Evaluation of Fall Arrest Harness Sizing Schemes

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Objective: This paper evaluated harness sizing schemes and anthropometric criteria for harness design applications. **Background:** Updated harness sizing systems are needed to accommodate diverse populations in the current workforce. **Method:** Three-dimensional torso scan data and human-harness interfaces from 108 women and 108 men were digitally captured. A bounding box approach was employed to quantify the effect of torso shape and size on fall harness fit. **Results:** A logistic regression model with eight equations was developed and tested to classify more than 96% of participants to the best-fitting size. **Conclusion:** Study outcomes suggested an alternative system of two sizes for women and three sizes for men over the current four-size unisex system. In addition, thigh strap angle and back D ring location could be utilized along with current harness static fit test criteria to further enhance postfall harness fit predictions. **Application:** This research could help reduce the risk of worker injury resulting from poor fit, improper size selection, or failure to don the harness properly.

INTRODUCTION

Fall arrest harnesses provide the last line of defense to the 5 million construction workers in situations where fall hazards cannot be completely eliminated (U.S. Department of Labor, 1997). Full-body harnesses have replaced waist belts and chest-waist harnesses for over 10 years and are considered the standard body support component of a personal fall arrest system in the United States and Canada (Ellis, 2001). Although full-body harnesses have demonstrated mechanical advantages over the old waist belts and chest-waist harnesses, the fit of full-body harnesses to worker populations has not been fully evaluated yet.

A review of historical anthropometric sources for commercial harness sizing reveals that they are based on dimensions that were derived from U.S. military population databases collected in the 1970s and 1980s (Bradtmiller, Whitestone, Feldstein, Hsiao, & Snyder, 2000). The harness manufacturing industry has a pressing need to reassess the current sizing schemes for three reasons. First, anthropometric data for the military populations do not represent the civilian worker population, given the relatively strict anthropometric entry requirements for the armed forces and height and weight guidelines for troop retention (Hsiao, Bradtmiller, & Whitestone, 2003). Next, population anthropometry evolves over time (Bodzsar, 2000; Hertzberg, 1972); large changes in body dimensions have taken place over the last decades among the U.S. civilian population (U.S. Department of Health and Human Services, 2001). Finally, diverse workforces in the construction industry, as well as new roles for women in the workforce, make it likely that more construction occupations will show a greater variation in their workers' range of body dimensions and shapes, compared with those in the 1970s and 1980s.

In addition to the unavailability of adequate anthropometric data for evaluating the static harness-torso interface, information is also lacking in suspension fit for full-body fall harnesses on workers after a fall. A typical postfall suspension test, which involves human dimension measurements and evaluation of the adequacy of the rigging assembly while a harness wearer is suspended, would take 20 to 30 min to complete. This poses a potential risk of suspension trauma to study participants; they may experience respiration distress within 5 to 30 min of suspension in a full-body

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harness (Brinkley, 1988). Fortunately, the newly available, rapid 3-D scanning technology takes only 17 s to register the range data of a human body, as well as the interface between human and harness, which makes it feasible to objectively assess the suspension fit of a harness.

This study utilized anthropometric data for the current U.S. workforce and a new 3-D scanning technology to identify the anthropometric characteristics that affect the fit of fall arrest harnesses to workers. The objectives were to (a) evaluate the adequacy of current sizing systems for overhead- and vest-style fall arrest harnesses and develop enhanced sizing schemes for them; and (b) determine whether static fit criteria such as thigh strap angle, shoulder strap location relative to the neck, and back D ring location are useful predictors of postfall dynamic human-harness interfaces. The results have a direct impact on practical design considerations for harnesses and have a potential impact on the development of national standards for fall arrest harness sizing systems.

METHOD

Participants

Two hundred sixteen volunteers (108 men and 108 women) participated in this study. The sample covered the four racial categories of White, Black, Hispanic, and other (including multiracial). There were 27 participants for each category per gender group. Their ages ranged from 18 to 56 years. The average height was 175.7 cm (*SD* = 6.5 cm) and mass was 85.5 kg (*SD* = 14.2 kg) for men and 162.6 cm (*SD* = 6.6 cm) and 66.2 kg (*SD* = 12.4 kg) for women. Means and standard deviations for stature and weight were estimated using the sample data (216 participants) weighted for the U.S. general population. The latest National Health and Nutrition Examination Survey (NHANES) data (1999–2000), cross-referenced with the U.S. Census Bureau Quick Tables for Morgantown, West Virginia, were used to determine the weighting composition (Centers for Disease Control and Prevention, 2004). Participants were compensated for time and inconvenience. The protocol was approved by the Institutional Review Board of the National Institute for Occupational Safety and Health.

