ERGONOMICS, 2002, VOL. 45, NO. 1, 49–60

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Quantitative prediction of body diameter in severely obese individuals

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Keywords: Obesity; Body diameter; Mobility.

The prevalence of obesity and severe obesity continues to increase in the developed world. Apart from obesity's strong association with a variety of health conditions, severely obese individuals (i.e. ⩾300 lb [136 kg]) sometimes have difficulty with ambulation, and often cannot use regular sized clothes, furniture, and assistive devices such as walkers and wheelchairs. The purpose of this study was to assess the relationship between linear body measurements (anthropometry) and weight in severely obese people in order to generate equations to predict such measurements from weight alone. Various body size measurements were obtained from three independent data sets (74 severely obese individuals evaluated at the New York Obesity Research Center, 103 severely obese individuals who participated in the National Center for Health Statistics' National Health and Nutrition Examination Survey III, and a further 90 severely obese individuals evaluated at the New York Obesity Research Center). Linear regression analyses revealed that for each increase of 10 kg (22.04 lb) above 136 kg (300 lb), body diameter measurements increase by 0.9–1.1 cm. These analyses provide body size-to-weight estimates that may help manufacturers develop products and services that are more appropriate for increasing numbers of severely obese individuals.

1. Introduction

Obesity is a major health problem in the USA and in most of the developed world (Popkin and Doak 1998, Antipatis and Gill 2001). Moreover, the prevalence of severe obesity (i.e. Body Mass Index (BMI) ⩾35) continues to

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Ergonomics ISSN 0014-0139 print/ISSN 1366-5847 online
http://www.tandf.co.uk/journals
DOI: 10.1080/00140130110112627

increase dramatically (Mokdad *et al.* 1999, Antipatis and Gill 2001). Apart from obesity's strong association with cardiovascular disease, knee osteoarthritis, sleep apnea, and type II diabetes mellitus (National Heart, Lung and Blood Institute (NHLBI) 1998), obesity poses many unique challenges pertaining to activities of daily living, including mobility that adversely affect the quality of life (Sullivan *et al.* 1987, Himes 2000). Thus, severely obese individuals often have special needs with regard to clothing, beds, furniture, and assistive devices such as walkers and wheelchairs (Allison *et al.* 1998). Cooper *et al.* (1999) recently reported the augmentation of the 100 kg International Organization for Standardization (ISO) wheelchair test dummy to better represent severely obese individuals. However, they did not take into account any increase in body size measurements associated with severe obesity. This is not surprising because little is known about the relationships between selected body size measurements and body weight in severely obese individuals.

Recently, a major wheelchair manufacturer contacted the authors to obtain information about the body shape and size of individuals weighing greater than 136 kg (300 lb). Although such information is necessary to design products for severely obese individuals, there is scant information available. Thus, the purpose of this study is to: (1) compile descriptive statistics on body measurements for individuals over 136 kg, corresponding to a BMI >35; (2) delineate the relationship of selected body size measurements and weight in order to develop prediction equations; and (3) compare the resulting equations using three independent datasets to assess replicability.

2. Methods

2.1. *Data sources*

To evaluate whether the results generated were sensitive to the particular data set used, analyses were conducted using data from three different sources. The data sources were: (1) 74 adults (44 women) aged 18 to 76 years, the majority of whom were research volunteers or patients/candidates for obesity surgery screened at the New York Obesity Research Center (NYORC dataset no. 1) weighing $\geqslant 136$ kg (300 lb); (2) 103 adults (46 women) over 136 kg who participated in the National Center for Health Statistics' National Health and Nutrition Examination Survey III (NHANES III), 1988–1994 (revised); and (3) 90 adults (37 women) aged 18 to 73 years over 136 kg, screened at the New York Obesity Research Center (NYORC dataset no. 2), who volunteered to participate in a study designed to investigate the 'genetics of super obesity'.

2.2. *Measurements*

The NYORC dataset no. 1 contains the following body measurements: (1) body weight, measured by a self-zeroing digital scale; (2) iliac crest (i.e. hip) circumference (CIC); (3) waist circumference [maximum circumference above the iliac crest] (CW); and (4) chest circumference (CC). The NHANES III dataset contains: (1) body weight, measured by a Toledo self-zeroing digital scale; (2) biiliac breadth (BIB; i.e. hip-to-hip breadth); (3) buttocks circumference (BC); (4) waist circumference (WC); and (5) biacromial breadth (BAB, i.e. shoulder-to-shoulder breadth). In addition to the aforementioned measures, the NYORC dataset no. 2 also contained a measure of sagittal abdominal diameter (SAD).

SAD is obtained by measuring the distance from the examination table to a horizontal level placed over the abdomen of a recumbent person at the iliac crest to navel (L4–5). Visceral fat contributes to the depth of the abdomen while subcutaneous abdominal fat reduces the SAD due to the force of gravity (Sjostrom 1991). SAD correlates strongly ($r > 0.80$) with abdominal diameters from CT or MRI images (van der Kooy and Seidell 1993)

2.3. *Data analysis*

For each dataset a variety of descriptive statistics (e.g. mean, median, quartiles) were calculated to characterize the distributions of the various body measurements. The relationship between body weight and the various circumference measures was then plotted. Finally, linear regression methods were used to develop prediction equations of selected diameter/breadth measures for variations in body weight. Because no significant weight × gender interaction (i.e. the relationship between weight and body diameter measures did not differ significantly as a function of gender) was observed in any of the analyses, the analyses that are presented combine the data from both men and women.

