

# Harness Sizing and Strap Length Configurations

Hongwei Hsiao, National Institute for Occupational Safety and Health, Morgantown, West Virginia, Jennifer Whitestone, Total Contact, Germantown, Ohio, Stacie Taylor, Tailored Statistical Solutions, Dayton, Ohio, Mary Godby, Sumaria Systems, Wright-Patterson Air Force Base, Ohio, and Jinhua Guan, National Institute for Occupational Safety and Health, Morgantown, West Virginia

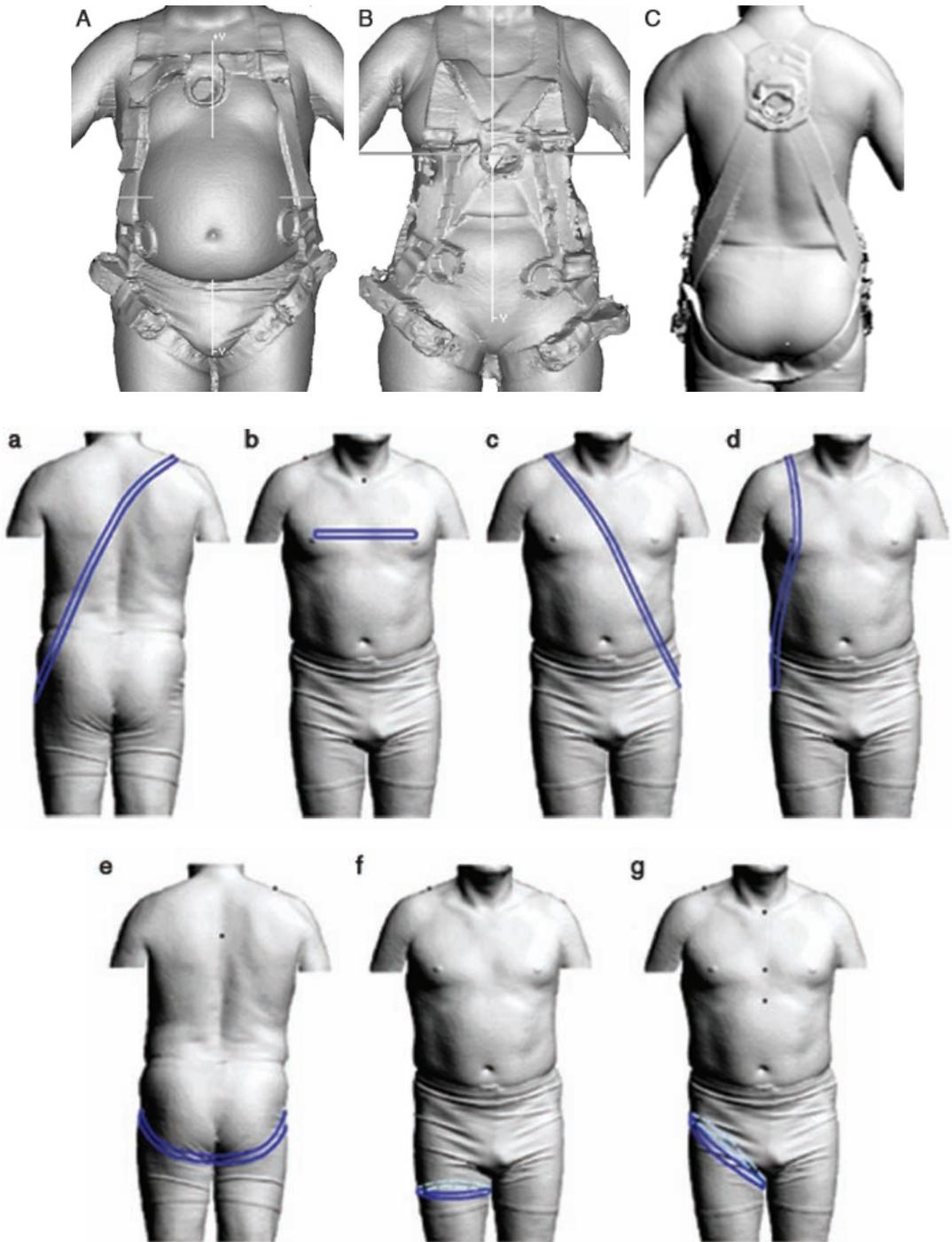
**Objective:** This article describes the derivation of strap lengths and adjustments to fall-arrest harnesses and the development of harness size configurations. **Background:** Updated harness sizing configurations are needed to accommodate diverse populations in the current workforce. **Method:** Three-dimensional torso anthropometric data from 243 women and 258 men were incorporated into eight validated equations to develop a cost-effective harness sizing plan and to define strap lengths. **Results:** To meet strap adjustable range goals and to accommodate 95% to 98% of the estimated population, two sizing options were identified. **Conclusion:** Study outcomes suggest system improvement with three to four sizes for women and three to four sizes for men, on which the adjustment ranges of the torso straps were within 15 to 17 cm and within 20 to 23 cm on thigh and hip straps. **Application:** This research provided harness sizing and cut-length information for harness design to reduce the risk of worker injury that results from poor fit or improper size selection.

## INTRODUCTION

About 6.3 million U.S. construction workers were exposed to fall hazards in 2009 (U.S. Department of Labor, 2009). Early efforts to protect workers from falls involved a simple fall protection system consisting of a waist belt and a lanyard. Studies of serious injury resulting from prolonged suspension in a waist belt led safety professionals to recommend the use of full body harnesses exclusively for fall arrest. The full body harness is an arrangement of straps designed to contain the human torso and to distribute loads in fall arrest to the areas of the body best able to resist the forces of a fall. This includes load-bearing straps around the upper thighs, pelvis, chest, and shoulders (Figures 1A, 1B, and 1C). In 1999, the Occupational Safety and Health Administration (OSHA) promulgated a construction standard under 29 CFR Part 1926 Subpart M that prohibited the continued use of waist belts for fall arrest and specified that only full body harnesses shall be used in a personal fall arrest system.

The modern full body harness has evolved to become a more comfortable, easy-to-use body support system that offers a high level of security for a variety of work tasks at height. However, the basis for determining proper fit of the modern full body harness is rooted in data extrapolated from earlier military studies conducted on service-age males from the 1970s and 1980s. Lacking more robust data, manufacturers of full body harnesses were left to develop their own sizing schemes in the past several decades, based on little more than the anecdotal evidence of their end-user customers. Moreover, U.S. regulations and national consensus standards offered no guidance on proper size and fit for fall protection harnesses, aside from a suggested body weight limit of 59 kg to 141 kg for users.

Unlike the workforce of the early 1990s, when full body harnesses first came into widespread use, today's workforce has changed to include a wider range of body sizes and weights as well as an increased participation by female workers



*Figure 1.* (A) Vest-type harness, front view; (B) overhead-style harness, front view; (C) rear view of vest and overhead harnesses. The seven key harness component dimensions for the two types of harness are (a) back strap, (b) chest strap, (c) front cross-chest strap, (d) front strap, (e) hip strap (gluteal furrow arc), (f) thigh flat strap (thigh circumference), and (g) thigh bikini strap (trochanter-crotch circumference).

exposed to the hazard of falls at the workplace. In addition, changes in U.S. demographics have resulted in many smaller, lighter workers in the U.S. labor force from Asia and Latin America. Changes in U.S. diet have also created demand for fall protection for heavier workers whose weight exceeds 141 kg. Over time, each harness manufacturer was left to adapt their harness designs to the needs of diverse populations. In some cases, manufacturers attempted a “one-size-fits-all” approach to harness sizing in an effort to further simplify selection and reduce costs, whereas some manufacturers simply ignored the trend.

The efficiency of the full body harness in distributing the forces of a fall to the areas of the body best able to resist these loads depends, to a large extent, on how the harness is fitted to the body; the goal of harness design is to establish the minimum number of sizes capable of achieving proper fit of the harness to the widest range of foreseeable body shapes and sizes. In 2002, the National Institute for Occupational Safety and Health (NIOSH) and experienced fall protection manufacturers entered into the study of harness sizing with a goal to collect data that were immediately useful to manufacturers for achieving proper harness fit with the least number of sizes. Using 3-D full body scan data from 108 men and 108 women, Hsiao, Whitestone, and Kau (2007) developed two logistic regression models per gender group to predict the best-fitting size for each of two tested harness types (vest type and overhead style; see Figure 1) with a total of eight equations. The effort was a significant step toward reducing the risk of worker injury resulting from improper fit.

To transfer the initial research findings to general harness design and manufacturing practice, two additional sets of data are needed: sizing configurations for small-size men and large-size women and strap lengths for manufacturing purposes. First, while Hsiao et al. (2007) captured the 3-D torso shape data and human-harness interfaces of 108 women and 108 men from the four racial categories (White, Black, Hispanic, and Other), an expansion of the study to a larger population to include small-size men and large-size women is desirable. However, it is plainly cost-prohibitive to conduct the same type of fit and scan study as Hsiao et al. for a larger population.

One solution to this tractability issue is to apply the eight logistic regression equations from the Hsiao et al. study to an existing, large-scale human 3-D scan database, such as the Civilian American and European Surface Anthropometry Resource (CAESAR) database (SAE International, 2008), to obtain a better assessment of the physical variation of the U.S. workforce.

