WHOLE-BODY CENTER OF MASS LOCATION IN SEATED POSTURES

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14. ABSTRACT

The location of the body center of mass (CM) is useful for a wide range of biomechanics analyses relevant to the design of seats, chairs, restraint systems, and other products and environments intended for human use. The body CM is usually estimated by summing the contributions of individual body segments, often using on cadaver-based estimates calculated from regression equations, using standard anthropometric variables as inputs. However, torso CM location may not be well estimated by these methods for seated postures, in which the torso is in a markedly different posture than the supine in which cadavers are segmented. For the current analysis, whole-body laser scan data were analyzed to estimate the location of the center of mass in relaxed seated postures. Scan data from 447 women and 315 men were analyzed by computing the center of volume of horizontal slices through the body from the knees through the top of the head, excluding the upper extremities. Constant density was assumed. Estimates of the mass of the legs and upper extremities were applied at the knees and elbows, respectively. The fore-aft CM location was significantly related to body weight. In the measured posture, the CM is about 220 mm forward of the back of the buttocks for adult men of median body mass (about 77 kg). The average fore-aft CM location for a person with a body mass of 140 kg (308 lb) is about 273 mm forward of the back of the buttocks, a difference of 63 mm.

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ABSTRACT

The location of the body center of mass (CM) is useful for a wide range of biomechanics analyses relevant to the design of seats, chairs, restraint systems, and other products and environments intended for human use. The body CM is usually estimated by summing the contributions of individual body segments, often using on cadaver-based estimates calculated from regression equations, using standard anthropometric variables as inputs. However, torso CM location may not be well estimated by these methods for seated postures, in which the torso is in a markedly different posture than the supine in which cadavers are segmented. For the current analysis, whole-body laser scan data were analyzed to estimate the location of the center of mass in relaxed seated postures. Scan data from 447 women and 315 men were analyzed by computing the center of volume of horizontal slices through the body from the knees through the top of the head, excluding the upper extremities. Constant density was assumed. Estimates of the mass of the legs and upper extremities were applied at the knees and elbows, respectively. The fore-aft CM location was significantly related to body weight. In the measured posture, the CM is about 220 mm forward of the back of the buttocks for adult men of median body mass (about 77 kg). The average fore-aft CM location for a person with a body mass of 140 kg (308 lb) is about 273 mm forward of the back of the buttocks, a difference of 63 mm.

INTRODUCTION

Information on human center of mass (CM) locations in seated postures is useful for a variety of design and analysis problems. CM locations are usually estimated by summing the contributions of the masses of individual body segments. The body segment masses are estimated using regression equations developed from cadaver studies (e.g., McConville et al. 1980). Recently, three-dimensional imaging techniques have made it possible to estimate body mass distributions from body contour data.

The Civilian American and European Survey Anthropometry Resource (CAESAR) study gathered whole-body laser-scan data from over 2300 U.S. civilians with a wide range of body dimensions in the late 1990s. Participants were scanned in three postures, shown in Figure 1, and a set of standard anthropometric measures, such as stature and body weight, were recorded. Each scan data file contains over 100,000 polygons representing the surface contour of the participant's body.

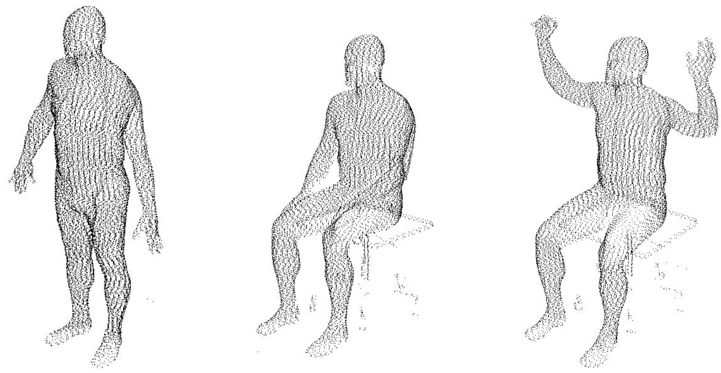

Figure 1. The three CAESAR scan postures: standing, relaxed-seated, and coverage-seated (from left). Approximately one-tenth of the surface data points are shown.

The CAESAR data can be used to estimate body mass distributions by computing the volume enclosed by the body scans and applying an estimate of body density. This report presents an analysis of whole-body CM location in the relaxed-seated scan posture. The CM locations are reported with respect to the back of the buttocks (fore-aft) and the seat surface (vertical). The back-of-buttock point was estimated from the location of a 50-mm cube placed on the seat surface in contact with the sitter's buttocks on the lateral midline.