3. Results

3.1. *NYORC dataset no. 1*

Figure 1 presents a box plot that summarizes the data on body weight, and figure 2 does the same for CIC, CW, and CC (there are 6 missing values for these three variables). Shown in figure 1 are the minimum weight 136 kg (300 lb), the 1st quartile 151 kg (333 lb), the median 163 kg (359 lb), the 3rd quartile 187 kg (412 lb), and the maximum weight without the outlying observation (351 kg) was 234 kg (516 lb). The mean weight, including the outlying observation, was 171 kg (377 lb).

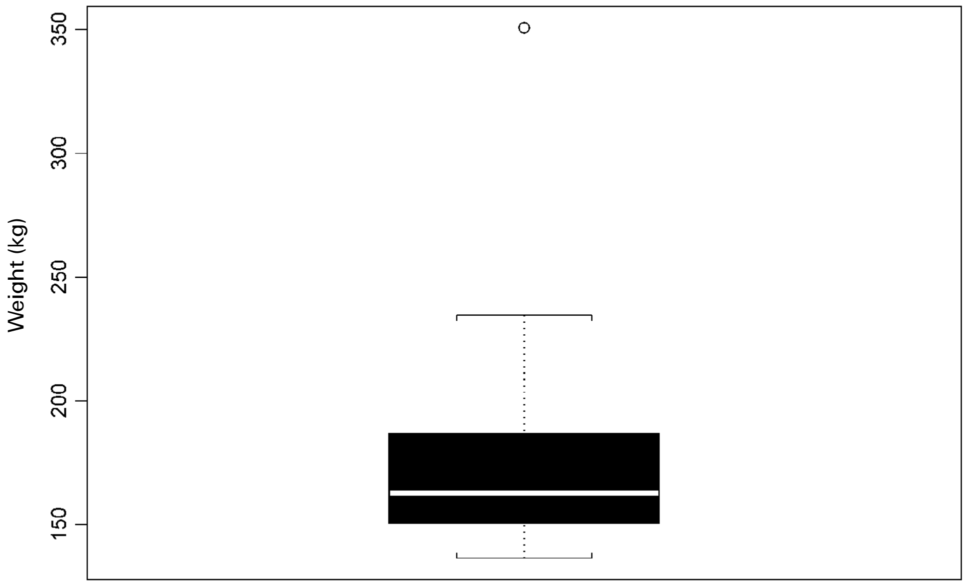

Figure 1. Box plot of distribution of weight from NYORC dataset no. 1.

As can be seen in figure 2, the CIC measurements tend to be the largest although there is some overlap of the three distributions of measurements. For this reason, the maximum value among the three measurements was chosen as a representative body-size measurement. For instance, if a person's CIC measurement is larger than his or her CW and CC measurement, then CIC is chosen. This new representative circumference will be labelled maximum circumference (MC). The distribution of MC is shown in figure 3. The characteristics of this distribution were as follows: minimum (122.7 cm) 1st quartile (152.2 cm), median (157.0 cm), 3rd quartile (170.4 cm) and maximum (215.5 cm). The mean MC was 160.7 cm.

The relationship between weight and MC is plotted in figure 4. Using these data, the following equation was derived that predicts, among individuals of 136 kg or greater, a person's MC given their weight:

$$\text{Predicted MC (cm)} = 101.7 + 0.343 \times \text{Weight (kg)}.$$

However, since MC is not directly interpretable as a 'breadth' measurement, it has been transformed into a diameter measurement (figure 5). Operationally, this diameter measurement can be considered to be the maximum diameter (MD) of an individual assuming that individual human cross-sections are circular in shape. The new breadth measurement is in units of centimetres. The relationship between weight