Independent Variables

Type of harnesses. Two broad categories, vest- and overhead-style harnesses, were tested (Figure 1).

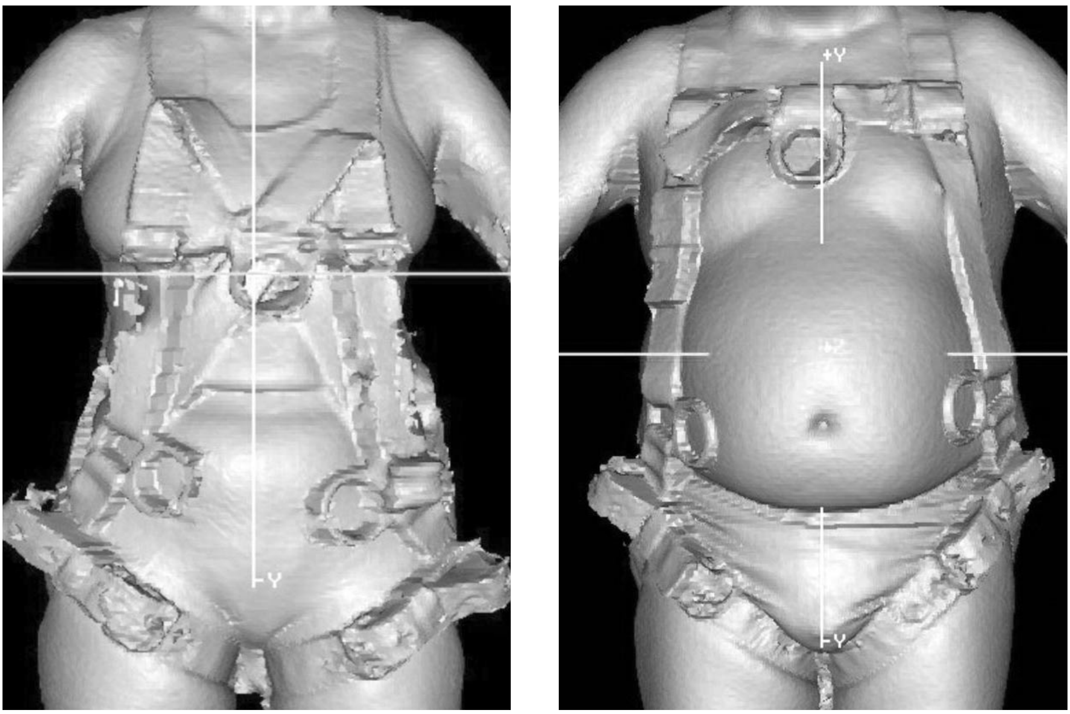


Figure 1. The overhead-style harness (left) and vest-type harness (right) used in the study.

Harness fit rating. Harnesses were tested for fit while participants were standing and when they were suspended, and a pass or fail rating was assigned based on four criteria that are in use in the harness manufacturing industry to minimize any potential biomechanical stress and suspension trauma. For the standing condition, the pass criterion was that the harness back D ring was positioned between the inferior and superior borders of the scapula. For the suspended condition, three criteria needed to be met to receive a pass rating: The suspension angle had to be ≤35°; the chest strap should not make contact with the neck; and the center of gravity (COG) of the body had to be behind the hip rings. We evaluated these criteria by examining the interface between the harness and the human torso through 3-D scan images, specifically the landmark coordinates of human torsos and the harness components (Figure 2). A harness fit rating of pass was assigned if both standing and suspended conditions received a pass rating.

Goodness of fit of harness component. In addition to the four performance criteria of fit used in