METHODS

Data Source

A subset of the "relaxed seated" scan data have been converted to a standardized torso-model format for detailed analysis. Figure 2 shows one of the torso models, which consist of the body contour from the knees to the top of the head, with the arms removed below the shoulders. The torso models consist of slices at 12 mm vertical increments with 60 surface points per slice. Torso models from 447 women and 315 men were used for the current analysis. The sample is not representative of any particular population, but the female sample includes all of the obese women in the U.S. CAESAR sample.

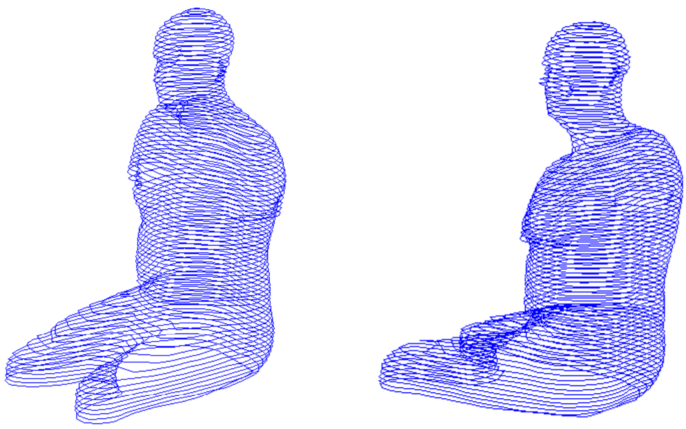

Figure 2. Sample torso model of a large man.

Calculating Whole-Body Center of Mass

Figure 3 shows several torso models. For each model, the volumetric centroid of each slice has been calculated (dark dots). The weighted average of these centroids is the estimated center of mass location for whole torso model. The mass can be estimated by multiplying the calculated volume by 1 g/cm^3, which is approximately the average body density. For the individual in Figure 2, the estimated torso model mass is 85 kg, or 83 percent of whole-body mass. The torso model center of mass is located 310 mm above the seat surface.

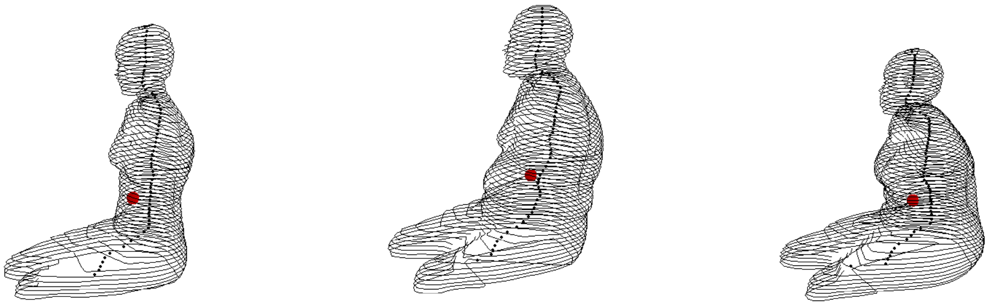

Figure 3. Slice centers of mass (black dots) and torso-model center of mass (large red dot).

Adding Arms and Legs

Because the torso models lack the lower extremities below the knees and the upper extremities below the shoulders, the contribution of these segments to the overall center of mass was estimated. The calculated mass for the torso model was subtracted from the whole-body mass (measured for the CAESAR subjects using the standard method) to quantify the missing mass. The missing mass, which was typically about 20% of total body mass, was divided between the lower and upper extremities using the constant proportion of 0.57/0.43. The proportion was obtained from the body segment masses given by NBDL (1988) for a large male, after reducing the arm mass by 20% to account for the portion of the upper arm that is included in the torso models. The weight of the right and left legs and feet was applied 39% of the distance from the knee joint to the ankle joint (NBDL 1988). The arm, forearm, and hand mass was applied at the elbow.

RESULTS

Figure 4 shows the whole-body center of mass (CM) fore-aft location with respect to the back of the buttocks. The average fore-aft CM position was about 10 mm larger for the women in the sample than for the men. The fore-aft CM position was approximately linearly related to body mass by the function

$$\text{CMX (mm)} = 155 + 0.848\ \text{BM},\ R^2 = 0.51,\ \text{RMSE} = 16.7\ \text{mm} \qquad [1]$$

where CMX is the location of the CM forward of the buttocks, BM is the whole body mass in kg (in minimal clothing, without shoes), and RMSE is the residual (root mean square) error from the regression. The slope of the linear relationship was not significantly different for men and women.

Equation 1 indicates that the fore-aft CM position in the measured posture is about 220 mm forward of the back of the buttocks for adult men of median body mass (about 77 kg). The average fore-aft CM location for a person with a body mass of 140 kg (308 lb) is about 273 mm forward of the back of the buttocks, a difference of 63 mm.