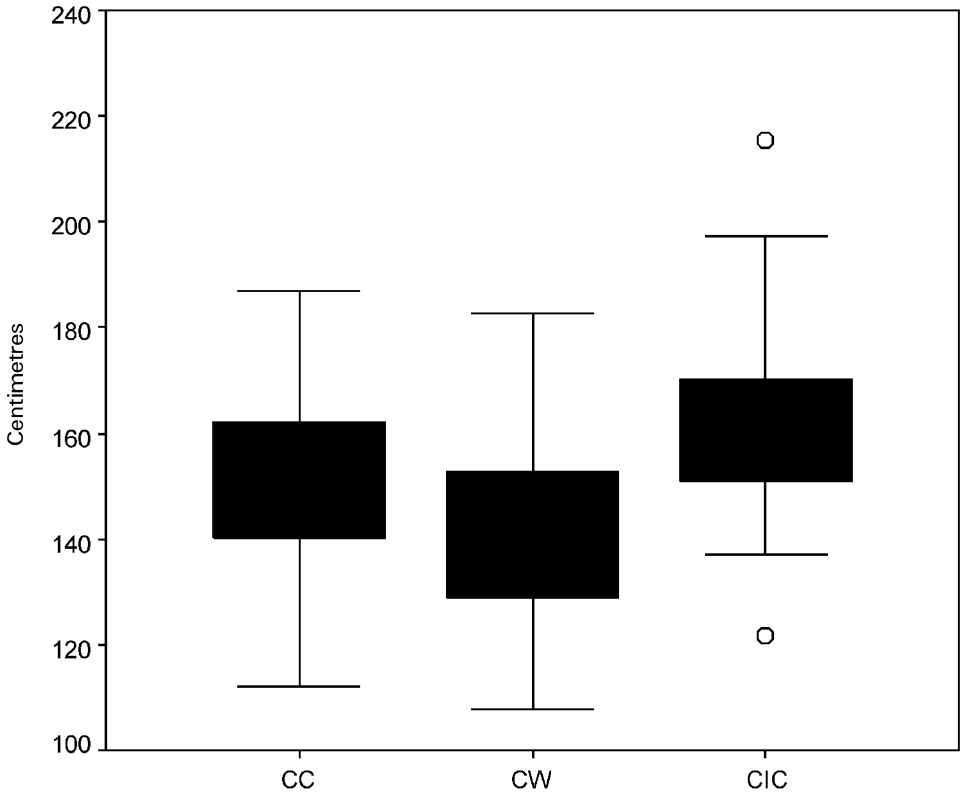

Figure 2. Box plots of distributions of chest circumference (CC), waist circumference (CW), and hip circumference (CIC), and derived from NYORC dataset no. 1.

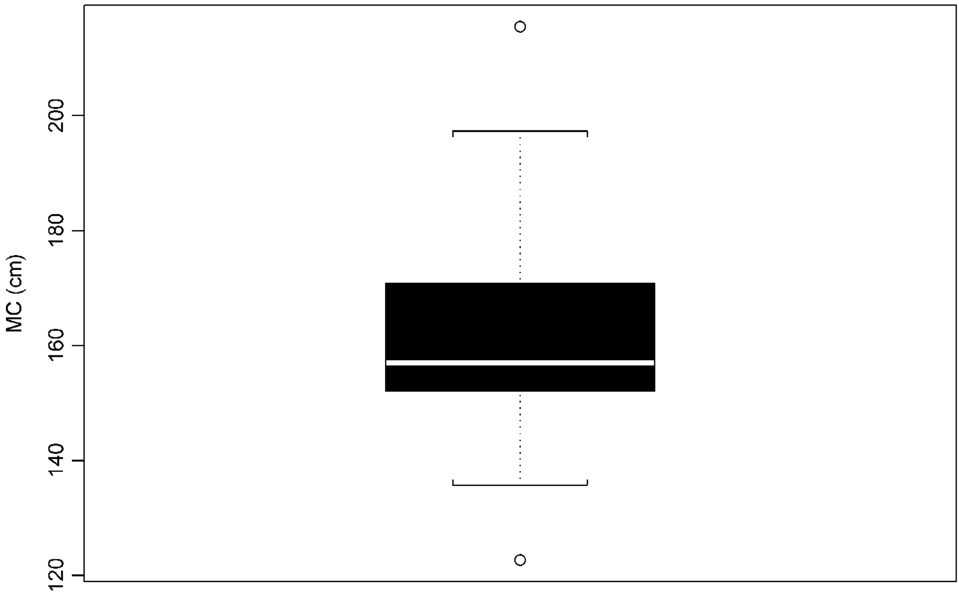

Figure 3. Box plot of distribution of maximum circumference (MC) derived from NYORC dataset no. 1.