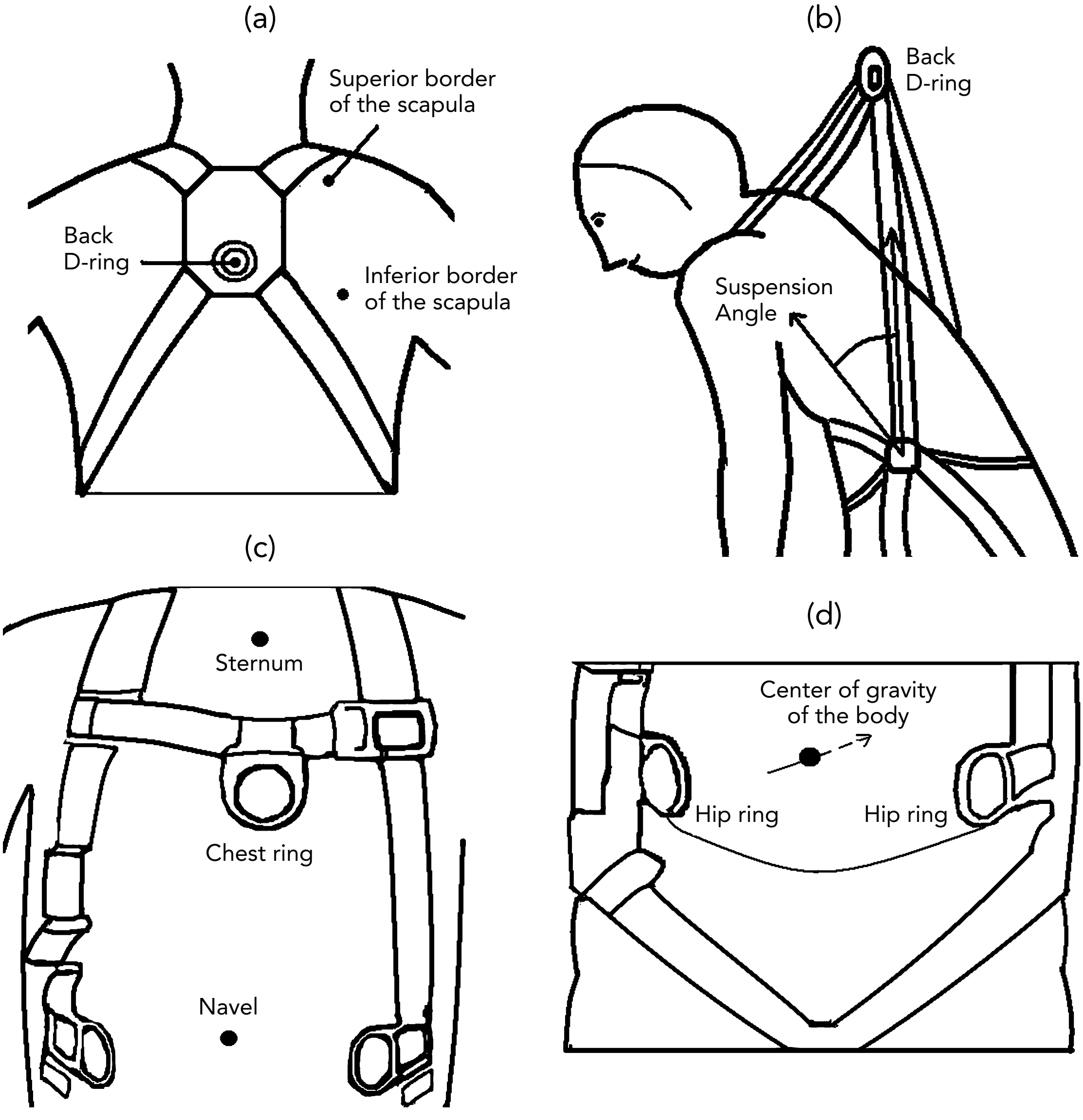


Figure 2. Four criteria – (a) back D ring location, (b) suspension angle, (c) chest ring location, and (d) hip ring location – were used to determine the harness fit score.

determining harness fit rating, two goodness-of-fit criteria for harness components, based on the research team's experience and participants' comments from a pilot study (Hsiao et al., 2003), were also evaluated for possible use in predicting dynamic (suspended) test results (i.e., suspension angles) from static standing test information. These two goodness-of-fit parameters were (a) fit of shoulder strap (i.e., shoulder strap location in relation to the neck base and acromion) and (b) thigh strap angle (defined as the angle between the thigh strap and the horizontal plane).

Gender. The participants were 108 men and 108 women. Gender is therefore a testable independent variable.

Bounding box dimensions. The maximum breadth (side-to-side distance), depth (front-to-back distance), and height (top-to-bottom distance) of both the upper torso volume space and the lower torso volume space (also known as "torso bounding boxes") were extracted from 3-D scan images. The 10th rib landmarks were used to separate the torso images into the upper and lower torso regions (Figure 3). These dimensions were used to explore the interaction of the general body shape and dimensions with harness fit. The bounding box concept originated within the computer graphics field; computer programs have assigned sizes to on-screen objects, such as images, by placing them in an invisible rectangle or box, called a *bounding box,* which constrains their maximum dimensions along two or three axes, respectively.