Second, strap lengths for each harness size need to be determined for design and manufacturing purposes. However, strap length determination is affected by adjustment range. Currently, there are no standard methods or anthropometric data in the literature that can be directly used for deriving harness adjustability and sizing. The same is true for determining strap length configurations. Fortunately, technical experts from the harness industry were able to share their criteria on harness adjustability on a general basis. Per interactions with the harness manufacturing industry, the *common* acceptable adjustable range limit is 17 cm for the back strap, chest strap, front cross-chest strap, and front strap and 23 cm for the gluteal furrow arc, thigh circumference, and trochanter-crotch circumference. A *conservative* adjustable range limit is 15 cm for the back strap, chest strap, front cross-chest strap, and front strap and 20 cm for the gluteal furrow arc, thigh circumference, and trochanter-crotch circumference.

With the availability of (a) the logistic regression models to predict the best-fitting size from the Hsiao et al. (2007) study, (b) a wider range of human torso sizes and shapes from the CAESAR database, and (c) the criteria on harness adjustability from the harness industry, the creation of a harness sizing scheme that optimizes the number of harness sizes and strap lengths for the current working population in the United States can be achieved. This article outlines the derivation of strap lengths and adjustments to the fall-arrest harnesses as well as resulting harness sizing configurations. Through an iterative process, this study determined the most favorable number of harness sizes and their strap lengths while meeting the common and conservative adjustment range criteria for each harness component and provided sizing charts associated with the newly defined sizes. The results of this study have had a direct impact on harness design and have a potential impact on the development of national standards for fall-arrest harness sizing configurations.

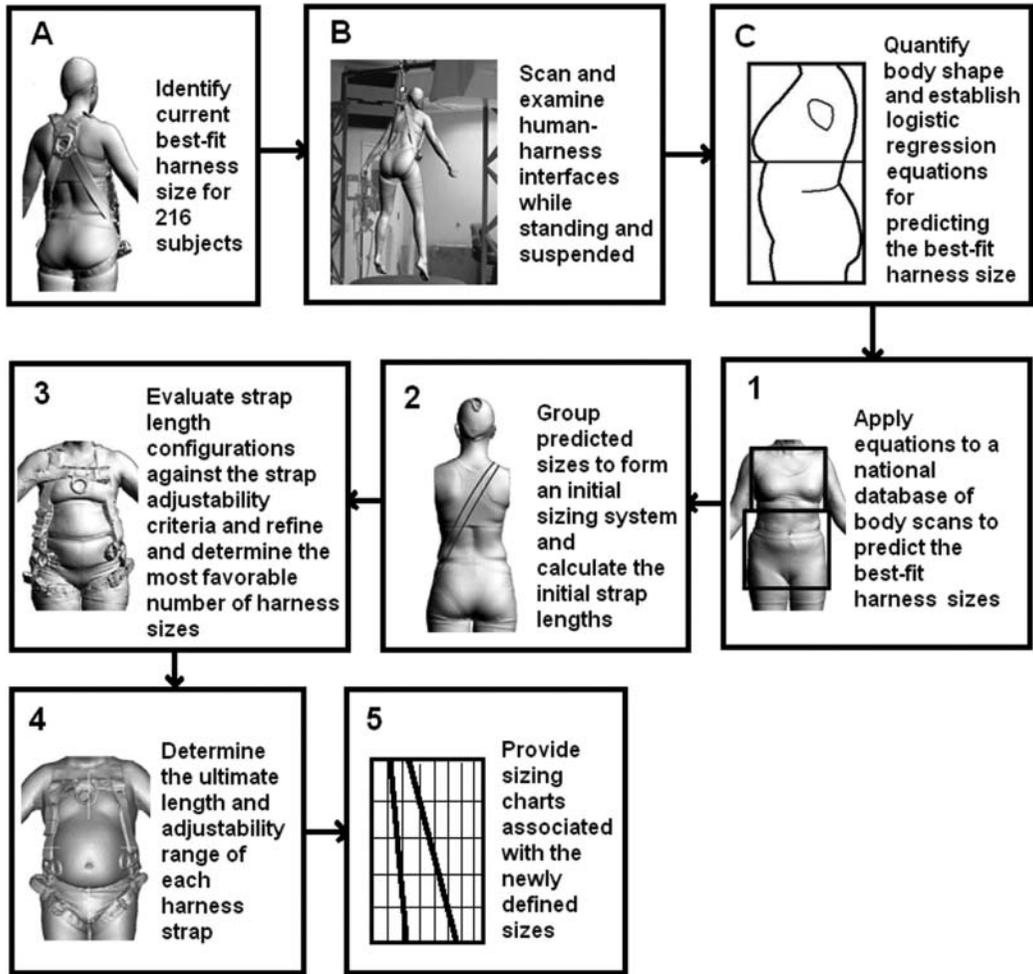


Figure 2. The entire harness sizing research involved with eight steps of action. The first three steps (Actions A, B, and C) were reported in details in Hsiao, Whitestone, and Kau (2007). This article on the derivation of strap lengths and sizing configurations involves the last five steps of action (i.e., Actions 1, 2, 3, 4, and 5).

## METHOD

The entire harness sizing research was divided into eight steps (Figure 2). The first three steps were reported in the Hsiao et al. (2007) study, which identified existing best-fit harness sizes for 216 construction workers, examined their harness-torso interfaces, and established eight logistic regression equations for predicting best-fit harness size. This article, focusing on the derivation of strap lengths and sizing configurations, involves (1) quantifying torso dimensions and shapes of selected representative CAESAR body scans and applying their torso dimension and shape information to the aforementioned eight logistic regression equations to predict the best-fit harness size for

each of them, (2) grouping the predicted sizes to form an initial sizing system and calculating the initial strap lengths, (3) evaluating strap length configurations against the strap adjustability criteria and refining and determining the most favorable number of harness sizes, (4) determining the ultimate mean length and adjustability range of each harness strap, and (5) providing sizing charts associated with the newly defined sizes.

### Quantifying Torso Shapes and Predicting the Best-Fit Harness Size

*Harness size prediction equations.* In the Hsiao et al. (2007) study, eight logistic regression equations for harness sizing prediction were

developed and validated to correctly classify 96% of the study population for the vest-type harness and 100% for the overhead-style harness. This study applied the body shape information obtained from the selected representative body scans of the CAESAR database to these eight equations to predict the best-fit harness sizes for these representative body scans. Each equation was based on upper and lower torso breadth and depth as well as height, weight, and gender, which will be further explained in the next section, Quantification of Torso Shapes and Dimensions. Standard (STD) size was set as the reference size; the resulting probability for choosing a specific size versus STD fell between 0 and 1. The equations for the vest-type harness are described in Vest 1 through Vest 4 and the overhead style in Overhead 1 through Overhead 4.

Vest 1: The probability of wearing extra small (XSM) size instead of STD size for men is  $1 / [1 + \exp(-386.137 + 2.874breadth_{low} + 2.837breadth_{up} - 2.111depth_{low} + 0.675stature + 1.157weight + 1.756depth_{up})]$ .

Vest 2: The probability of wearing XSM size instead of STD size for women is  $1 / [1 + \exp(-385.676 + 2.874breadth_{low} + 2.837breadth_{up} - 2.111depth_{low} + 0.675stature + 1.157weight + 1.756depth_{up})]$ .

Vest 3: The probability equation of wearing extra large (XLG) size instead of STD size for men is  $1 / [1 + \exp(287.430 - 7.9breadth_{low} - 6.007breadth_{up} - 6.557depth_{low} + 1.119stature + 1.7349weight + 4.6849depth_{up})]$ .

Vest 4: The probability equation of wearing XLG size instead of STD size for women is  $1 / [1 + \exp(353.459 - 7.9breadth_{low} - 6.007breadth_{up} - 6.557depth_{low} + 1.119stature + 1.734weight + 4.684depth_{up})]$ .

Overhead 1: The probability of wearing XSM size instead of STD size for men is  $1 / [1 + \exp(-681.075 + 3.894breadth_{up} - 3.66depth_{low} + 3.164depth_{up} + 1.854stature + 2.441weight + 2.001breadth_{low})]$ .

Overhead 2: The probability of wearing XSM size instead of STD size for women is  $1 / [1 + \exp(-657.348 + 3.894breadth_{up} - 3.66depth_{low}$

$$+ 3.164depth_{up} + 1.854stature + 2.441weight + 2.001breadth_{low})]$$

Overhead 3: The probability of wearing XLG size instead of STD size for men is  $1 / [1 + \exp(79.220 - 0.386breadth_{up} - 2.464depth_{low} + 1.77depth_{up} + 0.035stature - 0.409weight - 0.038breadth_{low})]$ .

Overhead 4: The probability of wearing XLG size instead of STD size for women is  $1 / (1 + \exp(81.315 - 0.386breadth_{up} - 2.464depth_{low} + 1.77depth_{up} + 0.035stature - 0.409weight - 0.038breadth_{low})]$ .

In these equations,  $breadth_{low}$  is the breadth of the lower torso,  $breadth_{up}$  is the breadth of the upper torso,  $depth_{low}$  is the depth of the lower torso, and  $depth_{up}$  is the depth of the upper torso.