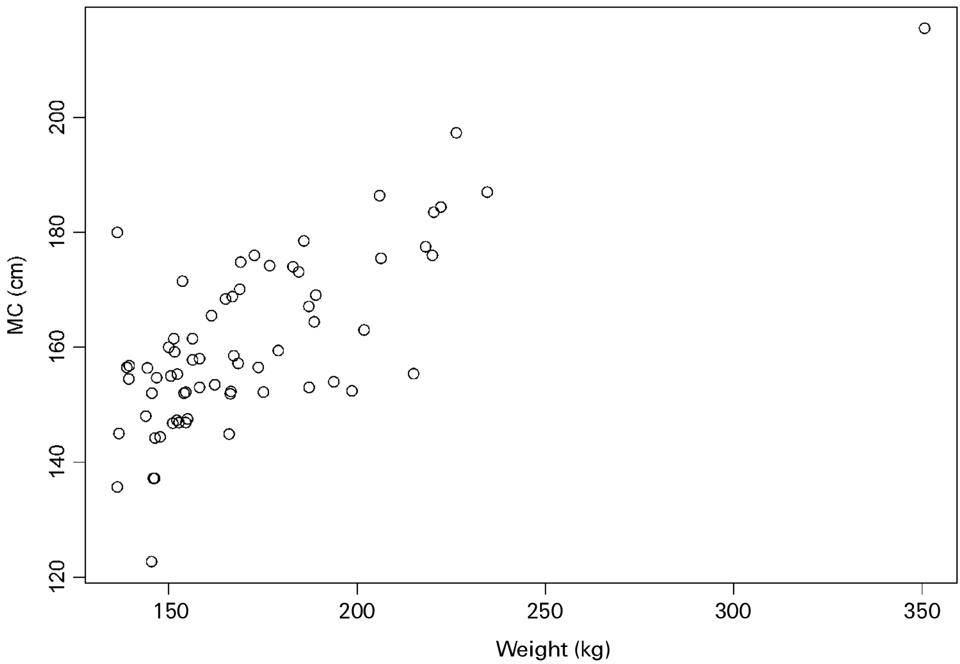

Figure 4. Scatter plot of relationship between maximum circumference (MC) and weight derived from NYORC dataset no. 1.

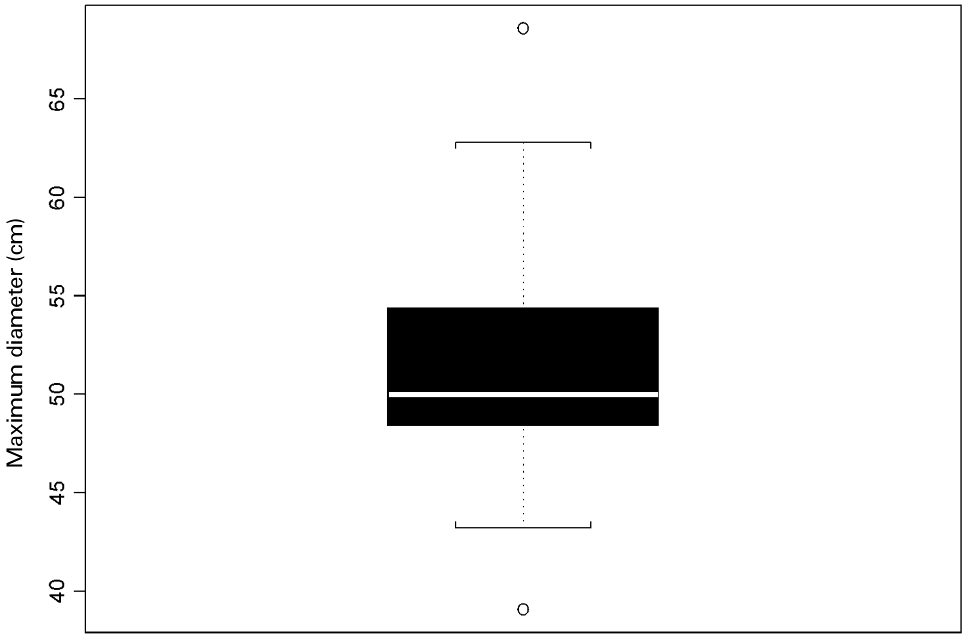

Figure 5. Box plot of the distribution of maximum diameter (MD) and weight derived from NYORC dataset no. 1.

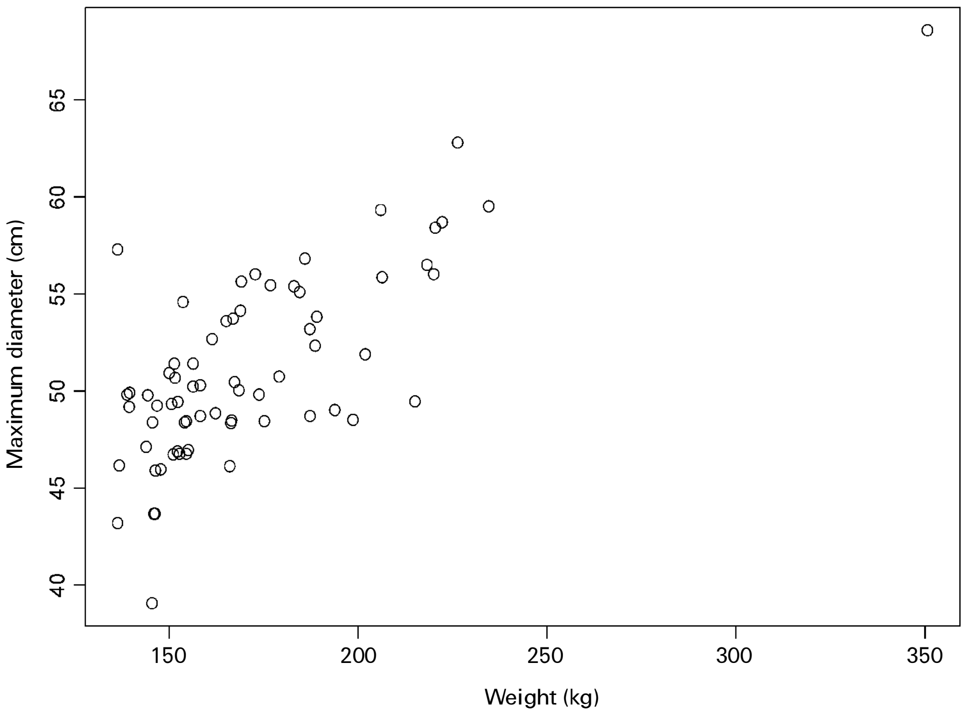

Figure 6. Scatter plot of relationship between maximum diameter (MD) weight derived NYORC dataset no. 1.