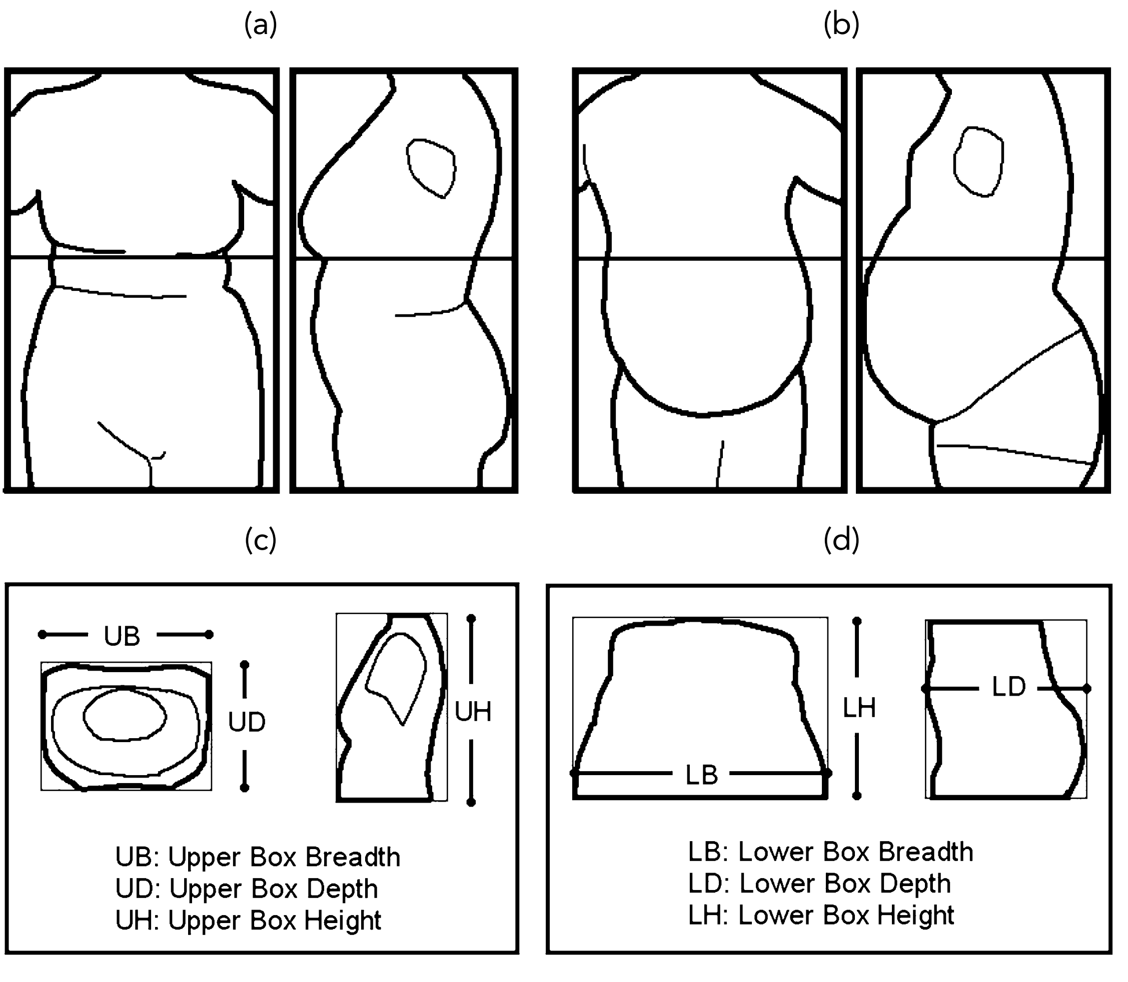


Figure 3. (a and b) The 10th rib location was used to separate the torso images into the upper and lower torso boxes. (c and d) The maximum breadths, depths, and heights of upper and lower torso volumes were defined as upper and lower box dimensions. Panels a and b also show female and male participants, respectively, with the same overall torso length but different size and shape between upper and lower torsos.

Dependent Variable

Four sizes of each type of harness were available: extra small (XS), standard (STD), extra large (XL), and super extra large (SXL). Each of the 216 participants was fitted in both types of harness for all sizes. The investigator adjusted the harness to achieve the best possible fit, asked participants about the comfort or discomfort of the harness, and recorded the best fit size.

Apparatus

Traditional anthropometry measurement device. An anthropometer (GPM Instruments Inc., Zurich, Switzerland) and a Toledo scale (Mettler-Toledo Inc., Worthington, OH) were used to measure stature and body weight.

Three-dimensional body scans. A Cyberware WB4 3-D full-body scanner (Cyberware Inc., Monterey, CA) was used to register the interface between the harness and participant during normal standing, as well as to quantify the changes in the harness fit when the participant was suspended (Figure 4). The accuracy of the scanning system was tested to an average error of 2.9 mm, ranging from +6 to –6 mm (Hsiao et al., 2003).

