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Assessing the Effects of the Design Population on Seat Dimensions

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16. Abstract

Dimensional recommendations for automotive seat design are often based on populations different from the intended user population. Military data are commonly used to provide guidance for seats used by civilians, for example, because detailed military data are more readily obtained. Even when data from an anthropometric study of civilians are available, target dimensions for automotive seats are often selected under the assumption that the design population is the same as the population measured in the anthropometric study. This report examines the consequences of these assumptions by comparing target values for key anthropometric dimensions for the general U.S. population with estimates for specific populations that may be of interest for seat design. The focus of the investigation is on the importance of gender mix, ethnicity, and market country in selecting target dimensions for seat design. Data from CAESAR, NHANES, the U.S. Census, and ISO 7250-2 were used. The report analysis demonstrates that population definition is important in computing distributions of anthropometric dimensions to be used to guide seat design. In the U.S., gender mix has the potential to be more important than ethnicity distributions across regions.

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ABSTRACT

In widely used ergonomics texts, dimensional guidance for automotive seat design is often based on populations different from the intended user population. Military data are commonly used to provide guidance for seats used by civilians, for example. Even when data from an anthropometric study of civilians are available, target dimensions for automotive seats are often selected under the assumption that the design population is the same as the population measured in the anthropometric study. This report examines the consequences of these assumptions by comparing target values for key anthropometric dimensions for the general U.S. population with estimates for specific populations that may be of interest for seat design. The focus of the investigation is on the importance of gender mix, ethnicity, and market country in selecting target dimensions for seat design. Data from CAESAR, NHANES, the U.S. Census, and ISO 7250-2 were used. The report analysis demonstrates that population definition is important in computing distributions of anthropometric dimensions to be used to guide seat design. In the U.S., gender mix has the potential to be more important than ethnicity distributions across regions.

INTRODUCTION

Seat dimensions are critical in determining the comfort of a seat. A seat that is too long or too narrow can rapidly produce discomfort. Many seats are designed using dimension recommendations from ergonomics texts (e.g., Pheasant 1996, Diffrient et al. 1990). These recommendations are typically based on several simplifying assumptions:

1. A human population for which anthropometric data are available is assumed to be sufficiently representative of the design (target) population. For example, many chair and seat design recommendations are based on data from the 1988 U.S. Army anthropometric survey (ANSUR) because those data are publicly available and contain many dimensions of interest. However, the ANSUR population is not the design population for any current seat. The design population is also commonly assumed to be evenly divided between men and women and to match the available anthropometric data with respect to race and ethnicity.

2. A one-to-one mapping between seat dimensions (for example, seat cushion length) and a body dimension (buttock-popliteal length) is assumed, and hence the target dimension for the seat is taken directly from a particular percentile of the body dimension distribution.

3. The explicit goal of the dimension definition is usually accommodation of a particular percentage of the design population, often 95 percent.

4. Univariate disaccommodation is assumed, and either 5^{th} or 95^{th} percentile values of either the male or female distribution of the selected body dimension are used to establish the design target. For example, the 5^{th} percentile of the female buttock-popliteal length is commonly used to specify a target for seat cushion length. If all males are assumed to be accommodated by this dimension, this one-sided disaccommodation will accommodate considerably more than 95% of a two-gender population, depending on the gender mix.

The importance of simultaneous consideration of multiple dimensions when calculating the overall disaccommodation has been highlighted by several researchers (Manjrekar and Parkinson, 2011). The relationship between body dimensions and accommodation is complicated by posture and subjective preference with the relationship closest to 1:1 observed for width measures related to clearance (Reed et al. 1994).

The current analysis focuses on the importance of the design population definition in relation to the population for which anthropometric data are available. That is, how important for seat design is an accurate representation of the design population? And how can the available anthropometric data be used to obtain good design targets for various populations?

Anthropometric data from the U.S. sample of the Civilian American and European Surface Anthropometry Resource (CAESAR) study were combined with data from the ongoing National Health and Nutrition Examination Survey (NHANES) to estimate body dimensions for various possible design populations. Body dimension data from Italy, Japan, and the Netherlands were obtained from ISO 7250-2. The consequences of deviations between the study and design populations and methods for addressing those issues are discussed.