and MD is plotted in figure 6. Using MD as the dependent variable, the following prediction equation was derived:

$$\text{Predicted MD (cm)} = 32 + 0.11 \times \text{Weight (kg)}.$$

3.2. *NHANES III data*

Figure 7 shows the characteristics of the body weight distribution. Shown are the minimum weight 136 kg (300 lb), the 1st quartile 139 kg (306 lb), the median 144 kg (318 lb), the 3rd quartile 155 kg (342 lb), and the maximum weight of 219 kg (482 lb). The mean body weight was 150 kg (332 lb). Of the 103 individuals, 5 were over 181 kg (400 lb).

As noted, in this set of data there are four body size measurements to consider: BIB (6 missing values), BC (8 missing), WC (8 missing), and BAB (2 missing). The distributions of these variables are shown in figure 8. All measurements are in centimetres.

Figure 9 plots the relationship between the four body size measurements and weight. Of particular interest for the manufacturers' of furniture and wheelchairs is BIB. For individuals weighing more than 136 kg, a crude prediction of the BIB measurement in centimetres at a given weight (kg) is represented by the equation:

$$\text{Predicted BIB (cm)} = 21.2 + 0.11 \times \text{Weight (kg)}.$$

3.3. *NYORC dataset no. 2*

Figure 10 presents box plots that summarize the data on body weight and SAD (there were 13 missing SAD values). Shown are the minimum weight (138 kg),

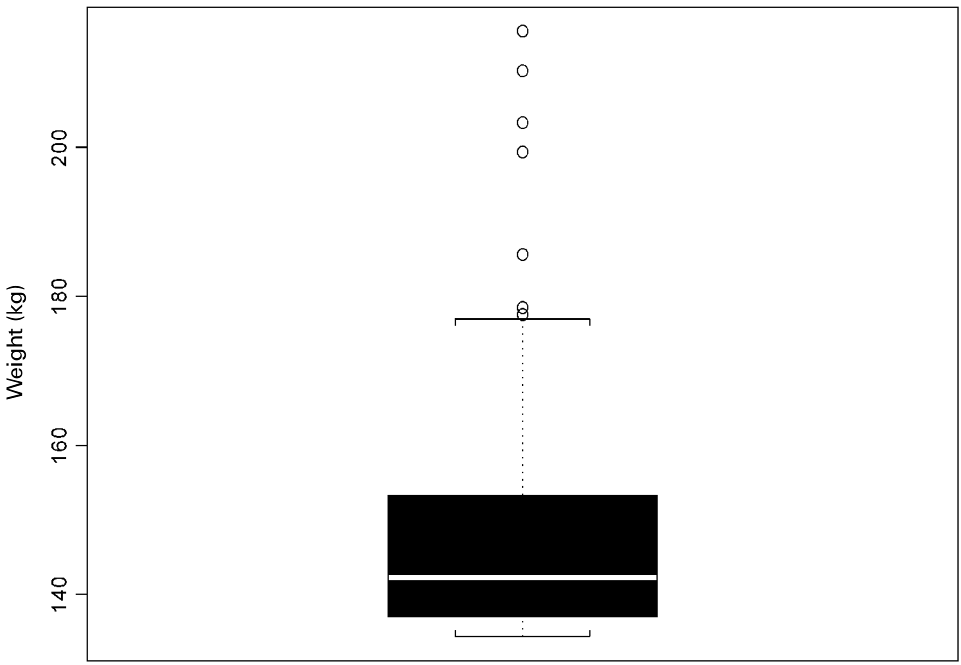

Figure 7. Box plot depicting distribution of weight derived from NHANES III data.

