
Anthropometric and Postural Variability: Limitations of the Boundary Manikin Approach

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ABSTRACT

Human figure models are commonly used to facilitate ergonomic assessments of vehicle driver stations and other workplaces. One routine method of workstation assessment is to conduct a suite of ergonomic analyses using a family of boundary manikins, chosen to represent a range of anthropometric extremes on several dimensions. The suitability of the resulting analysis depends both on the methods by which the boundary manikins are selected and on the methods used to posture the manikins. The automobile driver station design problem is used to examine the relative importance of anthropometric and postural variability in ergonomic assessments. Postural variability is demonstrated to be nearly as important as anthropometric variability when the operator is allowed a substantial range of component adjustment. The consequences for boundary manikin procedures are discussed, as well as methods for conducting accurate and complete assessments using the available tools.

INTRODUCTION

The design of workstations, including automobile interiors, now often includes the use of human figure models. Implemented as computer software, these models provide extensive capability to represent people with a wide range of body sizes and shapes (1). In typical use, a number of manikins representing anthropometric extremes of the target user population are placed in a virtual mockup of the system to be evaluated. The design is evaluated with respect to the users' reach, vision, clearance, and other requirements.

The family of manikins used in automobile design applications usually includes both males and females and emphasizes people who have one or more extreme dimensions, such as stature or sitting height. These human figures are often referred to as boundary manikins, because some of their anthropometric dimensions lie on the boundaries of the anthropometric ranges that are to be accommodated by the design.

The use of anthropometric boundary manikins to evaluate a design is based on the assumption that the evaluated variables (reach, vision, etc.) are affected to an important extent by anthropometric variables. For example, driver head clearance to the roof is reasonably assumed to be related to the sitting height of drivers, so evaluating the headroom using drivers who are extreme in sitting height might be useful. The selection of boundary manikins must be based on a careful evaluation of the anthropometric variables that are importantly related to fit or accommodation in the particular environment to be evaluated.

Although body dimensions do affect driver vision, reach, and clearances, anthropometry does not account for all of the observed range of driver posture and position. This paper examines the extent to which body dimensions determine posture, and hence the extent to which boundary manikins can be used to evaluate population accommodation in a design. Similar analyses reaching comparable conclusions have been conducted in other recent studies (2-5), but this paper is the first to focus on posture variance not attributable to anthropometry.

METHODS

The examples in this paper are based on data collected in a study of driver eye locations (6). In that study, eye locations and other measures of driver posture were collected for 50 to 120 drivers in each of 33 vehicles. The data were recorded after the drivers had selected their preferred driving positions while operating the vehicle over a road route.

Men and women with a wide range of stature and age were recruited by newspaper ads to participate. In each session, they drove four to six vehicles. The driver adjusted the seat and steering wheel to obtain a comfortable position, and then drove the vehicle for about 15 minutes, readjusting as necessary. When the driver returned to the measurement station, a Faro Arm coordinate measurement machine was used to record the three-dimensional location of body landmarks describing the posture, including eye locations.

Seat positions and driver eye locations from a typical vehicle were used for this analysis. Regression and principal component analysis were used to examine the relationships among the dependent measures and to determine the extent to which the posture variables could be predicted from body dimensions. For clarity, the data from a single vehicle are used, but the conclusions have been found to be generally valid for passenger cars and light trucks (3, 6).

RESULTS

DRIVER SEAT POSITION – Figure 1 shows driver-selected seat positions for 96 men and women in a late-model passenger car equipped with a two-way (fore-aft-adjustable) seat track. These data were collected after the subjects drove the vehicle on a fifteen-minute local road route. The seat position is expressed as the horizontal position of the seat H-point aft of the Ball-of-Foot landmark on the accelerator pedal.

The seat positions are plotted with respect to stature, which varies from shorter than the 5th-percentile for U.S. females to taller than the 95th-percentile for U.S. males. The figure shows that fore-aft seat position has a strong linear relationship with stature. The R^2 value for a linear regression fit (shown in the figure) is 0.67, with a root mean square error (RMSE) of 30.1 mm. While stature accounts for a substantial percentage of the variance in seat position, there is considerable residual variance. In each narrow stature range, there is a large range of fore-aft seat position. For example, people with statures near 1650 mm have seat positions extending over an 80-mm range. The standard assumptions of linear regression are well met in this case, so the residual variance in seat position, after taking into account stature effects, is well modeled by a normal distribution having mean zero and standard deviation equal to the RMSE. Figure 1 shows the residual variance distributions for each boundary stature along the vertical (seat position) axis).