METHODS

Variable Selection

Example calculations were conducted using three variables related to seat design. Seated hip breadth (SHB) is the maximum breadth at the hips when the subject is seated erect on a flat, rigid platform with the knees together and thighs horizontal. SHB is a useful dimension in seat design that is related to the clearance needed in the hip area. Buttock-popliteal length (BPL) is the horizontal (fore-aft) distance from the maximum rearward protrusion of the buttocks to the popliteal fossa at the back of the knee, obtained in the same posture as hip breadth. BPL is related to dimensional requirements for seat cushion length. Because BPL is not available in CAESAR, the current analysis uses buttock-knee length (BKL), which is measured to the front of the knee from the same buttock reference point as BPL. For some evaluations, BPL is estimated from BKL (see below).

Seated acromion height (SAH) is measured from the rigid, flat sitting surface to the acromion process of the scapula in the shoulder area with the subject sitting maximally erect and the shoulders relaxed. SAH is related to the length of the torso and could be used to estimate the needed backrest height. For the international comparisons, seated shoulder height is used and assumed to be equivalent to SAH. As shown below, SHB is strongly related to BMI but not stature, BKL is strongly related to both stature and BMI, and SAH is closely related to stature but not BMI.

Population Definitions and Data Sources

Detailed body dimension data were obtained from the Civilian American and European Surface Anthropometry Resource (CAESAR) dataset (Robinette et al. 2002). The U.S. sample of 2400 adults sampled at five locations across the U.S. was used for the current analysis. CAESAR is a convenience sample of people with a wide range of body size that must be weighted to represent any particular population of interest.

Anthropometric and race/ethnicity distribution data for the U.S. adult population were obtained from the ongoing National Health and Nutrition Examination Survey (NHANES). Using a probability sample of U.S. civilians, NHANES examines several thousand people every year. A small number of anthropometric dimensions are recorded along with many other measures of health and development. Since 1999, NHANES data have been released in two-year blocks. Data from multiple years can be combined to increase the sample size for statistical calculations. For the current analysis, gender, race and ethnicity, stature, and body weight from 1999 to 2008 (13079 men and 12848 women) were used.

Body measurement data from Italy, Japan, and the Netherlands were obtained from ISO 7250-2. These populations were selected due to the availability of detailed data, representation of both Asia and Europe, including populations among the tallest and shortest in Europe.

The analyses here were conducted with the populations listed in Table 1. Dimensions for populations 1-4 were computed using data from NHANES to establish distributions of stature and BMI by gender. These results were used with regression analyses of CAESAR data to estimate SAH, BKL, and SHB distributions.

Table 1
Reference Populations

Population	Reference	% Males	% Females	Data Sources
1	1999-2008 U.S. Adults	50	50	CAESAR, NHANES
2	1999-2008 U.S. Adults, Female-Preponderant	25	75	CAESAR, NHANES
3	2008 U.S. Adults, Male Preponderant	75	25	CAESAR, NHANES
4	2008 California Adults	50	50	CAESAR, NHANES
5	Japan	50	50	ISO 7250-2
6	Netherlands	50	50	ISO 7250-2
7	Italy	50	50	ISO 7250-2

Calculation Procedure

A reweighting technique based on linear regression was used to obtain U.S. population dimension estimates for the current analysis. The methodology, a simpler version of the procedures introduced by Parkinson and Reed (2010), is illustrated in Figure 1. The CAESAR data contain detailed dimensions of interest (for example, seated hip breadth) but the population is not representative of the design population, or representative within gender/race/ethnicity groups. NHANES has representative stature and body weight data for the U.S. population as a whole, but lacks detailed dimensions. The reweighting procedure is based on mathematical functions describing the relationships between overall dimensions (e.g., stature) and the seating-specific dimensions (e.g., seated hip breadth) from CAESAR. The distributions of overall dimensions estimated for the target population are convolved with the CAESAR-based functions to obtain estimates of the seating-specific dimensions for the target population.