Device for simulating postfall condition. A custom-made suspension system was developed to suspend participants safely without interfering with the mechanics of the 3-D body scanner (Figure 4). Participants were raised or lowered slowly by the manually operated control, which included an automatic brake to keep the participants in position when the control was released. The system can handle up to 227 kg.

Procedure

Upon arrival, participants viewed a Web page that described the details of the study and the tasks that they were to perform. Each participant signed an informed consent form and filled out a short demographic questionnaire. The participant was then taken to a dressing room, where men changed from street clothes into bicycle shorts and women changed into bicycle shorts with a halter top.

By gently palpating subsurface skeletal structures, an investigator located 18 skeletal landmarks on the participant's skin: right and left neck base lateral, right and left acromion, right and left iliocristale, right and left anterior superior iliac spine (ASIS), crotch, midpoint of gluteal furrow (right), suprasternale, superior scapula point (right), inferior scapula point (right), right and left posterior superior iliac spine (PSIS), right and left 10th rib, and C7 (the 7th vertebra). They were then marked with a nonpermanent cosmetic marker. Another investigator then measured the stature and body weight. The participant tried on four sizes of the first style of harness. One investigator performed the fit test with feedback from the participant and recorded the fitting result of each size. The "best-fitting" size was then selected for a subsequent fit assessment.

During the subsequent fit assessment, the landmarks were covered with adhesive dots for 3-D scanning. The participant was scanned with the Cyberware full-body scanner (see Apparatus section) in an erect standing posture with a harness. The participant lined up his or her feet with the premarked footprints on the scanner platform. The participant's arms were held 45° away from his or her torso, and the legs were about 41 cm apart at the heels with the toes angled about 30° away from the sagittal plane (referred to as the A-O scan for this posture with an overhead-style harness or the A-V scan for the vest-type harness; Figures 1 and 4). Although the effect of human sway on image fidelity in Cyberware whole-body scans is minimal (Corner & Hu, 1998), a sway-reduction cup was placed on top of the participant's head to further control any possible body movement (Brunsman, Daanen, & Files, 1996). The scan took 17 s. Participants were instructed to hold their breath during the scan to reduce the variation in torso measurements resulting from respiration (Daanen, Brunsman, & Robinette, 1997). The scans were visually inspected for quality.

After the first scan, investigators attached the steel cable of the suspension system (see Apparatus section) to the back D ring of the harness and raised the participant until the participant's toes were off the floor to simulate a postfall condition. While the participant was off the floor, he or she was scanned a second time (referred to as the B-O scan for this suspended scan with the overhead-style harness or the B-V scan for the vest-type harness; Figure 4). After the second scan, the participant was lowered to the floor and the fall arrest harness was removed. The participant was then fit in the second style of harness. If initially assigned the vest style, he or she was

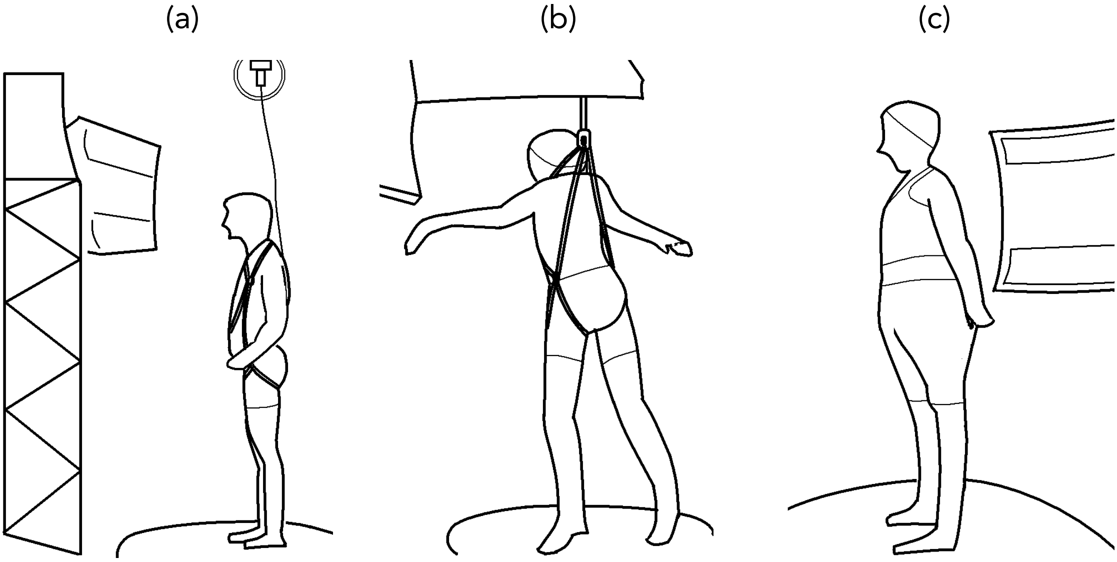


Figure 4. Equipment and positions used to evaluate the human-harness interface. (a) The custom-made suspension system (marked with a double circle) used in this study, and a standing posture with harness donned (A scan). (b) Suspended position (B scan). (c) Standing posture without harness (C scan). (d) The Cyberware WB4 3-D full-body scanner.