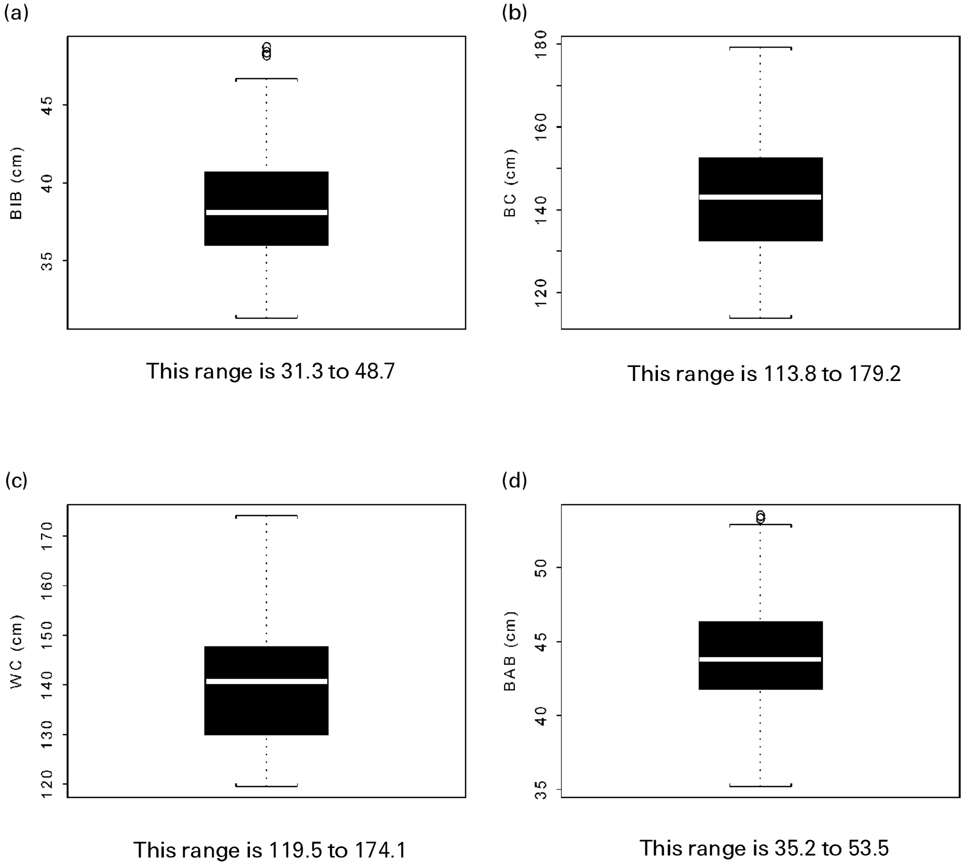

Figure 8. Box plots depicting the distributions of (a) biiliac breadth (BIB), (b) buttocks circumference (BC), (c) waist circumference (WC), and (d) biacromial breadth (BAB) derived from NHANES III data.

the 1st quartile 151 kg (339 lb), the median 163 kg (359 lb), the 3rd quartile 191 kg (421 lb), and the maximum weight was 311 kg (685 lb). The mean weight, including the outlying observation, was 176 kg (388 lb). The characteristics of the SAD distribution were as follows: minimum (28 cm), 1st quartile (33 cm), median (36 cm), 3rd quartile (38 cm) and maximum (49 cm). The mean SAD was 36 cm.

Figure 11 depicts the relationship between SAD and weight. Using SAD as the dependent variable, the following prediction equation was derived:

$$\text{Predicted SAD (cm)} = 20 + 0.092 \times \text{Weight (kg)}.$$

Under the assumption that the maximal 'horizontal' dimension (i.e. MD for the NYORC dataset no. 1, BIB for the NHANES III data set, and SAD for NYORC dataset no. 2) of a person's body is a critical variable for wheelchair and furniture design, and that a maximum diameter is a reasonable approximation of this dimension, a table was generated, based on the regression equations presented above, of diameter measures for given body weights based on the three datasets (table 1).

Table 1. Diameter measurements for a severely obese individual derived from the three regression equations.

Weight (kg)	NYORC Dataset no.1 Maximum diameter (MD) (cm)	NHANES III Hip to Hip breadth (BIB) (cm)	NYORC Dataset no.2 Sagittal abdominal diameter (SAD) (cm)
136	47.0	36.2	32.9
159	49.5	38.7	35.1
181	52.0	41.2	37.2
204	54.5	43.7	39.4
227	57.0	46.2	41.5
249	59.5	48.7	43.7
272	62.0	51.2	45.8
295	64.5	53.7	48.0
317	67.0	56.2	50.2
340	69.5	58.7	52.3

