104.2
86	156.0	162.4	173.0	98.0	83.6	113.5
89	170.8	181.5	188.0	109.8	98.8	122.9
91	185.6	200.6	203.0	121.6	114.0	132.2
94	200.3	219.7	218.0	133.4	129.2	141.5
97	215.1	238.9	233.0	145.2	144.4	150.9
99	229.9	258.0	248.0	157.0	159.6	160.3
102	244.7	277.2	262.3	168.8	174.8	169.7
104	259.5	296.3	278.0	180.6	190.0	179.0
107	274.2	315.4	293.0	192.5	205.2	188.4
109	289.0	334.5	308.0	204.3	220.4	197.7
112	303.8	353.6	322.9	216.1	235.6	207.1
114	318.5	372.8	338.0	227.8	250.8	216.4
127	392.4	468.4	412.9	286.9	326.8	263.2
140	466.3	564.0	487.4	346.0	402.7	310.0
152	540.0	659.6	562.7	405.0	478.8	356.7
165	614.0	755.2	637.7	464.0	554.7	403.5
178	687.9	850.8	712.7	523.0	630.8	450.2

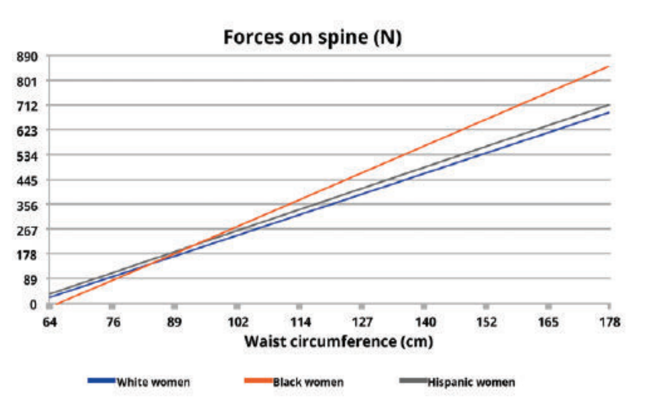

Figure 13. Forces exerted on the spine plotted against waist circumference as a surrogate for abdominal fat (according to Grundy et al.[8]). Among women, Blacks had significantly greater abdominal fat forces than Whites ($P < 0.004$) and Hispanics ($P < 0.02$), while there was no difference between Whites and Hispanics ($P < 0.9$).

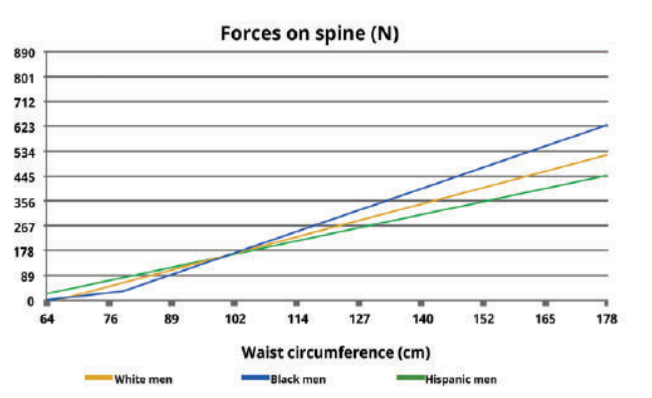

Figure 14. Forces exerted on the spine plotted against waist circumference as a surrogate for abdominal fat (according to Grundy et al.[8]). Among men, Blacks had significantly greater abdominal fat forces than Whites ($P < 0.009$) and Hispanics ($P < 0.007$) while there was no difference between Whites and Hispanics ($P < 0.17$).

In men with a 127 cm waist, the average belly fat mass was 8.2 kg in Hispanic males, 9.1 in White males, and 11.3 in Black males, which exerted 263, 287, and 327 N.m of force on the lumbar spine, respectively.

DISCUSSION

Fundamentally, the results of our study lead to a conclusion that increased waist circumference is associated with increased abdominal fat and a related increased force exerted on the lower thoracic and abdominal spine. This helps to explain the mechanical effect of the abdominal fat exerted on the lumbar and thoracic spine. An incremental increase in waist circumference is associated with an incremental increase in the amount of belly fat and a concomitant increase in forces exerted on the spine. Abdominal fat is a physical lever borne in the fashion of a moment arm. We noted that different ethnicities and sexes displayed differing belly fat mass profiles even when the waist circumference is held stable (Figs. 13,14).

It has been established that obesity or the fat content of the belly is associated with diabetes,[1] heart conditions,[2] metabolic syndrome[3] and back pain.[4-7] Adipose tissue is related to metabolic syndrome.[3] Studies have shown that intraperitoneal fat and anterior subcutaneous fat may contribute to metabolic risks and syndromes.[8-10]

Fat itself is considered to be an endocrine organ that is biologically active.[21] Abdominal fat cells disrupt the balance of the body's normal hormones.[22] Fat cells play a role in inflammation, secrete tumor necrosis factors and interleukin-6 [23] and increase the risk of heart disease.[22] Furthermore, fat cells blunt the body's sensitivity to insulin and propagate high blood pressure.[1-3,21-24] Data suggests that adipose tissue is linked to an increased risk and aggressiveness of carcinoma.[25] STI

CONCLUSION

Our report identifies a relationship between increased waist circumference, increased abdominal fat content, and an increased force exerted on the lower thoracic and abdominal spine. Different ethnicities and sexes displayed differing belly fat mass profiles. These findings should help clarify the stress forces experienced by the spine in relation to the size of the abdomen and could help to explain an association between obesity and back pain.

AUTHORS' DISCLOSURES

The authors declare that there are no conflicts of interest.

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