A reasonable assumption is that including additional anthropometric variables will improve the prediction and reduce the residual variance. In particular, fore-aft seat position might be related more strongly to leg length than overall stature. Since functional leg length is difficult to measure, an effective leg length calculated as stature minus erect sitting height was used as a potential predictor. In this case, the R^2 value is 0.68, with an RMSE of 29.6 mm. Leg length has only slightly better predictive ability than stature. Another way to include a persons “limbiness” in the prediction is use both stature and the ratio of sitting height to stature as predictors. This approach gives an adjusted R^2 value of 0.69 and an RMSE of 29.1 mm, again showing that stature is approximately as effective as leg length dimensions in accounting for seat position. Similar analyses with data from dozens of vehicles and hundreds of drivers has shown that these conclusions are generalizable: after accounting for driver anthropometry, the residual

variance in seat position in any given vehicle has an average standard deviation of about 30 mm (3).

The finding that stature is the primary anthropometric factor affecting driver-selected seat position might lead to the selection of two boundary manikins at extremes of stature to determine the seat track adjustment range. Suppose the objective is to develop a seat track that will accommodate 95 percent of the U.S. adult population. Applying the typical boundary manikin approach, a small female manikin of 5th-percentile female stature (1511 mm tall) and a large male manikin of 95th-percentile male stature (1870 mm tall) would be chosen.

The observed linear relationship between stature and seat position can be used to identify the most likely seat position to use with these boundary manikins. Using the regression model for the vehicle in Figure 1, the fore-aft seat position for the small female boundary manikin is 826.7 mm aft of the accelerator pedal, while the large male manikin would be positioned with the seat 974.7 mm aft of the accelerator pedal. Under the assumptions of the regression model, these are the most likely (mean) seat positions expected for people with the specified statures. Figure 1 shows the relative mean seat positions predicted for these two boundary manikins, along with the distribution of seat positions expected for people who have these two statures. Because seat position is not perfectly predicted by stature (or any combination of anthropometric variables), people who have a particular stature can be expected to choose any of a range of seat positions, modeled as a normal distribution with a standard deviation of 30 mm. Note that the seat-position distributions for these two extreme statures span a considerable portion of the overall seat position distribution, and even overlap slightly in the middle of the seat track range.

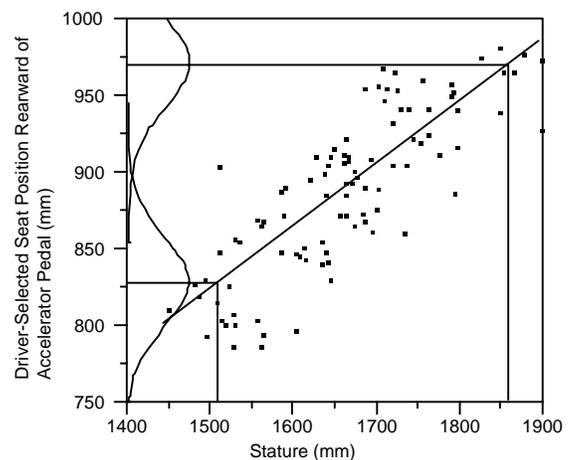


Figure 1. Fore-aft driver-selected seat positions (H-point locations) aft of the ball-of-foot landmark on the accelerator pedal for one vehicle. Fit line is linear regression predicting seat position from stature. Horizontal and vertical lines show predicted seat positions for small women and large men. Seat position distributions are discussed in text.