The approach is based on the observation that many dimensions of interest are approximately normally distributed, or can be transformed to be approximately normally distributed. Further, most dimensions of interest (or their transformed versions) are linearly related to stature or a measure of body weight, typically body mass index (BMI) or a transformed version of BMI. (Body mass index is computed as the body weight in kg divided by the stature in meters squared.) This method exploits the fact that a linear transformation of a normal distribution produces a normal distribution with mean and standard deviation that can be calculated directly.

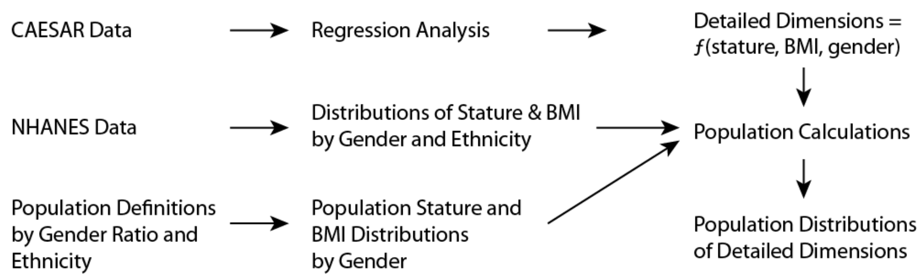

Figure 1. Schematic of regression-based reweighting methodology used for U.S. population dimension estimates.

RESULTS

Regression Relationships in CAESAR

Tables 2 and 3 list regression functions predicting the seating-related dimensions from overall dimensions. We use the inverse of BMI rather than BMI as a predictor to obtain a distribution that is closer to normal. Because the distribution of SBH has a long right tail, particularly for women, we fit the natural log of SBH and take the exponential $e^{\ln(SBH)}$ to obtain the original units. Tables 2 and 3 compare the empirical percentiles with those obtained using the normal approximations. Specifically, we create a predicted normal distribution with the mean value obtained by inputting the means of both stature and 1/BMI into the regression functions. We estimate the standard deviation as

$$\sigma = \sqrt{\sum_k \left(\beta_i s_i\right)^2 + \varepsilon^2} \quad [1]$$

where the β_i are the slopes of the regression predictors (for example, stature), the s_i are the standard deviations of the regression factors, and epsilon is the root mean square error (RMSE) from the regression. This calculation assumes that the predictors are independent of eachother and the residual.

We then take the 95th%ile of the normal distribution given by the estimated mean and standard deviation and compare with the empirical quantile. In effect, this is a test of the extent to which the data and model support the normal distribution assumption. The small delta values in Tables 2 and 3, which in all cases are less than 8 mm and 2 percent, indicate that the normal distribution model is reasonably accurate for estimates of the 95th percentiles of these variables in CAESAR.

Table 2
Regression Functions in CAESAR: Men

Variable	Intercept	Stature	1/BMI	R^2adj	RMSE	95th%ile	Predicted 95th%ile*	Delta (mm)
Seated Acromion Height (mm)	84.95	0.3161	-1046	0.59	22.01	663	663	0
Buttock Knee Length (mm)	95.09	0.3401	-2132	0.72	18.84	679	680	1
Seated Hip Breadth † (mm)	5.618	0.0004281	-11.59	0.78	0.04297	447	446	-1

* Predicted using normal distribution approximation of predictors.
† Equation predicts natural log of seated hip breadth. Percentiles are in original units.

Table 3
Regression Functions in CAESAR: Women

Variable	Intercept	Stature	1/BMI	R^2adj	RMSE	95^{th}%ile	Predicted 95^{th}%ile*	Delta (mm)
Seated Acromion Height (mm)	130.3	0.2838	-688.2	0.50	20.98	616	618	2
Buttock Knee Length (mm)	116.4	0.3524	-2618	0.72	19.69	648	655	7
Seated Hip Breadth † (mm)	5.704	0.0004736	-11.58	0.77	0.05149	492	497	5

* Predicted using normal distribution approximation of predictors.
† Equation predicts natural log of seated hip breadth. Percentiles are in original units.