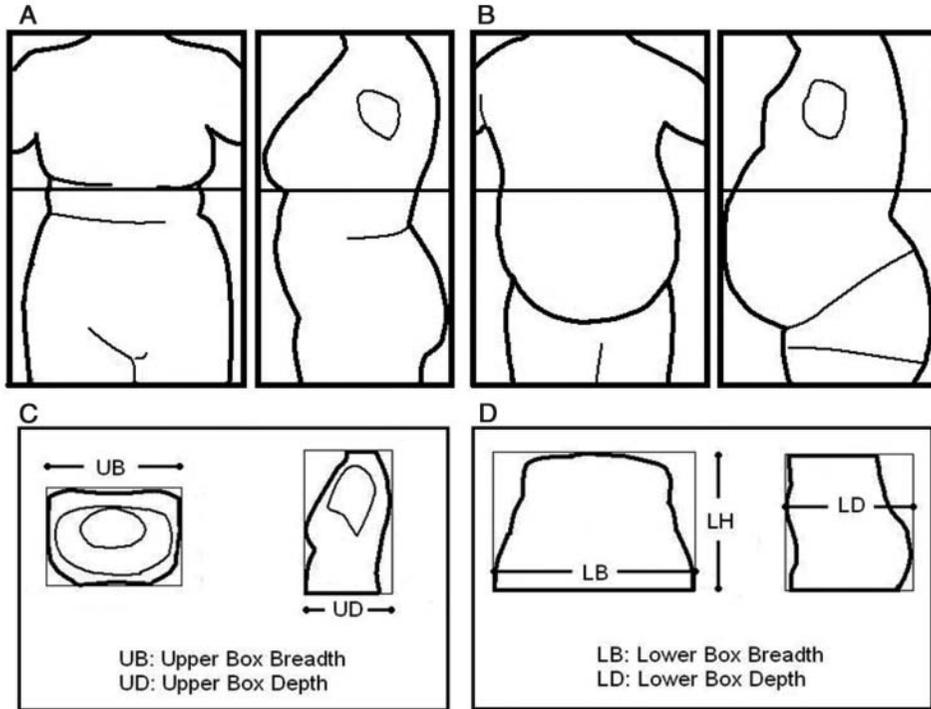
*Quantification of torso shapes and dimensions.* Four bounding box dimensions as well as body height, weight, and gender were used as input parameters to the harness size prediction equations. The bounding box dimensions were the maximum breadth (side-to-side distance) and depth (front-to-back distance) of both the upper torso volume space and the lower torso volume space, which were extracted from the CAESAR 3-D scan images. The 10th rib locations were used to separate the torso images into the upper and lower torso regions (Figure 3). These dimensions were empirically tested and found to suitably explain the interaction of the general body shape and dimensions with harness fit (Hsiao et al., 2007).

*Sample selection.* For anthropometric surveys, good sampling involves determining the sample size as well as determining the sample structure in terms of age, gender, and race. The gender factor was the most critical issue for the harness sizing study (Hsiao et al., 2007).

The needed within-cell sample size (i.e., the number of participants needed for each gender group in this case) can be calculated using the following equation:

$$|\bar{X} - v| = \frac{\delta * \sigma}{\sqrt{n}}$$

where  $|\bar{X} - v|$  is within-cell accuracy,  $\bar{X}$  is the sample mean of the subgroup,  $v$  is the true



*Figure 3.* (A) and (B): The 10th-rib location was used to separate the torso images into the upper and lower torso boxes. (C) and (D): The maximum breadths and depths of upper and lower torso volumes were defined as upper and lower box dimensions. Figures 3A and 3B also show female and male participants, respectively, with the same overall torso length but different size and shape between upper and lower torsos.

mean of the subgroup,  $n$  is the sample size,  $\sigma$  is the standard deviation of the subgroup, and  $\delta$  is the eccentricity (1.96 for 5% two-sided probability).

Based on the standard deviation of stature from the CAESAR database (73 mm for women and 79 mm for men) and the desired cell accuracy of 10 mm for this extended study, the estimated sample size is 204 for women and 240 for men. Namely, at a 95% confidence level, the sample sizes of 204 to 240 would have sufficient power for the sample mean to be within 10 mm of the true mean of the gender group. The sample size was set at 250 as the starting point for each gender. This sample size is small enough to be cost-effective and large enough to contain the human variation needed to allow investigators to examine a full range of body sizes.

Given the physical differences among racial groups, the ethnic mix of the U.S. population needed to be taken into consideration. This can be achieved in two ways. The first option is to

replicate the demographic profile of the U.S. population so that minorities are represented at their actual percentage relative to the entire population. The advantage of this approach is that it allows for a direct estimate of the population parameters without weighting. An alternative is to have a balanced sample containing the same number of males, females, Whites, Blacks, Hispanics, and individuals of other races. Such a sample is suitable for testing between-group differences, such as sexual dimorphism described in Hsiao et al. (2007). This study involved the use of the latter option.

During the subsampling process, the authors encountered a problem wherein the Hispanic segment of the population could not be properly represented: Of the overall 2,382 CAESAR participants, only 33 were Hispanic males and 18 were Hispanic females. We took all Hispanic participants and gave a target of 75 for each remaining race category by gender to reach the goal of 500 participants overall. Because

of the possibility of unusable scan data, we decided to construct a larger random sample of 95 participants from each category. Thus, we selected a random sample of 95 participants from each gender and race category, and then we randomized their order and included the first 75 usable participants in the final sample.

The final sample data turned out to include 258 men (76 White, 75 Black, and 107 Hispanic and other races) and 243 women (75 White, 75 Black, and 93 Hispanic and other races), for a total of 501 participants. The Hispanic participants were rolled into the Hispanic-and-other-races category to comply with the year 2000 National Health and Nutritional Examination Survey (NHANES) guidelines in presenting small counts. With this process, the use of sampling weights is critical to obtain proper survey estimates. The sampling weights for men were 34.45 for Whites, 5.10 for Blacks, and 6.63 for Hispanics and other races; whereas for women, the sampling weights were 34.21 for Whites, 6.42 for Blacks, and 7.91 for Hispanics and other races.

The sample of 501 participants from CAESAR, with their corresponding sampling weights, was evaluated to adequately represent the year 2000 U.S. population as presented in the 1999–2002 Centers for Disease Control and Prevention's (CDC; 2004) NHANES database. The evaluation includes (a) Kolmogorov-Smirnov tests to compare the empirical distribution functions of stature and weight between the NHANES sample and the selected CAESAR participants to determine if those CAESAR participants would adequately represent the U.S. population, (b) post hoc Siegel-Tukey (Dispersion) tests to confirm that the data being used for harness size prediction did not differ significantly from the population, (c) determination of whether they are meaningful to harness design when post hoc distributional tests on gender and race subgroups show statistically significant differences between the selected CAESAR and NHANES samples, and (d) adjustment of sampling weights for unequal cell sizes.

These 501 representative CAESAR scans were subjected to the procedure of extracting torso dimension data and using the data as input to the eight logistic regression equations to predict the best-fit harness size.

### **Categorizing and Grouping Predicted Harness Sizes**

Three possible sizes of harness can be expected initially, on the basis of the eight logistic regression equations, for each gender: XSM, STD, and XLG. The strap lengths and their adjustment ranges for each harness size were first calculated after the grouping of predicted harness sizes was done. The final sizing structure, however, was determined according to the iterative process as described below.

### **Evaluating Strap Length Configurations Against the Strap Adjustability Criteria**

Seven key harness straps were evaluated: back strap, chest strap, front cross-chest strap, front strap, gluteal furrow arc, thigh circumference, and trochanter-crotch circumference (Figures 1a through 1g). They were labeled as Key Dimension 1 (KD1) through Key Dimension 7 (KD7), respectively. Although some harness manufacturers may use additional dimensions (usually, additional fractions of the seven straps mentioned previously) in determining strap cut lengths and sewing locations, the seven key dimensions serve as the general primary dimensions. The strap lengths and their adjustment ranges for each harness size were first calculated per the grouping of predicted harness sizes and gender.

For the smallest size (XSM), the lower bound, mean, and upper bound represented 1st-percentile, 50th-percentile, and 97.5th-percentile cut length, respectively, and the adjustable range = 97.5th percentile – 1st percentile. For the middle sizes (STD), the lower bound, mean, and upper bound represented 2.5th-percentile, 50th-percentile, and 97.5th-percentile cut length, respectively, and the adjustable range = 97.5th percentile – 2.5th percentile. For the largest size (XLG), the lower bound, mean, and upper bound represented 2.5th-percentile, 50th-percentile, and 99th-percentile cut length, respectively, and the adjustable range = 99th percentile – 2.5th percentile. This cut length configuration strategy was useful in covering extended XSM and XLG sizes cost-effectively while accommodating approximately 96% to 98% of the estimated population.