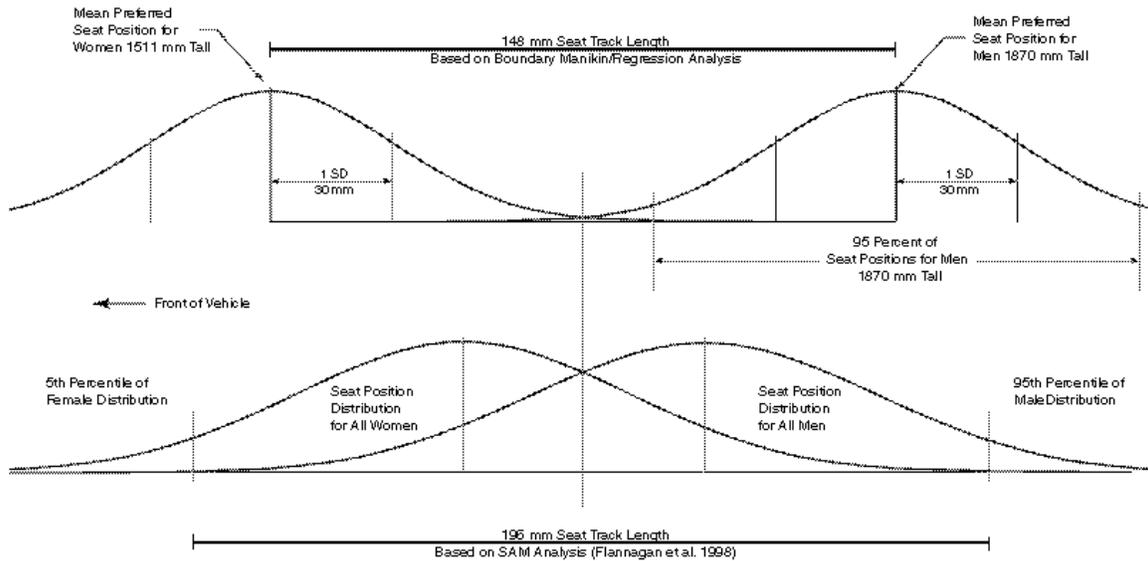


Figure 2. Illustration of seat position distributions. The top curves show predicted seat positions for large men (right) and small women (left). The bottom curves show distributions of seat positions for all men and women, along with the seat track length necessary to accommodate 95 percent of the combined population.

Figure 2 compares the predicted seat positions for the boundary manikins to the overall distribution of male and female seat positions, for men and women of all statures. The overall distributions were calculated from the UMTRI Seating Accommodation Model (3). Because of the residual variance not accounted for by stature, the seat track length that is required to accommodate 95 percent of the a 50-percent-male U.S. driver population is 26 percent larger than the track length between the mean seat positions of people who span 95 percent of the population stature.

The preceding illustration demonstrates that using mean predicted postures for boundary manikins spanning 95 percent of the stature range will result in a seat track design that accommodates substantially less than 95 percent of the target population. As the regression analysis in Figure 1 demonstrates, about 30 percent of the variance in seat position is not accounted for by anthropometry. Many other design evaluations are affected by seat position. Knee position and clearance, for example, are determined by the interaction between thigh length and seat position. A knee bolster position based on an analysis with these boundary manikins would be excessively restrictive to some occupants.

DRIVER EYE LOCATION – Driver eye location is perhaps the most important variable for evaluating a vehicle design. The design of the instrument panel, in particular, is based on eye location. From an anthropometric perspective, vertical eye location can be expected to be influenced primarily by torso length (erect sitting height). Fore-aft eye location might be influenced by seat position (shown to be influenced by stature) and possibly some other anthropometric variables related to torso recline angle (the driver seat back angle was driver-adjusted in this study).

Figure 3 shows measured driver eye locations for 96 men and women in the same vehicle from which the data in Figure 1 were generated. Eye location is given in millimeters above accelerator heel point and aft of the ball of foot landmark on the accelerator pedal (6). Note that the distribution of eye locations angles downward slightly at the front. As noted above, shorter-statured people tend to sit further forward. Since they also tend to have shorter torsos, their eye locations are lower than for taller people sitting more rearward.

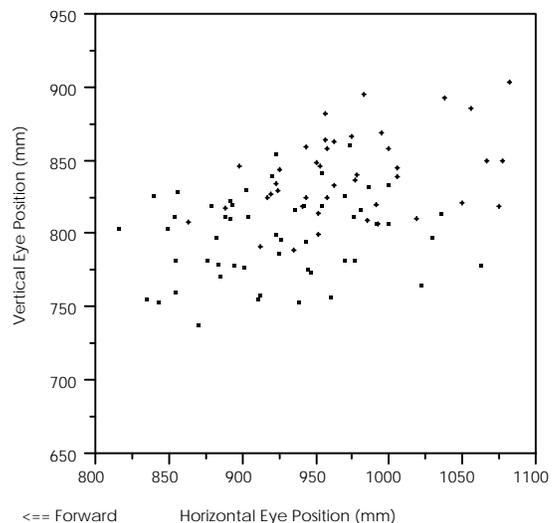


Figure 3. Driver eye locations relative to accelerator heel point (Z) and ball of foot (X) in one vehicle for 42 men (+) and 54 women (•).