Population Definitions: Overall Body Dimensions

For each of the populations in Table 1, normal-approximation estimates of stature and 1/BMI distributions were computed for each gender. For the U.S. populations (populations 1-4), the estimates were obtained using NHANES 1999-2008. For population 4, the results were obtained by weighting the overall U.S. population to match the race/ethnicity distribution of California based on U.S. Census data. Using data from www.census.gov, California was estimated to be 40% non-Hispanic White, 5.8% non-Hispanic Black, 37.9% Hispanic (of any race), and 16.3% Asian, Pacific Islander, and other races. For purposes of this analysis, Mexican-Americans were pooled with other Hispanic ethnicities in NHANES. Table 4 shows the 5^{th}%ile, 50^{th}%ile, and 95^{th}%ile for stature and BMI by gender for the U.S. population and the estimated California population. For both men and women, the biggest differences are observed in the stature quantiles, with the median male stature in California about 24 mm shorter than the U.S. median. For women, the difference in stature at the median is 18 mm. The differences in BMI are small, less than 0.5 kg/m^2 in all cases.

Table 4
U.S. Population Estimates from NHANES

Population	Male			Female		
	5^{th}%ile	50^{th}%ile	95^{th}%ile	5^{th}%ile	50^{th}%ile	95^{th}%ile
1999-2008 NHANES						
Stature (mm)	1634	1762	1885	1508	1622	1733
BMI (kg/m^2)	20.5	27.3	38.3	19.4	26.9	41.6
1999-2008 NHANES California*						
Stature (mm)	1608	1738	1871	1490	1604	1720
BMI (kg/m^2)	20.3	27.1	37.9	19.4	26.8	41.1

* Estimated by reweighting the national NHANES data to California's 2010 race/ethnicity. See text.

Table 5 shows reference dimension distributions (means and standard deviations) for each population. Values for the U.S. and California populations were calculated from the CAESAR regression relationships using the NHANES data as inputs. Values for Italy, the Netherlands, and Japan were computed by taking the midpoint between the 5th and 95th percentiles as the mean, and dividing the difference between the 5th and 95th percentiles by 2*1.645 (the standard normal deviate of the 95th%ile) to obtain an estimate of standard deviation. Using this approach, rather than the actual mean and standard deviation given in ISO 7250-2, provides a better fit in the tails of the distribution when using the normal distribution assumption.

Table 5
Population Dimension Estimates, Normal Approximation Mean (SD)

Population	Male			Female		
	SAH	BKL	SHB	SAH	BKL	SHB
U.S.	602 (33.4)	614 (35.3)	379 (36.8)	564 (29.2)	589 (38.0)	417 (48.2)
California	595 (34.3)	606 (36.2)	374 (36.7)	560 (29.4)	583 (38.3)	414 (47.4)
Italy	576 (33.7)*	578 (34.7) †	351 (28.0)	552 (30.7)*	568 (34.0) †	365 (31.9)
Netherlands	627 (37.0)*	643 (36.4)	389 (29.8)	589 (32.2) *	611 (32.5)	425 (37.8)
Japan	588 (27.7)	567 (25.2)	360 (20.1)	545 (25.0)	534 (22.2)	363 (21.5)

* Used seated shoulder height.
† Used 1.2 times buttock-popliteal length.