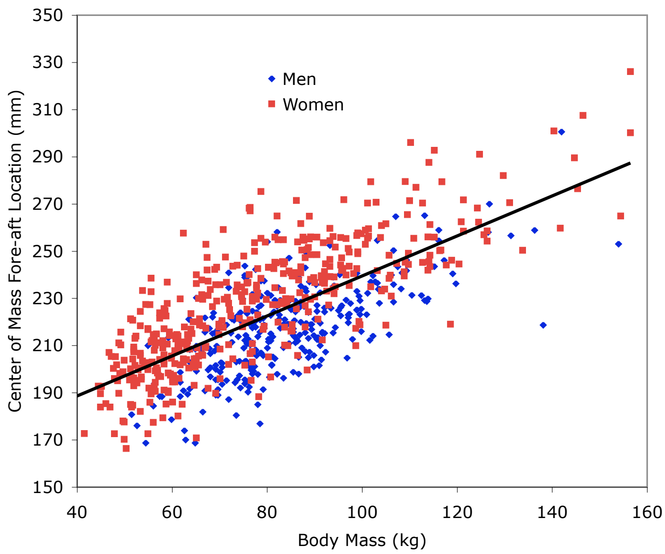

Figure 4. Fore-aft location of whole-body center of mass relative to back of the buttocks as a function of body mass. The average female value is 10 mm greater than the average male value (p<0.01), but the slopes of the linear regression lines are not significantly different. The linear fit shown is for both men and women. R^2 for the regression is 0.51, root mean square error is 16.7 mm.

Figure 5 shows the vertical position of the center of mass with respect to the seat surface. The average value for men (244 mm) is significantly higher than for women (226 mm) in this sample ($p<0.001$). The overall average, weighted for a 50/50 male/female mix, is 235 mm. The height of the CM above the seat surface is not significantly related to body mass in this sample.

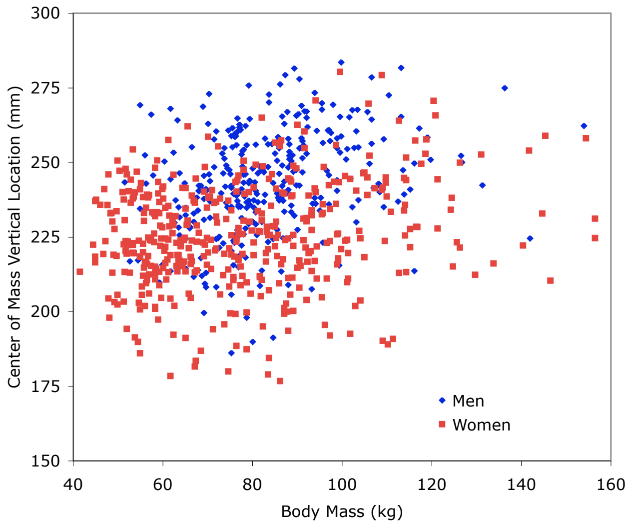

Figure 4. Vertical location of whole-body center of mass above to the seat surface as a function of body mass.

DISCUSSION

The observed effect of body mass on center of mass location is relatively small, less than 65 mm, on average, for an increase in body mass from 77 kg to 140 kg. The scatter in the relationship shown in Figure 5, quantified by the RMSE for equation 1, suggests that the CM locations about 95% of people weighing 140 kg will lie within 273 + 1.64*16.7 = 300 mm of the back of the buttocks.

The most important limitation on the applicability of these results is the correspondence between the measured posture and the application posture. The scans were obtained with the participants sitting with no backrest in a "comfortable working" posture. If a backrest were available, the participants may have reclined against the backrest, resulting in a more rearward CM location. Of course, a sitter could also lean forward, possibly supported by armrests, producing a more-forward CM location. One way to quantify the likely magnitude of this effect is to pivot the calculated CM location around a point on seat surface lying directly below the CM. Given that the average CM height above the seat is about 230 mm, reclining by 10 degrees can be expected to move the average CM rearward by approximately 235 Sin(10˚) = 41 mm. If posture data or predictive models are available for a particular application, more accurate estimates could be obtained by re-posturing the torso models prior to calculating CM locations.

Because of the limitations of the sample used for this analysis, the distributions of results for men and women are probably not accurate representations of the distributions for any particular population of interest. For example, compared to the U.S. population as a whole, the male sample used for this analysis contains proportionately fewer men with high body mass and slightly more women with high body mass. The sample used for this analysis also has more women than men, although the results do not suggest that this bias has a large effect. The results could be reweighted to represent any particular target population, but the differences would be small for typical populations (e.g., U.S. adults).

The calculation procedures used several approximations that probably had negligible effects on the results. The entire body volume was assumed to have a density of 1 gm/cm^3, whereas the head and extremities are usually slightly more dense and the abdomen slightly less dense. Some error was also introduced in using proportional estimates for the lower and upper extremities, but the magnitude of this effect is small, considering that the total estimated segment mass was generally only about 20% of the total body mass.

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