A regression analysis shows that driver eye location in the fore-aft direction can be predicted from stature, while vertical eye location is best predicted by sitting height. Because the correlation between stature and sitting

height is so strong ($r = 0.91$ in these data) either variable could be used alone to nearly equal effect. However, using sitting height for the vertical component and stature for the fore-aft component preserves the expected relationships between the anthropometric and postural variables. To simplify this example, only data from males ($N=42$) are included in the subsequent analysis. For this vehicle, the regression functions are:

$$\begin{aligned} \text{Eye}(X) &= 273.0 + 0.4008 (\text{Stature}), \\ R^2 &= 0.33, \text{RMSE} = 43.8 \end{aligned} \quad (1)$$

$$\begin{aligned} \text{Eye}(Z) &= 349.0 + 0.5388 (\text{Sitting Height}), \\ R^2 &= 0.62, \text{RMSE} = 15.5 \end{aligned} \quad (2)$$

Both the R^2 value and the RMSE for Eye(X) show that a considerable amount of variance in the fore-aft eye location remains unpredicted by stature. As with fore-aft seat position, adding anthropometric variables to the analysis does not substantially improve the fit. This large residual variance results from differences in posture among individuals with similar body dimensions.

With two anthropometric variables used as inputs to posture prediction, the selection of boundary manikins is more complex. Two different approaches are used for this illustration, although there are many other possible techniques. In both cases, the objective is to capture in the selection of boundary manikins the bivariate variability in stature and sitting height. Figure 4 shows the distribution of stature and sitting height for men in a survey of U.S. army personnel, known as ANSUR (7).

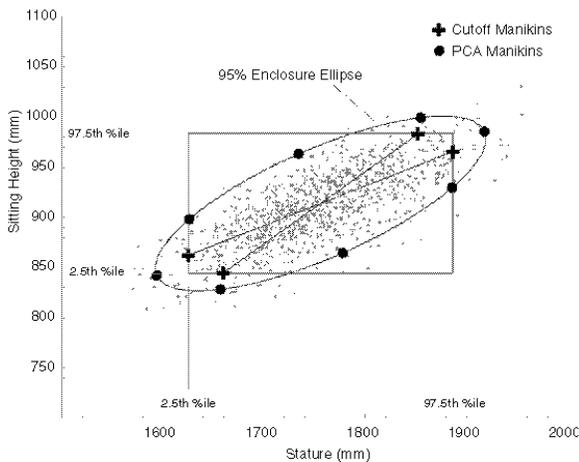


Figure 4. Distribution of male stature and sitting height (7), illustrating the selection of two types of boundary manikins.

The first family of manikins, termed “cutoff manikins,” are created by generalizing one-dimensional methods to multiple dimensions. In Figure 4, a box is constructed by drawing lines at the 2.5th and 97.5th percentiles of both the sitting height and stature distributions, spanning 95 percent of the distribution on each dimension. Linear regressions of stature on sitting height and sitting height on stature are performed, resulting in the crossed lines

seen in Figure 4. Cutoff manikins are defined at the points where the regression lines intercept the box. The resulting family of four manikins includes two representing the desired accommodation boundaries in stature and two in sitting height. For each manikin, the value of the second anthropometric variable is set to the most likely value, given the first. For example, when the stature is set to the 97.5th percentile, the sitting height is selected to be the average (most likely) sitting height for people who are that stature.

Another approach to boundary manikin selection is based on principal component analysis and is known as the PCA method (8). This method of selecting boundary manikins is widely used, particularly for military applications such as cockpit design (9). As input to the PCA, anthropometric dimensions that are expected to be related to accommodation are selected. In this example relating to eye location, only sitting height and stature are used, but more dimensions would be needed for a more general analysis.

A principal component analysis is conducted using anthropometric data for the selected measures obtained from a representative population. The PCA identifies the orthogonal directions within the anthropometric space in which the data have the greatest variance. These principal component directions are eigenvectors of the data covariance matrix. A small number of the strongest principal components are chosen to represent the whole dataset. Often, the first three principal components are chosen, which together will typically represent about ninety percent of the variance from six to ten anthropometric variables (8, 9).

Each of the principal components (eigenvectors) has an associated eigenvalue, which can be interpreted as the variance in the anthropometric data along the eigenvector. Using the (generally reasonable) assumption of multinormality, an ellipsoid can be constructed in the space defined by the principal components that encloses a chosen percentage of the anthropometric distribution.

In the current example, only stature and sitting height are used, so two principal components completely characterize the bivariate distribution (under the reasonable assumption of bivariate normality). Figure 4 shows the male sitting height and stature distributions from ANSUR, with an ellipse oriented according the two principal components and scaled to enclose 95% of the distribution. Following a typical approach (9), eight boundary manikins are selected on the perimeter of the ellipse, four on the principal components and four at points between them, as shown in Figure 4. This family of boundary manikins, constructed using these stature/sitting height pairs, will be termed PCA manikins. The PCA method, in this case, results in some manikins that have individual dimensions (sitting height or stature) exceeding the 99th percentile, or smaller than the first percentile.