Table 6 lists the 5th and 95th percentiles for each dimension and population of interest computed from the parameter values in Table 5. The 95th percentile of shoulder height, which could be related to appropriate backrest height, was about 30 mm higher for the Netherlands than the U.S. and more than 50 mm higher than for Italy. These differences are larger than the 20-mm difference for the male and female-preponderant U.S. populations. Buttock-popliteal length was estimated from buttock-knee length by dividing the BKL values by 1.2, using the ratio of BKL to BPL in the data from Italy. In general, seat cushion lengths exceeding an individual's BPL are expected to increase discomfort, so the lower percentiles of BPL are commonly used to establish seat cushion length. For the U.S. population, the difference in the 5th percentile BPL is 11 mm smaller when females are 75% of the target population than when they are 25%. The value for the California population is identical to the female-preponderant U.S. population, reflecting the importance of California's large Hispanic and Asian populations. The upper percentiles of BKL are related to knee clearance requirements, particularly in rear seats. The requirements for a male-preponderant U.S. population are about 10 mm more than for a female-preponderant population, but considerably larger differences are seen between the Netherlands and Italy, where the 95th percentiles differ by 91 mm, about 13%.

For seated hip breadth (SHB), the largest upper-tail value of 490 mm is seen in the female-preponderant U.S. population. Gender mix is most important on this variable: 27 mm less clearance is needed for the male-preponderant U.S. population than for the female-preponderant population to achieve the same level of accommodation.

Table 6
Target Dimensions by Population (mm)

Population	Reference (Fraction Male)	SAH		BKL		BPL*		SHB	
	Quantiles:	5	95	5	95	5	95	5	95
1	1999-2008 U.S. Adults (50%)	525	645	537	664	413	511	325	480
2	1999-2008 U.S. Adults, Female-Preponderant (25%)	520	633	531	659	408	507	330	**490**
3	2008 U.S. Adults, Male Preponderant (75%)	533	652	545	669	419	514	321	463
4	2008 California Adults (50%)	520	640	530	658	408	506	321	476
5	Italy (50%)	**508**	622	516	630	397	485	308	409
6	Netherlands (50%)	545	**675**	566	**691**	435	**532**	347	474
7	Japan (50%)	512	624	**505**	600	**388**	461	327	396

* Computed as BKL/1.2. See text.

An important question is the level of disaccommodation for each population that would be expected for a single seat design. To explore this issue, the percentage of each population with dimensions more extreme than the values for the U.S. population with 50% men (population 1) were estimated. So, for example, the fraction of the population with a hip breadth greater than 480 mm was calculated for each population. In Table 7, all values for population 1 (the reference) are 5%, as expected. On shoulder height, Italy has 12.6 percent of the population below the U.S. 5^{th} percentile value, or more than twice as many potentially disaccommodated on this dimension if the U.S. value were used. In the Netherlands, more than 3 times as many have shoulder height exceeding 645 mm (U.S. 95^{th}%ile value) than in the U.S.

On BKL, the accommodation percentage is somewhat affected by the gender mix in the U.S., but the biggest disaccommodation is seen in Japan. Over one third of the Japanese population would be disaccommodated in thigh length by a seat length based on the 5^{th} percentile of BKL for the U.S. population, which is about 32 mm longer than the 5^{th} percentile of BKL for the Japanese population. On seated hip breadth, designing to accommodate 95% of the U.S. population ensures enough space for more than 95% of the other populations considered, except for the female-preponderant U.S. population, for which only about 93% would be accommodated. A seat designed for the U.S. population would be considerably wider than is necessary for Italy or Japan.

Table 7
Percentage of Population Exceeding 5th and 95th Percentiles for Population 1 (%)

Population	Reference (Fraction Male)	SAH		BKL		SHB	
	Quantiles:	5	95	5	95	5	95
1	1999-2008 U.S. Adults (50%)	5.0	5.0	5.0	5.0	5.0	5.0
2	1999-2008 U.S. Adults, Female-Preponderant (25%)	7.0	2.6	6.8	3.7	3.9	**7.3**
3	2008 U.S. Adults, Male Preponderant (75%)	3.0	7.4	3.2	6.3	6.1	2.7
4	2008 California Adults (50%)	6.8	3.7	7.1	3.5	6.1	4.3
5	Italy (50%)	**12.6**	1.1	15.0	0.4	**14.2**	0.0
6	Netherlands (50%)	1.3	**17.5**	0.7	**16.4**	1.0	3.8
7	Japan (50%)	11.0	1.0	**33.5**	0.0	4.0	0.0

DISCUSSION

Overview of Findings

This analysis demonstrated that design targets for vehicle seats should vary depending on the target occupant population. Analyses of three anthropometric variables related to seat design were conducted for seven alternative design populations to examine the relative size of population differences. Because detailed anthropometric data are not available for most populations of interest, statistical methods were used to estimate dimensions for the U.S. population for three gender mixes and two ethnicity distributions.