These adjustment ranges for the seven straps were evaluated against both the common and the conservative adjustment range criteria to

determine whether a specific size structure (i.e., any of the three initial sizes) needed to be further divided into two or more sizes. The common adjustment range of the back, chest, front cross-chest, and front straps lengths (KD1 through KD4) was set to be within 17 cm, and the thigh and hip straps (i.e., gluteal furrow arc, thigh circumference, and trochanter-crotch circumference; KD5 through KD7) to be within 23 cm. A conservative adjustable range limit was set at 15 cm for KD1 through KD4 and 20 cm for KD5 through KD7, which would potentially result in a larger number of needed harness sizes.

### **Determining the Ultimate Length and Adjustability Range of Each Harness Strap**

Once a new sizing configuration (i.e., three, four, or more sizes) was defined and the strap adjustment ranges were verified to meet the common or conservative adjustment range criteria, the mean length and adjustment range of each harness strap defined in the previous section were considered the ultimate length and the ultimate adjustable range for each harness strap.

### **Providing Sizing Charts Associated With the Newly Defined Sizes**

An anthropometric sizing chart for harnesses is the link between the statistical calculations leading to the new sizing system and the “real-world” requirements for assigning the best-fit size to a person in a fast and accurate manner. For practical purposes, any size selection chart must be based on dimensions that are readily known or easily measured by the harness user. Body weight and stature are well known to individual workers and have fine correlations with harness sizing determination and thus were used in presenting the new sizing charts (Hsiao, Bradtmiller, and Whitestone, 2003, p. 1248).

## **RESULTS**

### **Initial Sizing Prediction and the Adjustable Range for Each Harness Component**

Table 1 indicates the predicted numbers and percentages of men and women by race from the CAESAR sample for each size of the vest-type and overhead-style harnesses. Tables 2 and

3 contain strap adjustment ranges by predicted size for men and women and for harness type, respectively, based on an initial prediction of three sizes for men and three sizes for women. The tables show that the adjustment ranges met the common adjustable range limit of 17 cm for KD1 through KD4 and 23 cm for KD5 through KD7 but not the conservative adjustable range limit of 15 cm for KD1 through KD4 and 20 cm for KD5 through KD7. Bold italic text in Tables 2 and 3 indicates a value greater than the conservative adjustable range limit; some sizes were divided to meet the adjustable range limits.

*Assessment of adjustment ranges for vest-type harness for men.* Table 2 shows that the adjustment ranges for size XSM fall within the conservative limit. However, problems existed for size STD with the KD3 (front cross-chest strap), KD6 (thigh circumference), and KD7 (trochanter-crotch circumference). Furthermore, there was a problem with KD6 in size XLG.

For size STD, we examined KD3, KD6, and KD7 against body weight for outliers and found no participants appearing to have a major effect on the adjustment ranges. We conducted a discriminant analysis to determine which variables contributed most to the separation of the sizes; predicted vest size was the grouping variable, and KD1 through KD7 were the independent variables. The first discriminant function had an eigenvalue of 0.462 and explained 78.6% of the variation in the data. KD3 (front cross-chest strap) was the most important variable related to size separation. A four-size system was then defined by dividing size STD into new sizes—small (SM) and medium (MD)—for KD3. Optimum results were obtained by assigning participants with a KD3 value of less than or equal to 72 cm to new size SM; participants with a KD3 value greater than 72 cm were assigned to new size MD.

For the XLG size, we examined KD6 (thigh circumference) for outliers. A bivariate plot of body weight and KD6 for men showed that 1 participant had a much smaller value for KD6 relative to all other participants of the same weight. Omitting this participant reduced the adjustable range to 15.5 cm, which met the 20-cm conservative adjustable range goal.

**TABLE 1: Initially Predicted Size Frequencies and Percentages (within parentheses) for the Vest-Type and Overhead-Style Harnesses**

Harness Type and Size	Unweighted					Weighted <sup>a</sup>				
	White	Black	Hispanic	Other	Total	White	Black	Hispanic	Other	Total
<b>Vest-type harness</b>										
Men										
XSM	0 (0.0)	11 (2.2)	5 (1.0)	25 (5.0)	41 (8.2)	0 (0.0)	55 (0.7)	33 (0.4)	167 (2.2)	255 (3.4)
STD	68 (13.6)	61 (12.2)	24 (4.8)	49 (9.8)	202 (40.3)	2,343 (31.3)	307 (4.1)	161 (2.1)	328 (4.4)	3,139 (41.9)
XLG	8 (1.6)	3 (0.6)	3 (0.6)	1 (0.2)	15 (3.0)	276 (3.7)	15 (0.2)	20 (0.4)	7 (0.1)	318 (4.2)
Women										
XSM	41 (8.2)	32 (6.4)	10 (2.0)	59 (11.8)	142 (28.3)	1,402 (18.7)	205 (2.7)	79 (1.1)	467 (6.2)	2,153 (28.7)
STD	31 (6.2)	37 (7.4)	8 (1.6)	15 (3.0)	91 (18.2)	1,060 (14.1)	238 (3.2)	63 (0.8)	119 (1.6)	1,480 (19.7)
XLG	3 (0.6)	6 (1.2)	0 (0.0)	1 (0.2)	10 (2.0)	103 (1.4)	39 (0.5)	0 (0.0)	8 (0.1)	150 (2.0)
<b>Overhead-style harness</b>										
Men										
XSM	2 (0.4)	11 (2.2)	7 (1.4)	32 (6.4)	52 (10.4)	69 (0.9)	55 (0.7)	47 (0.6)	214 (2.9)	385 (5.1)
STD	60 (12.0)	43 (8.6)	21 (4.2)	38 (7.6)	162 (32.3)	2,067 (27.6)	216 (2.9)	141 (1.9)	254 (3.4)	2,678 (35.7)
XLG	14 (2.8)	21 (4.2)	4 (0.8)	5 (1.0)	44 (8.8)	482 (6.4)	106 (1.4)	27 (0.4)	33 (0.4)	648 (8.6)
Women										
XSM	42 (8.4)	29 (5.8)	9 (1.8)	58 (11.6)	138 (27.5)	1,436 (19.2)	186 (2.5)	71 (0.9)	459 (6.1)	2,152 (28.7)
STD	26 (5.2)	31 (6.2)	8 (1.6)	14 (2.8)	79 (15.8)	889 (11.9)	199 (2.7)	63 (0.8)	111 (1.5)	1,262 (16.8)
XLG	7 (1.4)	15 (3.0)	1 (0.2)	3 (0.6)	26 (5.2)	239 (3.2)	96 (1.3)	8 (0.1)	24 (0.3)	367 (4.9)

Note: XSM = extra small; STD = standard; XLG = extra large.

<sup>a</sup>Weighted to match the year 2000 Census.

**TABLE 2: Adjustable Ranges for Harness Component for Men and Women for Vest-Type Harness, Based on the Initial Prediction of Three Sizes for Men and Three Sizes for Women (in millimeters)**

Size	Harness Component	Men				Women			
		Lower	Mean	Upper	Range	Lower	Mean	Upper	Range
XSM	a. Back strap (KD1)	625	669	721	96	578	654	702	124
	b. Chest strap (KD2)	159	197	252	93	139	172	204	65
	c. Front cross-chest strap (KD3)	610	649	699	89	558	643	701	143
	d. Front strap (KD4)	520	576	631	111	511	588	637	126
	e. Gluteal furrow arc (KD5)	472	577	669	197	544	624	681	137
	f. Thigh circumference (KD6)	426	520	571	145	469	558	638	169
	g. Trochanter-crotch circumference (KD7)	571	683	750	179	606	689	756	150
	a. Back strap (KD1)	671	727	821	150	635	691	767	132
	b. Chest strap (KD2)	192	226	290	98	148	196	242	94
STD	c. Front cross-chest strap (KD3)	656	718	815	159	639	696	776	137
	d. Front strap (KD4)	574	631	709	135	571	634	698	127
	e. Gluteal furrow arc (KD5)	545	606	714	169	608	671	756	148
	f. Thigh circumference (KD6)	507	586	710	203	535	637	766	231
	g. Trochanter-crotch circumference (KD7)	655	742	878	223	676	788	882	206
	a. Back strap (KD1)	704	744	813	109	653	723	758	105
	b. Chest strap (KD2)	215	257	284	69	199	212	252	53
	c. Front cross-chest strap (KD3)	727	770	857	130	707	729	872	165
	d. Front strap (KD4)	609	659	720	111	637	675	787	150
XLG	e. Gluteal furrow arc (KD5)	593	643	715	122	694	761	771	77
	f. Thigh circumference (KD6)	517	639	738	221	710	748	825	115
	g. Trochanter-crotch circumference (KD7)	771	852	931	160	849	900	994	145

Note. XSM = extrasmall; STD = standard; XLG = extralarge; KD = key dimension. The strap adjustment ranges were set to accommodate at least 95% of the estimated population within the specified size categories. The XSM size was set at 96.5% level (adjustable range = 97.5th percentile – 1st percentile). The STD size was set at 95% level (adjustable range = 97.5th percentile – 2.5th percentile), and the large size was set at 96.5% level (adjustable range = 99th percentile – 2.5th percentile). The overall arrangement provides an opportunity to accommodate approximately 96% to 98% of the estimated overall population. The three sizes were defined by the adjustable range limit of 17 cm for a, b, c, and d (KD1 through KD4), and 23 cm for e, f, and g (KD5 through KD7). Bold italic indicates a value greater than the conservative adjustable range limit.