then fit with the overhead style, and vice versa. The participant was then scanned in standing (A-O or A-V scan) and suspended (B-O or B-V scan) postures with the second type of harness. Next, the participant was scanned for the fifth time without the harness (referred to as the C scan; Figure 4). The same sway-reduction and breath-holding techniques used in A scans were used in this scan. Finally, the participant changed back into street clothes, was compensated for his or her time, and then was dismissed.

DATA EXTRACTION AND ANALYSIS

Alignment of Standing (C) Scans and Standing-With-Harness (A) Scans

Body landmarks from surface scans with the harness donned (i.e., A-O and A-V scans) are sometimes hidden by the placement of the harness. For instance, the suprasternale might disappear behind the chest ring or the gluteal furrow reference may be covered by the thigh strap. Alignment of the A and C scans allowed the hidden landmarks in the A scans to be copied from C scans to enable evaluations of the interface between the harness components and the body. Alignment of the A and C scans was performed using landmarks common and visible to both scans; both the right and left PSIS and the C7 were used in most circumstances. Although the arm and leg postures sometimes varied slightly between A and C poses, the torso postures were very consistent. Therefore, the right and left PSIS and C7 served the alignment process well.

In preparing for the alignment of B and A scans in the next section, it was necessary to establish the COG location in A scans from C scans. First, the COG location in the C scan was derived using the left ASIS, right ASIS, and crotch landmarks (McConville, Churchill, Kaleps, Clauser, & Cuzzi, 1980). The COG was then assigned to the A scan from the C scan when the alignment of the A and C scans was performed.

Alignment of Suspended (B) Scans and Standing-With-Harness (A) Scans

One of the harness fit tests is meant to determine whether the body's COG falls behind the harness hip rings during suspension. In order to assign the COG to the suspended conditions (B scans), an alignment of A and B scans was performed based on the crotch and the right and left ASIS landmarks, as used in the alignment of the A and C scans. Although some participants arched their back while being suspended in the harness, which slightly affected the alignment of upper torsos of the two scans, the three landmarks (crotch, right ASIS, and left ASIS) still served the COG transfer function from A scans to B scans well because the COG tended to fall in the lower region of the torso.

RESULTS

Harness Fit and Adequacy of the Current Sizing Systems

Best-fitting size of harness. Figure 5 shows the comparison of the size specified by the current size selection chart (based on body height and weight) and the best-fitting size determined in this study. For the overhead-style harness, 93% of the participants' best-fitting size matched their required size as defined by the current size selection chart based on their body height and weight, and for the vest-type harness, 97% matched. These are the percentages before the four criteria for the interface between harness and torso were applied. (Please see the following subsection, *Harness fit rate,* for information.)

In Figure 5a, for instance, based on the current sizing system for the overhead-style harness, individuals who are 40 to 70 kg and 140 to 170 cm tall (for some, up to 185 cm) are expected to use XS harnesses; 89 participants in this study were in this category based on their body weight and height (see the legend at the bottom left corner of Figure 5a). It turned out that the best fit size was STD for 11 of those 89 participants (see the unfilled and filled triangles in the XS area and in the legend area) and XS for 78 out of the 89 participants (see the unfilled and filled circles in the XS area and in the legend area). In total, the overall fit test failed for 23 out of these 89 participants when they were tested using their best fit size (see the filled circles and filled triangles in the XS area and in the legend area).

Also, in Figure 5b, for example, based on the current sizing system for the vest-style harness, 89 participants in this study were in the XS category by their body weight and height (see the legend at the bottom left corner of this figure). It turned out that the best fit size was STD for 5 of those 89 participants (see the unfilled and filled triangles in the XS area and in the legend area) and XS for 84 out of the 89 participants (see the unfilled and filled circles in the XS area and in the legend area). However, the overall fit test failed for 31 out of these 89 participants when they were tested using their best fit size (see the filled circles and filled triangles in the XS area and in the legend area).