Gender mix was more important than the ethnicity differences between California and the U.S. as a whole in determining target dimensions. The most notable difference in California was a smaller thigh length (BKL or BPL), due to the larger percentage of relatively short-statured Hispanics. The percentage of women in the population most strongly affected hip clearance targets.

Including Japan, Italy, and the Netherlands in the comparisons provide some estimates of international differences. As expected, the tall Netherlands population produced the largest target values for shoulder height, but also hip breadth requirements similar to those in the U.S.

Limitations

For clarity, the calculations in this analysis were simpler than those that should be used for seat design problems. In particular, a multivariate analysis that considers all relevant dimensions simultaneously is needed to obtain accurate accommodation estimates. The current univariate analysis neglects the reality that some individuals will be disaccommodated on more than one dimension. A multivariate analysis also allows tradeoffs between dimensions based on cost functions reflecting the relative importance of particular levels of disaccomodation (Manjrekar and Parkinson 2011).

Although used here for purposes of illustration, univariate 5th and 95th percentile values of anthropometric dimensions are rarely the appropriate targets for seat design. Even if disaccommodation on these dimensions is independent across individuals, designing to exclude 5% of the population on each dimension will ensure that the total disaccommodation is much larger than 5%. A multivariate analysis provides the opportunity to identify a design that achieves the desired overall level of accommodation.

The selection of variables in this analysis should not be taken to imply that these body dimensions directly translate to seat dimensions. For example, pelvis posture affects the relationship between buttock-popliteal length and the maximum acceptable seat cushion length, and a seat can be narrower than an individual's hip breadth without producing discomfort if sufficient clearance is provided.

The NHANES-based estimates for California assumed that the body dimensions of Hispanics nationwide match those of Hispanics in California. More generally, the

CAESAR data are assumed to be representative of U.S. civilians after taking into account stature and BMI, and body attributes across ethnicities are assumed to be fully described by stature and BMI distributions. This assumption is known to be faulty for populations, such as Black and Asian-Americans populations, who have an average ratio of sitting height to stature that differs from non-Hispanic White Americans.

Some apparent population differences may be due to differences between studies in measurement technique. This is particularly true for shoulder height, where ISO 7250-2 identifies differences in technique between "shoulder height, sitting" and "seated acromion height" in CAESAR. Nonetheless, differences in measurement methods are believed to be small compared to other factors, such as clothing and the variance in posture across vehicle seats.

A more important problem in the international comparisons is the reliability of the sample. The U.S. analysis is based on NHANES, which is a large-scale, robust, ongoing stratified sample that is weighted to be representative based on U.S. Census data. In contrast, data for Italy are based on a single survey of individuals in their own bathing suits at beach resort locations and may not be representative.

The regression methods used to estimate dimension distributions by combining CAESAR and NHANES are dependent on certain normality assumptions. Transformation of the variables provides a more robust analysis than using untransformed data, but some deviations are unavoidable. For comparisons across populations, the dimensions were assumed to be normally distributed and represented by a single mean and standard deviation. Although these parameter values were selected to fit well in the tails (rather than using the actual means and standard deviations for Italy, Japan, and the Netherlands), the lack of normality in hip breadth means that high percentiles are somewhat underestimated. Nonetheless, the approach used here provides greater clarity for the current purposes than would an analysis using transformed variables.

Conclusions

Population definition is important in computing distributions of anthropometric dimensions to be used to guide seat design. In the U.S., gender mix has the potential to be more important than ethnicity distributions across states, using California as an example. Differences in lower extremity and torso lengths between nations are large enough to be important for design. The upper percentiles of hip breadth in a target population are affected by the percentage of women and national origin.

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