**TABLE 3: Adjustable Ranges for Harness Component for Men and Women for Overhead-Style Harness, Based on the Initial Prediction of Three Sizes for Men and Three Sizes for Women (in millimeters)**

Size	Harness Component	Men				Women			
		Lower	Mean	Upper	Range	Lower	Mean	Upper	Range
XSM	a. Back strap (KD1)	625	683	729	104	578	656	702	124
	b. Chest strap (KD2)	159	206	248	89	139	172	204	65
	c. Front cross-chest strap (KD3)	610	657	699	89	558	643	701	143
	d. Front strap (KD4)	520	575	618	98	511	584	646	135
	e. Gluteal furrow arc (KD5)	472	580	625	153	544	624	686	142
	f. Thigh circumference (KD6)	426	528	587	161	469	557	638	169
	g. Trochanter-crotch circumference (KD7)	571	688	752	181	606	689	756	150
	a. Back strap (KD1)	675	727	803	128	630	686	746	116
	b. Chest strap (KD2)	192	224	274	82	148	194	238	90
STD	c. Front cross-chest strap (KD3)	663	717	789	126	639	693	768	129
	d. Front strap (KD4)	575	628	677	102	571	624	691	120
	e. Gluteal furrow arc (KD5)	545	605	688	143	608	663	747	139
	f. Thigh circumference (KD6)	505	582	650	145	539	622	732	193
	g. Trochanter-crotch circumference (KD7)	655	739	847	192	676	774	859	183
	a. Back strap (KD1)	704	759	842	138	650	735	796	146
	b. Chest strap (KD2)	215	259	291	76	175	213	252	77
	c. Front cross-chest strap (KD3)	723	787	857	134	690	741	872	<b>182</b>
	d. Front strap (KD4)	624	667	724	100	610	678	787	<b>177</b>
XLG	e. Gluteal furrow arc (KD5)	590	649	723	133	624	711	797	173
	f. Thigh circumference (KD6)	583	657	762	179	676	710	828	152
	g. Trochanter-crotch circumference (KD7)	746	852	931	185	822	856	994	172

Note. XSM = extrasmall; STD = standard; XLG = extralarge; KD = key dimension. The strap adjustment ranges were set to accommodate at least 95% of the estimated population within the specified size categories. The XSM size was set at 96.5% level (adjustable range = 97.5th percentile – 1st percentile). The STD size was set at 95% level (adjustable range = 97.5th percentile – 2.5th percentile), and the large size was set at 96.5% level (adjustable range = 99th percentile – 2.5th percentile). The overall arrangement provides an opportunity to accommodate approximately 96% to 98% of the estimated overall population. The three sizes were defined by the adjustable range limit of 17 cm for a, b, c, and d (KD1 through KD4), and 23 cm for e, f, and g (KD5 through KD7). Bold italic indicates a value greater than the conservative adjustable range limit.

Table 4 contains the adjustment ranges for the four-size system for men, excluding the one outlier. The four-size system, consisting of original sizes XSM and XLG and new sizes SM and MD, met the conservative adjustment range limits, except for the range of KD7 (trochanter-crotch circumference) for the MD size (20.2 cm), which is 0.2 cm greater than the limit. The 0.2-cm deviation has no practical importance. In summary, per the conservative adjustable range limit of 15 cm for KD1 through KD4 and 20 cm for KD5 through KD7, four sizes of the vest-type harness for men would be needed. However, per the common adjustable range limit of 17 cm for KD1 through KD4 and 23 cm for KD5 through KD7, three sizes for men would be sufficient.

*Assessment of adjustment ranges for vest-type harness for women.* Table 2 shows that the adjustment ranges for KD6 (thigh circumference) and KD7 (trochanter-crotch circumference) are more than 20 cm in size STD for women. In size XLG, the adjustment range for KD3 (front cross-chest strap) is more than 15 cm. We again conducted a discriminant analysis to determine which variables contribute most to the separation of the sizes, using predicted vest size as the grouping variable and KD1 through KD7 as the independent variables.

The first discriminant function had an eigenvalue of 2.27 and explained 96.9% of the variation in the data. It showed that KD7 was the most important variable to account for size separation. Size STD was divided into sizes SM and MD to define a new four-size system. We used a bivariate plot of body weight by KD7 and experimented with different values to determine where the boundary between the sizes should be by locating the value that minimizes the adjustment range limits within sizes. Participants with a KD7 value less than or equal to 86 cm were assigned to new size SM, and participants with a KD7 value more than 86 cm were assigned to size MD. Given that the adjustability range limit of KD3 for XLG is the only overrun and is so close to the goal of 15 cm, we feel that creating a five-size system was not necessary. Table 4 shows the adjustment ranges for the four-size system for women, which includes original size XSM, new sizes SM and MD, and original size XLG.

In summary, four sizes of the vest-type harness for women would be cost-effective in meeting the conservative adjustable range goal. If the common adjustable range limits of 17 cm for KD1 through KD4 and 23 cm for KD5 through KD7 are applied, three sizes of the vest-type harness for women would be sufficient.

*Assessment of adjustment ranges for overhead-style harness for men.* The adjustable ranges for the original three sizes were within the specified conservative limit goal (Table 3) and within the common limits for overhead-style harness for men. No additional sizing adjustment processes are needed.

*Assessment of adjustment ranges for overhead-style harness for women.* Table 3 shows that the adjustment ranges for KD3 (front cross-chest strap) and KD4 (front strap) in size XLG were greater than the specified conservative range limit goal. We examined these measurements for outliers that may be affecting the results by evaluating the distribution of KD3 and KD4, respectively, relative to body weight. There were two observations that stood out from the others. They were for the same 2 participants in both tests. We did not consider them outliers, because these participants fell well within a reasonable distance from regression lines. The gap between these 2 participants and the others was most likely attributable to sample bias.

We conducted a discriminant analysis to determine which variables contributed most to the separation of the sizes. We used predicted overhead size as the grouping variable and KD1 through KD7 as the independent variables. The first discriminant function had an eigenvalue of 2.78 and explained 98.1% of the variation in the data. It showed that KD7 was the most important variable contributing to size separation, although the adjustable ranges of KD7 met the original goal of range limit. We used a bivariate plot and experimented with different values of KD7 against body weight to determine where the boundary between the sizes should be placed so that the range limits of KD3 and KD4 could be resolved; the original size XLG was divided into new sizes large (LG) and very large (VLG) to create a four-size system (Table 5). Optimum results were obtained by assigning participants with a KD7 value of less than or equal to 92 cm

**TABLE 4: Adjustable Ranges of Harness Components for the Alternative Four-Size System for Men and Women for Vest-Type Harness (in millimeters)**

Size	Harness Component	Men				Women			
		Lower	Mean	Upper	Range	Lower	Mean	Upper	Range
XSM	a. Back strap (KD1)	625	669	721	96	578	654	702	124
	b. Chest strap (KD2)	159	197	252	93	139	172	204	65
	c. Front cross-chest strap (KD3)	610	649	699	89	558	643	701	143
	d. Front strap (KD4)	520	576	631	111	511	588	637	126
	e. Gluteal furrow arc (KD5)	472	577	669	197	544	624	681	137
	f. Thigh circumference (KD6)	426	520	571	145	469	558	638	169
	g. Trochanter-crotch circumference (KD7)	571	683	750	179	606	689	756	150
	a. Back strap (KD1)	669	711	760	91	636	691	767	131
	b. Chest strap (KD2)	187	215	242	55	148	196	242	94
SM	c. Front cross-chest strap (KD3)	650	700	718	69	639	696	775	136
	d. Front strap (KD4)	571	614	649	78	571	633	698	127
	e. Gluteal furrow arc (KD5)	544	598	683	138	608	667	747	139
	f. Thigh circumference (KD6)	505	568	642	137	535	624	709	174
	g. Trochanter-crotch circumference (KD7)	648	720	802	154	676	785	856	180
	a. Back strap (KD1)	685	746	829	144	608	691	749	141
	b. Chest strap (KD2)	208	242	291	82	156	198	232	76
	c. Front cross-chest strap (KD3)	721	749	818	97	647	717	795	148
	d. Front strap (KD4)	611	651	715	103	595	650	718	123
MD	e. Gluteal furrow arc (KD5)	572	616	714	142	633	721	797	164
	f. Thigh circumference (KD6)	532	610	728	196	689	756	828	139
	g. Trochanter-crotch circumference (KD7)	694	786	896	202	867	880	964	97
	a. Back strap (KD1)	704	750	813	109	653	723	758	105
	b. Chest strap (KD2)	215	257	284	69	199	212	252	53
	c. Front cross-chest strap (KD3)	727	770	857	130	707	729	872	165
	d. Front strap (KD4)	609	659	720	111	637	675	787	150
	e. Gluteal furrow arc (KD5)	593	642	715	122	694	761	771	77
	f. Thigh circumference (KD6)	583	639	738	155	710	748	825	115
g. Trochanter-crotch circumference (KD7)	771	852	931	160	849	900	994	145	
XLG									

Note. XSM = extrasmall; SM = small; MD = medium; XLG = extralarge; KD = key dimension.