Harness fit rate. Table 1 presents the fit rates by harness style, harness size, gender, and failure type (i.e., criterion) for the best-fitting harness sizes when the four fit criteria (suspension angle, hip ring location, chest ring location, and back ring location) were employed. More than one fit criterion failed for some individuals, so the combinations of fit rates are also shown in this table. Overall, 24% of fit ratings (19% for men and 28% for women) failed fit criteria when participants wore overhead-type harness; 31% (28% for men and 35% for women) failed when a vest-style harness was used. Although women faced a higher fit challenge than did men at the 31.5% versus 23.6% fail rates, the difference was not statistically significant, $\chi^2(1) = 3.3519$, $p = .0671$. All sizes within each harness type have a failure rate in the range of 23% to 36%, except for the overhead XL size at 14%.

A suspension angle of more than 30° from vertical is considered a failure of the harness system according to ANSI Z359.1-1992, Paragraph 3.1.2 (American National Standards Institute, 1992). This study broadened the range of acceptance to

(a)

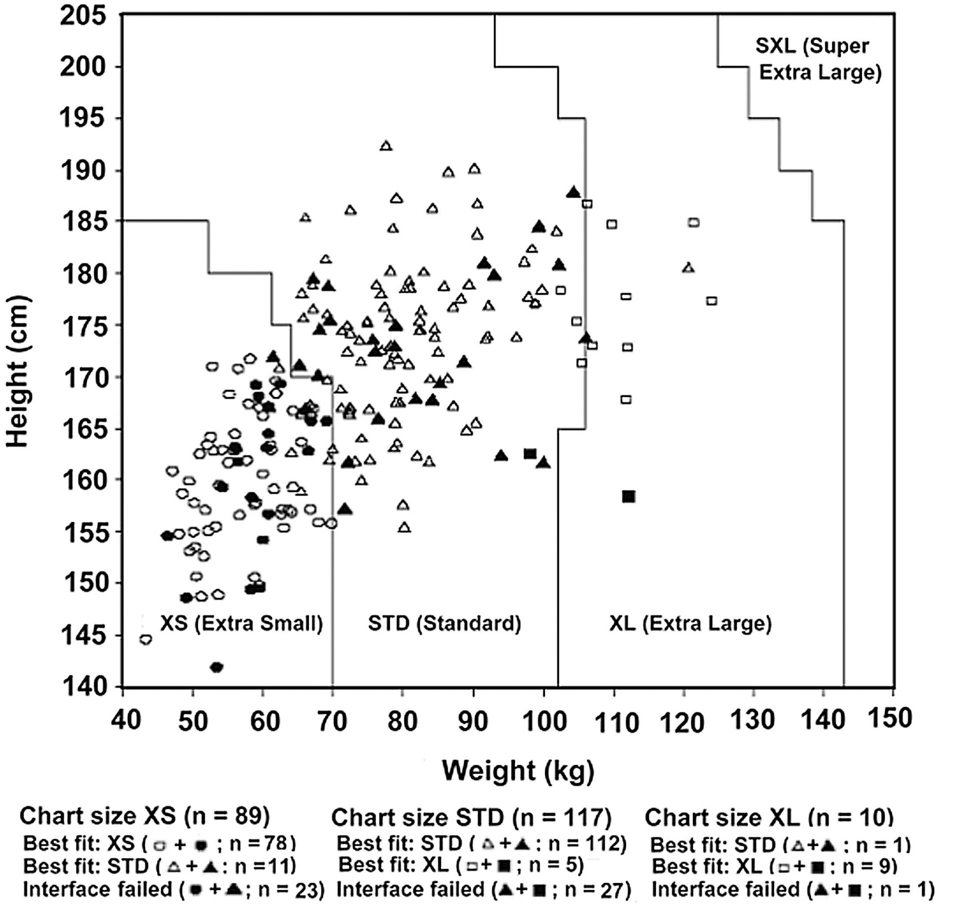


Figure 5. The four divided background areas of these harness size selection charts represent the four sizes of a current harness system based on harness wearers' body weights and body heights for (a) the overhead-style harness and (b) the vest-style harness. Symbols (circles = XS, triangles = STD, squares = XL) represent the best fit sizes. (No

35° in that the resolution of the inclinometer with the placement (angle) of this device on the participant's body image (along the lumbar region) could vary by as much as ±5°. About 85% of the male participants and 80% of the female participants met the criterion of no more than a 35° angular deviation while being suspended in an overhead-style harness. The rates were 81% for men and 68% for women for the vest-style harness.