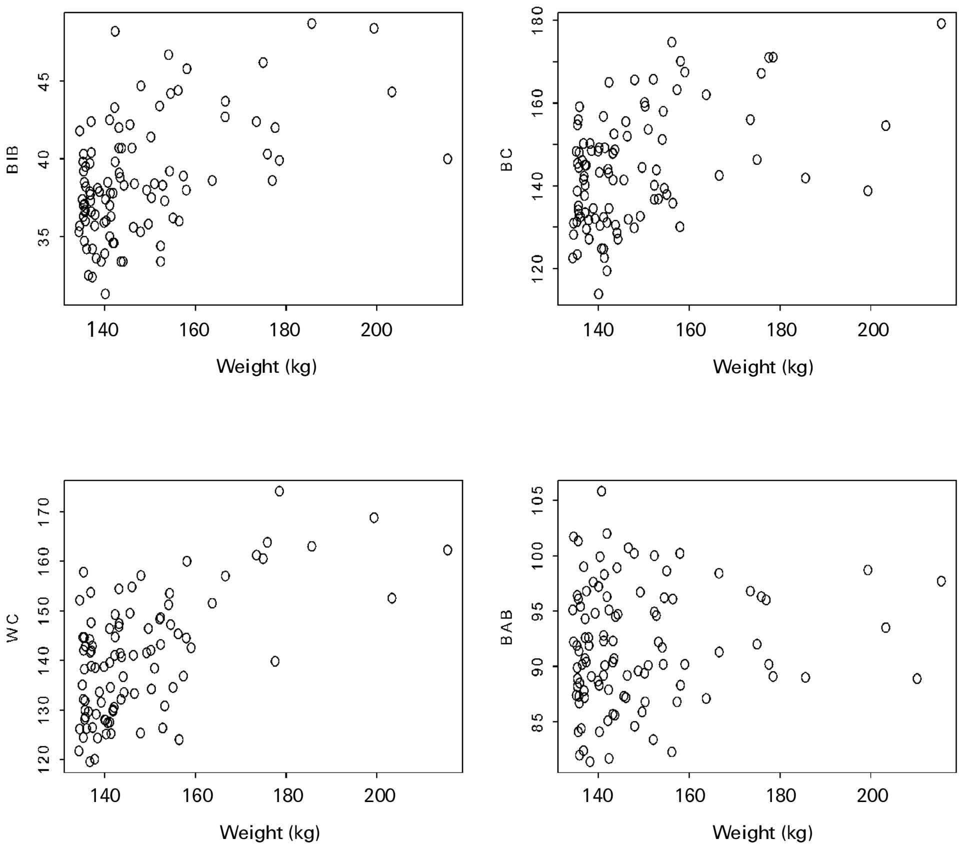

Figure 9. Scatter plots of the relationship between the four body size measurements and body weight (NHANES III).

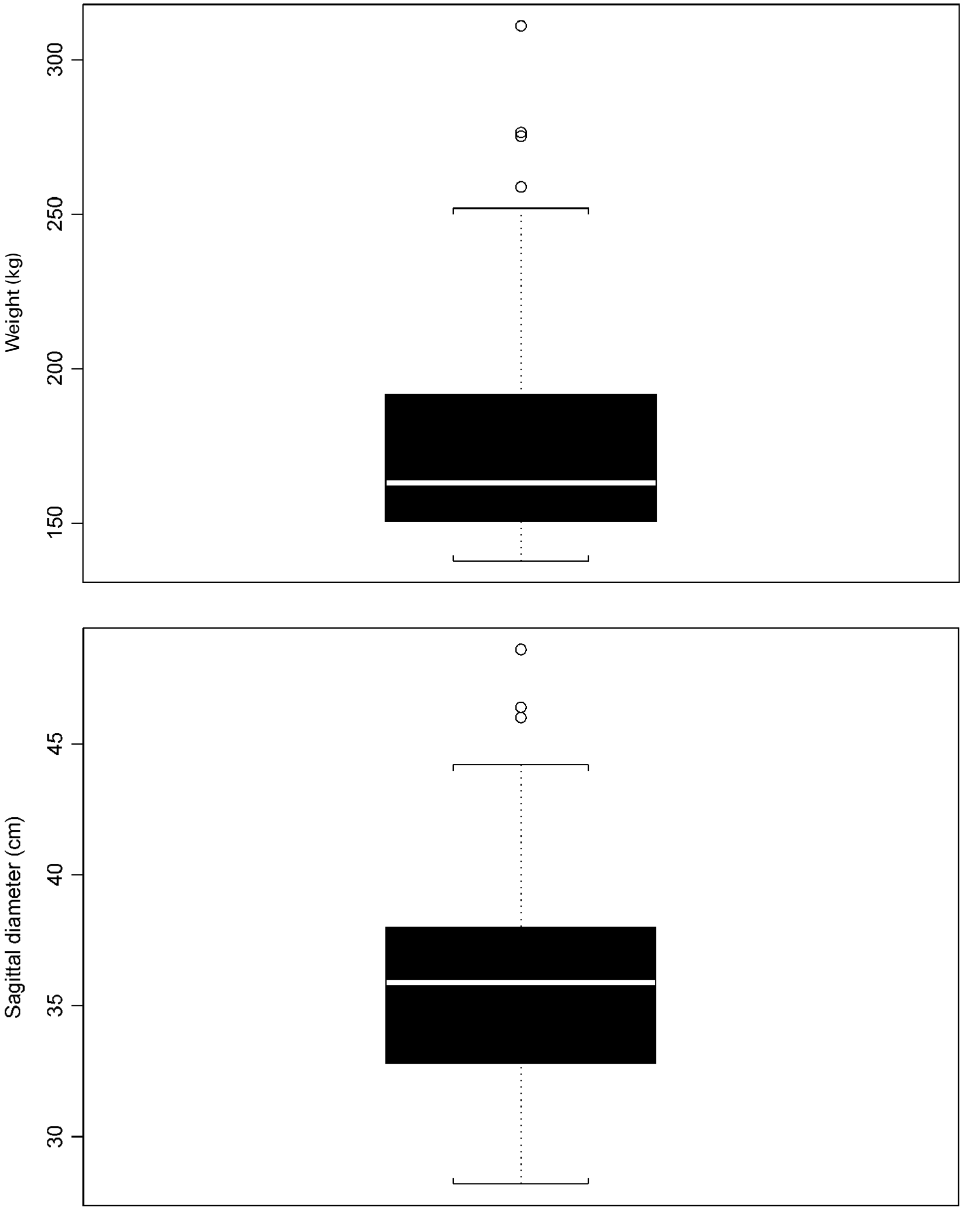

Figure 10. Box plots of distributions of body weight and sagittal abdominal diameter (SAD) (cm) derived from NYORC dataset no. 2.