**TABLE 5:** Adjustable Ranges of Harness Components for the Alternative Four-Size System for Men and Women for Overhead-Style Harness (in millimeters)

Size	Harness Component	Men				Women				
		Lower	Mean	Upper	Range	Lower	Mean	Upper	Range	
XSM	a. Back strap (KD1)	625	683	729	104	578	656	702	124	
	b. Chest strap (KD2)	159	206	248	89	139	172	204	65	
	c. Front cross-chest strap (KD3)	610	657	699	89	558	643	701	143	
	d. Front strap (KD4)	520	575	618	98	511	584	646	135	
	e. Gluteal furrow arc (KD5)	472	580	625	153	544	624	686	142	
	f. Thigh circumference (KD6)	426	528	587	161	469	557	638	169	
	g. Trochanter-crotch circumference (KD7)	571	688	752	181	606	689	756	150	
	a. Back strap (KD1)	675	727	803	128	630	686	746	116	
	b. Chest strap (KD2)	192	224	274	82	148	194	238	90	
STD	c. Front cross-chest strap (KD3)	663	717	789	126	639	693	768	129	
	d. Front strap (KD4)	575	628	677	102	571	624	691	120	
	e. Gluteal furrow arc (KD5)	545	605	688	143	608	663	747	139	
	f. Thigh circumference (KD6)	505	582	650	145	539	622	732	193	
	g. Trochanter-crotch circumference (KD7)	655	739	847	192	676	774	859	183	
	LG	a. Back strap (KD1)	—	—	—	—	650	735	796	146
		b. Chest strap (KD2)	—	—	—	—	175	213	243	68
		c. Front cross-chest strap (KD3)	—	—	—	—	690	741	776	86
		d. Front strap (KD4)	—	—	—	—	610	675	698	88
e. Gluteal furrow arc (KD5)		—	—	—	—	624	694	762	138	
f. Thigh circumference (KD6)		—	—	—	—	676	691	778	102	
g. Trochanter-crotch circumference (KD7)		—	—	—	—	822	852	910	88	
VLG		a. Back strap (KD1)	704	759	842	138	670	747	749	79
		b. Chest strap (KD2)	215	259	291	76	199	212	252	53
	c. Front cross-chest strap (KD3)	723	787	857	134	729	730	872	143	
	d. Front strap (KD4)	624	667	724	100	650	679	787	137	
	e. Gluteal furrow arc (KD5)	590	649	723	133	721	761	797	76	
	f. Thigh circumference (KD6)	583	657	762	179	771	779	828	57	
	g. Trochanter-crotch circumference (KD7)	746	852	931	185	921	927	994	73	

Note. XSM = extrasmall; STD = standard; LG = large; VLG = very large; KD = key dimension.

to new size LG. Participants with a value greater than 92 cm were assigned to new size VLG.

In summary, four sizes of the overhead-style harness for women would fit the need of female workers with the conservative adjustment range goal. When the common adjustment range limits of 17 cm for KD1 through KD4 and 23 cm for KD5 through KD7 were applied, three sizes would be sufficient, with an exception that KD3 and KD4 need to be slightly extended to 18 cm (in lieu of the 17-cm common adjustment range limit) to cover at least 96.5% of the estimated population.

### Anthropometric Sizing Charts

Two sizing options for each of the two harness types were identified to meet two strap adjustment range goals (i.e., common and conservative ranges). Figures 4A and 4B show the distribution of predicted sizes for men and women for vest-type harnesses. The solid lines indicate the size boundaries of the predicted sizes of Option 1 (three sizes for men and three sizes for women), with body weight and height as the reference parameters. The dotted line shows the additional size boundary for the extended four-size system (i.e., Option 2) for the vest-type harness for men and women. Specifically, in Figure 4A, the two size boundaries (solid lines) were defined by two logistic regression models:

Model 1: Probability of wearing XSM size instead of STD size (set as 0.5) =  $1 / [1 + \exp(-59.803 + 0.565weight + 0.126stature)]$ .

Model 2: Probability of wearing XLG size instead of STD (set as 0.5) =  $1 / [1 + \exp(-17.893 - 0.107weight + 0.174stature)]$ .

The dotted line was defined through a logistic regression model:

Model 3: Probability of wearing SM size instead of MD size (set as 0.5) =  $1 / [1 + \exp(-32.369 + 0.148weight + 0.112stature)]$ .

Similarly, in Figure 4B, the two size boundaries (solid lines) were defined by two logistic regression models:

Model 4: Probability of wearing XSM size instead of STD size (set as 0.5) =  $1 / [1 + \exp(-59.780 + 0.628weight + 0.100stature)]$ .

Model 5: Probability of wearing XLG size instead of STD size (set as 0.5) =  $1 / [1 + \exp(-24.816 - 0.160weight + 0.259stature)]$ .

The dotted line was defined through a logistic regression model:

Model 6: Probability of wearing SM instead of MD (set as 0.5) =  $1 / [1 + \exp(16.523 + 0.184weight - 0.215stature)]$ .

The same logistic regression concept is presented for overhead-style harnesses for men and women. In Figure 4C, the two size boundaries (solid lines) were defined by two models:

Model 7: Probability of wearing XSM size instead of STD size (set as 0.5) =  $1 / [1 + \exp(-153.046 + 0.885weight + 0.531stature)]$ .

Model 8: Probability of wearing XLG size instead of STD size (set as 0.5) =  $1 / [1 + \exp(15.522 - 0.291weight + 0.074stature)]$ .

In Figure 4D, the two size boundaries (solid lines) were determined by two logistic regression models:

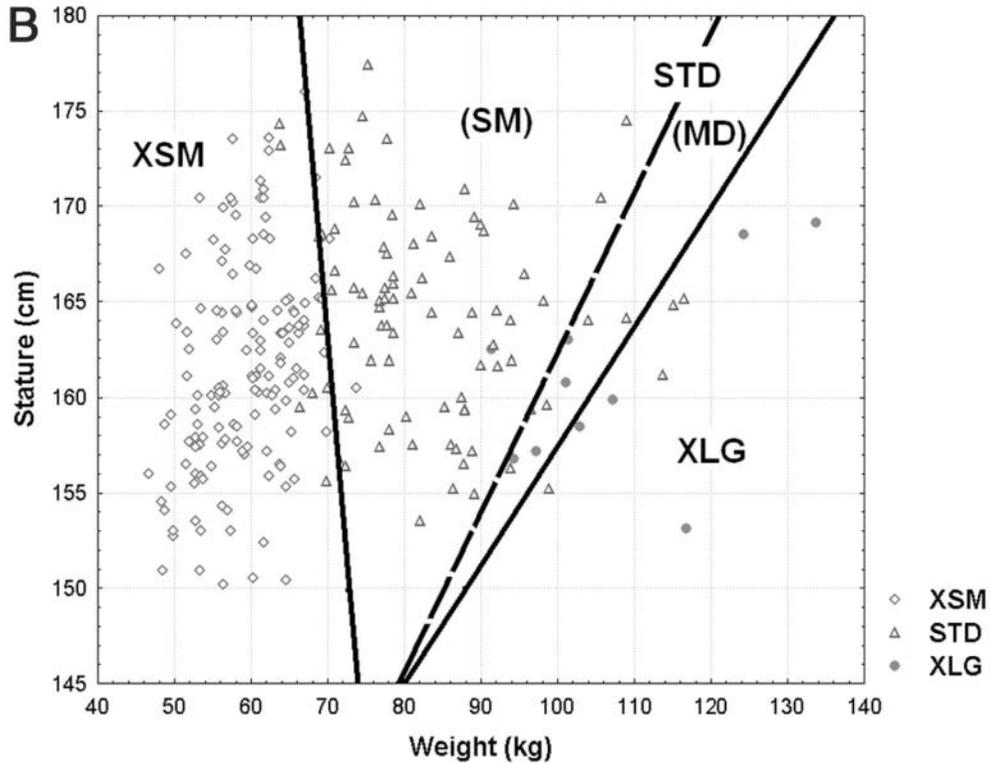
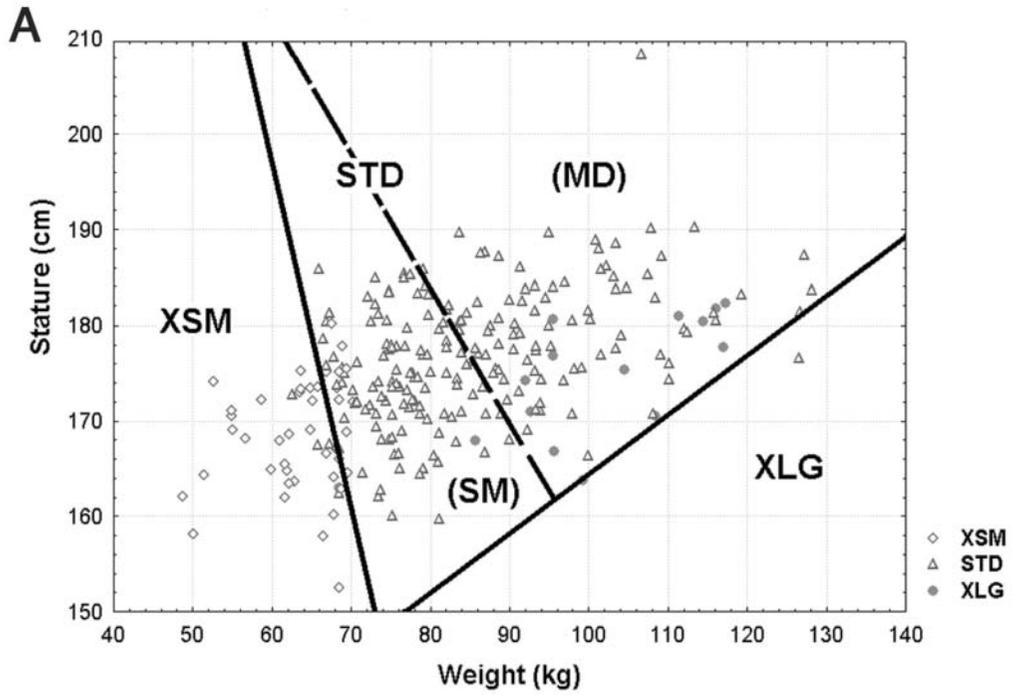
Model 9: Probability of wearing XSM size instead of STD size (set as 0.5) =  $1 / [1 + \exp(-77.447 + 0.594weight + 0.224stature)]$ .