For each boundary manikin identified in Figure 4, an eye location can be predicted using equations 1 and 2. Figure 5 shows these eye locations, along with the eye locations measured for 42 men (the data used to develop the regression functions). The predicted boundary-manikin eye locations span a much narrower range than the actual measured eye locations. For comparison, Figure 5 includes an ellipse estimated to include approximately 95 percent of eye locations for a male driver population having the same stature and sitting height distribution as the data from which the boundary manikins were developed. The ellipse was created using these data and analysis methods developed in earlier studies of driver eye location (6). The side-view range required to encompass 95 percent of driver eye locations is more than twice the size of the area spanned by even the PCA manikins, which include dimensions greater than the 99th percentile of stature and sitting height.

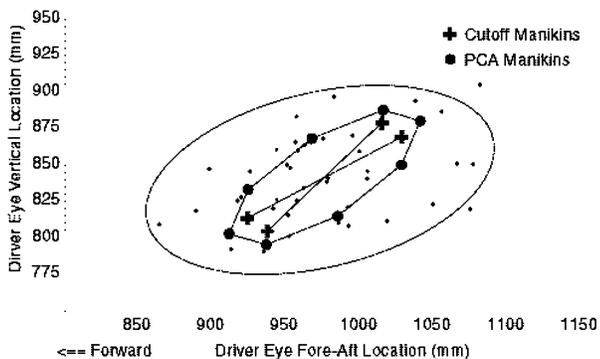


Figure 5. Distribution of 42 male driver eye locations in one vehicle (small dots). Boundary manikin predictions are shown with large dots and crosses. The empirical ellipse is estimated to enclose 95 percent of male driver eye locations.

DISCUSSION

The examples described above illustrate that the importance of postural variability is comparable to that of anthropometric variability for some types of ergonomic analyses. Analytically, we can expect that the importance of non-anthropometric variability will be greatest when the operator has postural flexibility. In the case of the car driver, the fore-aft seat adjustment and seat back recliner allow drivers a considerable range over which to adjust their postures.

Recently, substantial advances have been made in posture prediction for automobile occupants (10). However, improvements in posture prediction based on anthropometry will not eliminate the problem of residual posture variance, which, in general terms, is a typical example of regression to the mean. Analyses of data from hundreds of drivers confirm that 20 percent or more

of postural variance (depending on the variable) cannot be attributed to body dimensions (2, 3, 5, 6). By the nature of the distributions of postural variables, the most accurate posture predictions for extreme anthropometric percentiles will always be less extreme relative to the posture distribution. The posture of the 99th percentile individual on an anthropometric variable will, on average, always be less extreme than the 99th percentile of the related posture variable.

Some methods of posture prediction, such as those that rely on kinematic optimization, might produce a larger range of eye locations or seat positions than the posture-prediction methods used in this paper. Indeed, since some computerized figure models lack data-based posture prediction, a wide range of postures might be chosen for each figure. These wide-ranging postures are in error, however, if the correct posture is defined to be the average posture (mean values on selected posture parameters) for persons matching the anthropometric specifications of the manikin.

Similar observations concerning anthropometric and postural variability were the impetus for the development of the eyellipse (11, 12) and the original SAE driver seating accommodation model (13). However, the limitations of body dimensions as determinants of posture, and the implications for the use of human figure models in ergonomic analysis, have been frequently overlooked in recent years. In particular, the widespread availability of computerized human figure models has led to the use of these tools in ways that do not adequately account for postural variance.

Human figure models are valuable tools for workstation design. The ability to visualize people of a wide range of sizes in typical user postures often leads to more rapid development and the early correction of problems. However, current evaluation methods used with human figure models are not well suited to gauging population accommodation on some important variables. Appropriate manikin-independent design tools using statistical models have been developed for automobile driver seat position (13) and driver eye location (12), and have recently been updated to reflect modern vehicle geometries (3, 6).

Using automated analysis methods, figure models could be used to accurately assess population accommodation for automobile design. A large number of figures constructed based on the target population anthropometry would be positioned in the virtual mockup using accurate posture prediction combined with a random variance component based on data from ergonomics studies. The results of evaluations of hundreds of manikins postured in this way could be used to make accurate judgements about population accommodation.

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