4. Discussion

This study presented descriptive statistics of several body size measurements in severely obese individuals, assessed the relationship of these measurements to weight, and developed equations to predict body size measurements given weight. Despite the use of different body size measurements across the three datasets, the regression coefficients derived were generally consistent. Specifically, the coefficients generated from the maximum diameter (MD) (NYORC dataset no. 1), the hip-to-hip breadth

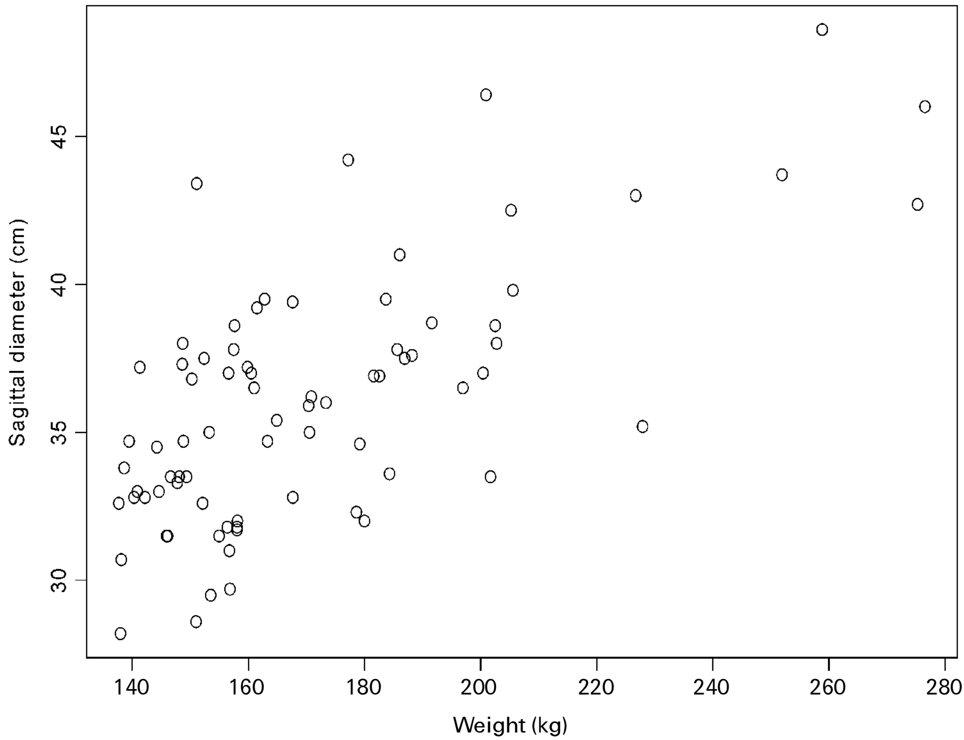

Figure 11. Scatter plot of the relationship between sagittal abdominal diameter (SAD) and weight derived from NYORC dataset no. 2.

(BIB; NHANES III dataset) and the sagittal abdomen diameter (SAD; NYORC dataset no. 2) ranged from 0.09 to 0.11. The consistency of these coefficients across both the different body size measurements and the three data sets suggests a fairly systematic linear relationship between weight and maximum body diameter measurements.

It should be noted, however, that BIB measurements in NHANES III were not taken while the individual was seated. A BIB on a seated person is likely to be somewhat larger than that for a recumbent person. Moreover, more complex models (i.e. higher order terms, the inclusion of variables such as age and gender, nonlinear transformations, etc.) could have been used. The main advantage of simple linear regression models, however, is their ease of use. Using the simple models it was found that, for each gain of 10 kg (22.04 lb) above 136 kg (300 lb), an individual's BIB, MD, and SAD measurements tend to increase by roughly 0.9–1.1 cm. These estimates may be particularly useful when a simple understanding of general trends is needed, as is the case for the manufacturing of wheelchairs, toilets, and furniture. It should be noted that a substantial proportion of the participants in NYORC datasets nos. 1 and 2 required the use of assistive devices, including wheelchairs, for ambulation.

In conclusion, it has been found that, despite the use of slightly different body size measurements across three independent data sets, the results obtained were similar. Given the ever-increasing prevalence of obesity and severe obesity in the developed world (Flegal *et al.* 1998, Popkin and Doak 1998, Mokdad *et al.* 1999, Antipatis and Gill 2001), however, further work, ideally international in scope, is needed to develop more complex anthropometric methods with increased precision and the requisite statistical methods to interpret these. Such methods could include the development of confidence limits for the predicted upper percentiles. None the less, the results from these simple models may help manufacturers to begin to develop products and services that are more appropriate for severely obese individuals

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