Model 10: Probability of wearing XLG size instead of STD size (set as 0.5) =  $1 / [1 + \exp(3.430 - 0.256weight + 0.127stature)]$ .

The dotted line was defined with a logistic regression model:

Model 11: Probability of wearing LG instead of VLG (set as 0.5) =  $1 / [1 + \exp(2.161 + 0.237weight - 0.175stature)]$ .

It must be noted that some harness users may need to try on more than one size to select the best-fit size because the overall combination of their body dimensions governs the size; body weight and stature only partially explain the



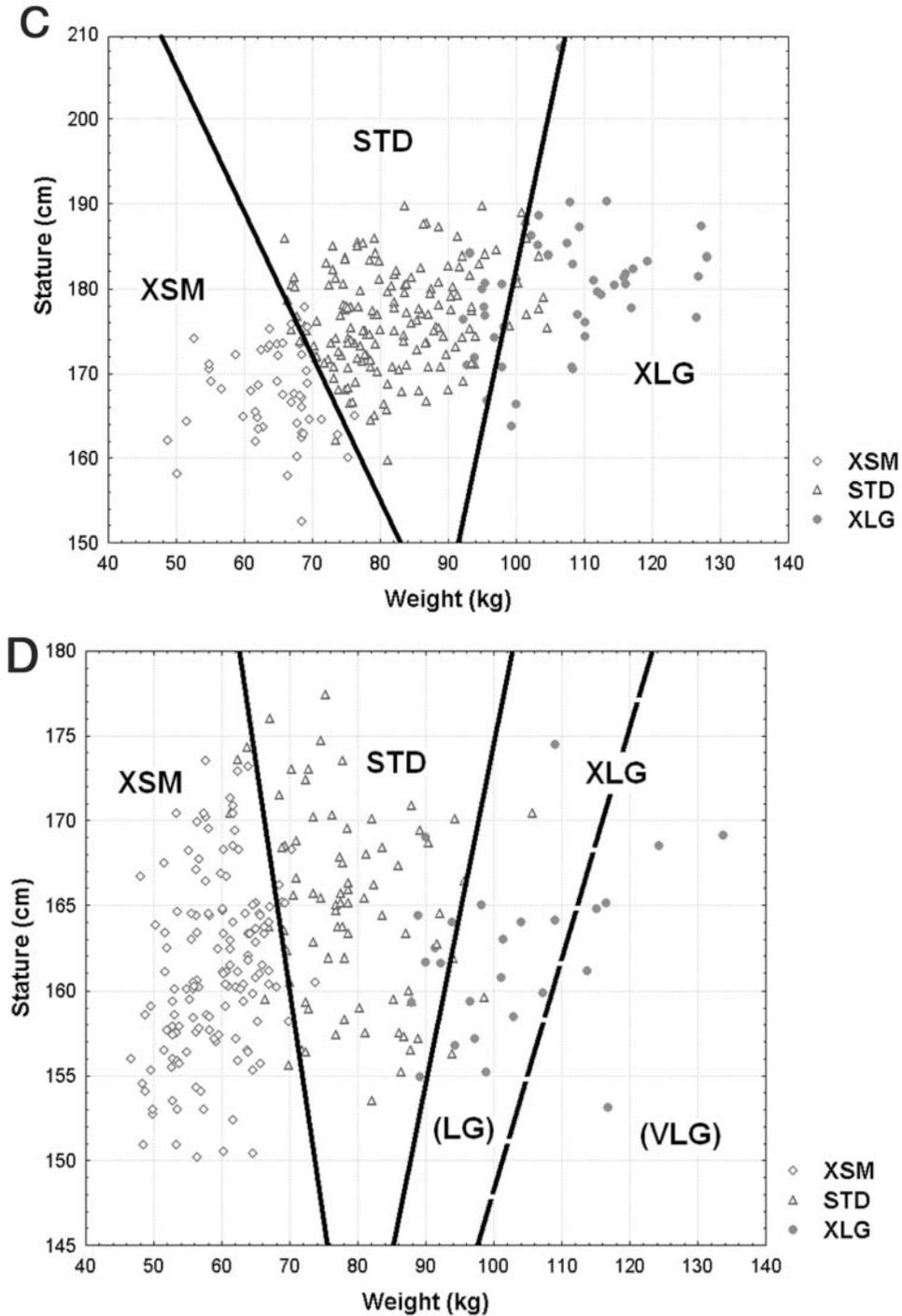


Figure 4. Distribution of predicted size by weight and height for (A) vest-type harness for men, (B) vest-type harness for women, (C) overhead-style harness for men, and (D) overhead-style harness for women. The solid lines indicate the size boundaries of the predicted sizes (three sizes for men and three sizes for woman for both vest-type and overhead harness), with weight and height as the reference parameters. The dotted lines indicate the additional size boundaries for the extended four-size system for the vest-type harness for men and for both vest-type and overhead-style harnesses for women. Where a dotted line is presented, the legends with parentheses indicate that the harness sizes were derived from an original size.

variation of torso-harness interfaces among individuals. Nevertheless, the sizing charts serve as a quick practical guide for harness users to make a proper size selection.

## DISCUSSION

### Harness Sizing Determination

In this study, the conservative adjustment ranges of the back, chest, front cross-chest, and front straps were set for no more than 15 cm and the thigh and hip strap (gluteal furrow arc, thigh circumference, and trochanter-crotch circumference) adjustment ranges for no more than 20 cm. The study results determined that four sizes for men and four sizes for women were the fewest sizes needed for the vest-type harness and three sizes for men and four sizes for women were adequate for the overhead-style harnesses. A few strap components turned out to slightly exceed the preset range but were not extreme enough to warrant further size extension.

The study results also determined that three sizes for men and three sizes for women were adequate for both the vest-type and overhead-type harnesses when the common adjustment range limits of 17 cm for KD1 through KD4 (back strap, chest strap, front cross-chest strap, and front strap) and 23 cm for KD5 through KD7 (gluteal furrow arc, thigh circumference, and trochanter-crotch circumference) were applied to accommodate at least 95% of the estimated population and, in most cases, 98% of the estimated population.

In standard harness design practice, the function of harnesses, worker task requirements, and the physical characteristics of the user group can affect the adjustment range limit and thus the determination of sizing systems. For instance, fall-arrest harnesses used in tower erection would benefit from a tighter adjustment range limit for a better positioning function, which would suggest that harness designers could employ more restrictive harness range limits for tower erectors. By contrast, general purpose fall-arrest harnesses, which are used in a broader range of tasks requiring fall protection, should afford a wider adjustment range limit to accommodate a wider range of body types. The diversity in harness design constraints reflects the functional requirements of different harness

designs, such as increased need for positioning while suspended, as well as the relative degree of variance or invariance in body morphology found in certain occupational groups.

Accounting for these different kinds of constraints makes good business sense; designers must be aware of the characteristic range of body types as well as harness functional requirements so that they may adapt design adjustments to accommodate these constraints. This study not only described a method to define harness sizing schemes based on designers' intent to meet requirements of worker task and harness functions but also provided two sizing plans for the harness industry. Harness manufacturers may choose one of the plans on the basis of their adjustment range goal of harness components.

It also must be noted that an adjustment for clothing or other equipment is necessary in anthropometry research and practices (Hsiao & Halperin, 1998). In the harness design application, we need to take into account the additional clothing workers wear in winter; however, harness users typically want one harness for all seasons.

After consultation with a harness manufacturer, we determined the following values for harness design. An average of 2.5 cm is suggested for the back strap and front-cross chest strap in that the two straps extend from shoulder to thigh. The value is derived from the calculation that 1 cm is used to cover the total thickness of clothing layers at shoulder and thigh (0.5 cm thickness for each location) for summer clothing and 4 cm for winter jackets, which results in an average of 2.5 cm. For the thigh and hip straps, an increment on circumference of 3 cm for hip-thigh areas for summer clothing ( $2\pi \times 0.5$ -cm thickness of clothing layers) and 12 cm for winter pants or overalls ( $2\pi \times 2$ -cm thickness of clothing layers) was adopted, which resulted in an average value of a 7.5-cm addition. Some manufacturers may even require an additional 7 cm for the thigh-hip area for better mobility for certain designs. No additional allowance would be needed for the chest strap and front strap.

### Sizing Structure and Strap Lengths

In harness manufacturing practices, torso straps and thigh-hip straps may be fabricated on different production runs or equipment using standardized machine settings. Adjusting manufacturing

tolerances for strap production machinery to increments smaller than 5 cm may be cost-ineffective or technically impractical and affects the success of transferring research results to practice.

Taking the sizing scheme of three sizes for men and three sizes for women for the vest-type harnesses as an example (Table 2) and considering just trochanter-crotch circumference (thigh strap) without the torso component, we could recommend four thigh strap sizes: universal XSM (57.1 cm to 75.6 cm for both genders combined: 57.1 cm to 75.0 cm for men and 60.6 cm to 75.6 cm for women), universal STD (65.5 cm to 88.2 cm for both genders combined: 65.5 cm to 87.8 cm for men and 67.6 cm to 88.2 cm for women), male XLG (77.1 cm to 93.1 cm) and female XLG (84.9 cm to 99.4 cm).

Similarly, considering just the front cross-chest strap (Table 2), we can suggest four sizes: universal XSM (55.8 cm to 70.1 cm for both genders combined: 61.0 cm to 69.9 cm for men and 55.8 cm to 70.1 cm for women), men STD (65.6 cm to 81.5 cm), women STD (63.9 cm to 77.6 cm), universal XLG (70.7 cm to 87.2 cm for both genders combined: 72.7 cm to 85.7 cm for men and 70.7 cm to 87.2 cm for women).

If we consider the back strap, chest strap, front cross-chest strap, and front strap as a group (Table 2), it is also reasonable to suggest five combined torso-strap sizes: universal XSM, men STD, women STD, men XLG, and women XLG. In this regard, it is possible for a harness manufacturer to consider merging women XSM (torso) size with men XSM (torso) size to become a universal XSM size, along with a XSM size thigh-hip strap. Similarly, it is reasonable to use a universal STD size thigh-hip strap for both women STD (torso) size and men STD (torso) size. The men XLG (torso) size will have an XLG thigh strap, and the women XLG (torso) size will correspond with a super-extralarge (SXL) thigh strap. The combinations would result in five sizes in total; this suggestion was made solely on the basis of existing practices in the harness manufacturing process.

Similarly, considering just hip and thigh dimensions without the torso component from the sizing plan of four sizes for men and four sizes for women for the vest-type harnesses (Table 2), we may conclude that there are six recommended hip-thigh strap sizes: universal

XSM, universal SM, men STD, women STD, men XLG, and women XLG. We also can suggest seven torso-strap sizes: universal XSM, men SM, women SM, men STD, women STD, men XLG, and women XLG.

However, composing composite harness designs for both genders is not a straightforward exercise. Merging a woman's size with a man's size introduces additional complicating factors related to proper harness fit. The Hsiao, Friess, Bradtmiller, and Rohlf (2009) study demonstrated that increased inclination of torso suspension angle (hence, fit failure) was associated with a reduction in torso length and a more developed chest (i.e., women's torso shape); a more upward design of back D-rings for women than the current unisex design is desirable to minimize this fit problem. Furthermore, because of differences in pelvic structure, women have demonstrated a "flatter" thigh strap angle than men. A flatter thigh strap angle is correlated to an increase in torso suspension angle, hence in fit failure (Hsiao et al., 2007). Finding a balance between designs and the manufacturing process (fewest possible total sizes) is both an art and a science and will require further efforts to minimize effective design variance by gender.

### Differences in Cut Lengths Between the Existing and Newly Proposed Sizing Structures

As a demonstration, Table 6 presents differences in cut lengths between existing and newly proposed sizing structures for two harness components for the vest-type harness: chest strap and thigh strap (trochanter-crotch circumference). It is clear that to save some materials, the chest strap length of the current harnesses can be reduced from 35 cm to 26 cm for XSM size, from 35.5 cm to 30 cm for STD size, and from 39.5 cm to 30 cm for XLG size. The thigh strap, however, needs to be enlarged for all sizes to accommodate the current worker population. That is, the adjustment range for men XSM would be 57.1 cm to 75.0 cm (plus 7.5 cm for clothing: 64.6 cm to 82.5 cm) and for women XSM would be 60.6 cm to 75.6 cm (plus 7.5 cm for clothing); the thigh strap range of existing unisex XSM of 39 cm to 66 cm seems too tight for harness users. Detailed information on other harness component cut lengths, sewing points,

**TABLE 6: Differences in Cut Lengths Between the Current and Newly Proposed Sizing Structures (in millimeters)**

Harness (Vest Type)		Proposed for Men			Proposed for Women			Current Unisex		
Size	Harness Component	Lower	Upper	Range	Lower	Upper	Range	Lower	Upper	Range
XSM	Chest strap	159	252	93	139	204	65	120	350	230
	Trochanter-crotch circumference	571	750	179	606	756	150	390	660	270
STD	Chest strap	192	290	98	148	242	94	125	355	230
	Trochanter-crotch circumference	655	878	223	676	882	206	490	750	260
XLG	Chest strap	215	284	69	199	252	53	125	395	230
	Trochanter-crotch circumference	771	931	160	849	994	145	660	930	270
SXL	Chest strap	—	—	—	—	—	—	125	425	300
	Trochanter-crotch circumference	—	—	—	—	—	—	730	1145	415

Note. XSM = extrasmall; STD = standard; XLG = extralarge; SXL = super-extralarge. See Figures 1b and 1g for the definitions of chest strap and trochanter-crotch circumference.

and connector locations are not presented here because they are associated with manufacturer-specific proprietary materials.

### Sample Size and Sampling Strategy Issues

The prediction equations derived from 216 participants in Hsiao et al. (2007) were adopted in this study to predict the best-fit harness size for individuals based on their gender, torso shape, body weight, and body height. It is worth mentioning that the average weight and stature of the 216 participants were very close to those of the general civilian populations that were described in the 1999–2000 NHANES (CDC, 2004; Hsiao, Long, & Snyder, 2002). The current study design included a stratified random sample of 501 out of 2,382 participants from the CAESAR database, a national 3-D anthropometry survey (Robinette, 2000; SAE International, 2008), to increase the statistical power needed to establish an inclusive harness sizing system for the national civilian population. With the addition of the strata from the larger 3-D body scan database from CAESAR, the constraint on determining the adjustment range of harness components for small-size men and large-size women (because of small counts for these two sizes, as noted in Hsiao et al., 2007) was adequately satisfied.

### CONCLUSION

Updated harness sizing systems and designs are needed to accommodate a diverse workforce in the construction industry. This study identified an improved harness sizing scheme of three sizes for women and three sizes for men in lieu of the existing four- to seven-size unisex system for both vest- and overhead-type harnesses. The adjustment ranges of the back, chest, front cross-chest, and front straps were within the 17-cm common range expectation, and the thigh and hip straps were in the 23-cm common adjustment range. To meet the further goal of tightening the adjustment ranges of the back, chest, front cross-chest, and front straps to be within 15 cm and the thigh and hip straps within 20 cm, harness sizing schemes for vest-type harnesses would require four sizes each for men and women. For the overhead-style harnesses, three sizes for men and four sizes for women appear necessary.

Harness manufacturers can use the parameters in Tables 2 through 5 plus the adjustment for clothing (2.5–7.5 cm) to set harness cut lengths for improved harness assemblies. The new sizing charts were graphed by gender, body weight, and body height in Figure 4 for manufacturers' consideration in developing next-generation harnesses. Workers can use the new sizing charts to select a proper harness size, which would help the construction industry reduce the risk of injury that results from poor user fit, improper size selection, and failure to don the harness properly. It should be remembered that some workers may need to try on more than one size to select the best-fit size because the overall combination of their body dimensions governs the size; body weight and stature alone do not exactly define who wears each size.

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Hongwei Hsiao is the chief of the Protective Technology Branch in the Division of Safety Research at the National Institute for Occupational Safety and Health and an adjunct professor at West Virginia University in Morgantown, West Virginia. He received his PhD in industrial engineering from the University of Michigan in Ann Arbor in 1990.

Jennifer Whitestone is the president of Total Contact, Inc., in Germantown, Ohio. She received her master's degree in biomedical engineering from Wright State University in Dayton, Ohio, in 1996.

Stacie Taylor is the president of Tailored Statistical Solutions, LLC, in Beavercreek, Ohio. She received her master of applied statistics in 1997 from Wright State University and is currently a doctoral candidate in statistics and mathematics at the Air Force Institute of Technology.

Mary Godby is an operations research analyst for Sumaria Systems, Inc., at the Supply Chain Diagnostics and Analysis Flight at Wright-Patterson Air Force Base, Ohio. She received her master's degree in statistics from Wright State University in Dayton, Ohio, in 1990.

Jinhua Guan is a health scientist in the Division of Safety Research at the National Institute for Occupational Safety and Health in Morgantown, West Virginia. He received his PhD in kinesiology (motor control/biomechanics) from the University of Minnesota.

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