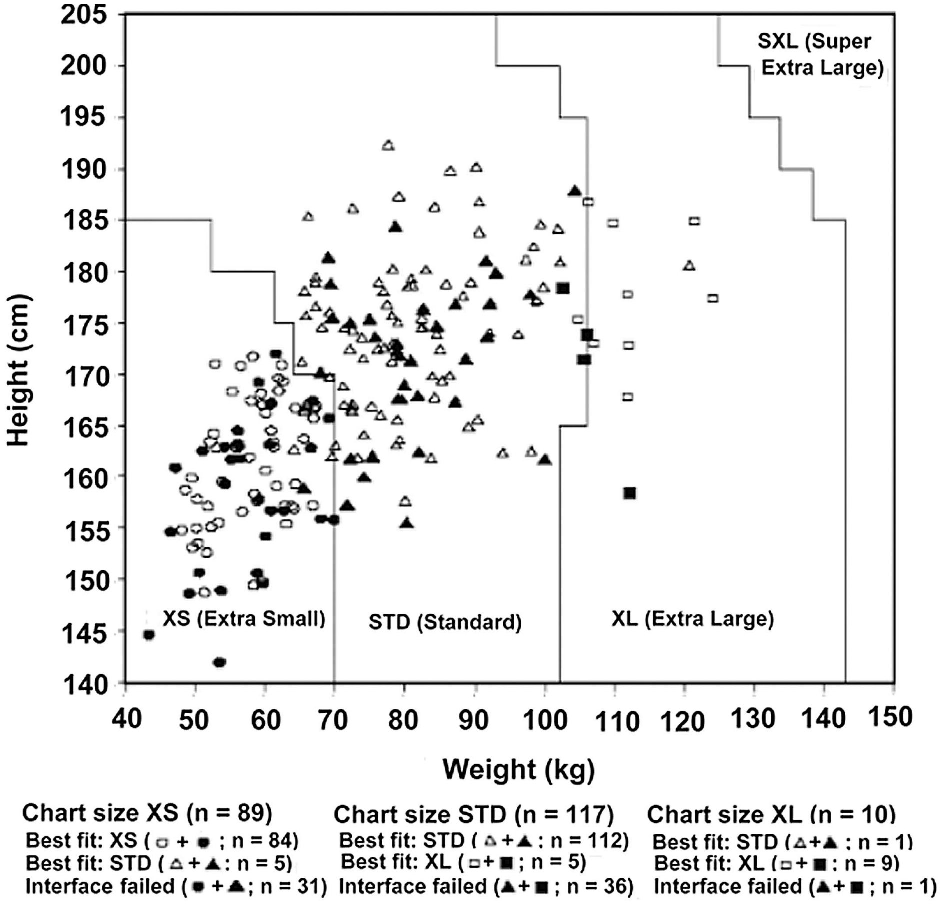
The COG is expected to fall behind the hip ring locations in order for the harness to be considered a fit when the participant is suspended. The data show that for 3 women the overhead harness failed this criterion; for 1 man and 1 woman the vest-style harness failed this criterion.

During the suspended condition, the chest strap and ring can ride up on the neck if the harness does not fit the participant well. In the suspension pose, an overhead-style harness failed for 5 men and 4 women; the same suspension pose using a vest-type harness failed for 8 men and 4 women.

Using the coordinates of the back ring's midpoint and the upper and lower edges of the shoulder blade (i.e., superior scapula point and inferior scapula point), the back ring fit was evaluated. The back ring was positioned appropriately on all the men tested in the overhead harness. The vest design was adequate for 106 of the 108 men. The ring was positioned unacceptably on 8 of the 108 women tested in the overhead style harness, and the vest design was unsatisfactory for 5 of the 108 women.

Bounding box dimensions. Summary statistics of the bounding box dimensions are presented in Table 2 in weighted population estimates. The significant differences in upper torso dimensions between the two gender groups ($p < .0001$) and the significant deviations on lower torso height and

(b)



selection was made for SXL as the best fit size in this study.) Filled symbols indicate participants for whom the harness interface failed the overall fit test criteria; unfilled symbols represent those for whom the interface passed the fit test criteria.

depth between the two genders ($p < .0001$) confirmed that dividing the torso into two "boxes" instead of having a complete torso box is advisable when investigating the effect of the torso's shape and size on fall harness fit.

Constructing an Enhanced Sizing Scheme

The influential factors and prediction models. A multinomial logistic regression with forward selection was used for each type of harness to search for the six most influential factors (i.e., independent variables) that determine sizes (McFadden, 1974; SAS Institute Inc., 2004). The dependent variable was the best-fitting size of the harness, and potential independent variables were gender, height, weight, and the six torso bounding box parameters. Only those participants who received a pass fit rating for that harness were used to construct the new sizing charts for the harness type. These participants were assigned to either the estimation or validation subset of data. The estimation subset was used to create a harness sizing classification model, whereas the validation subset gave a postestimate (i.e., validation) of the percentage of the user population that could be fit correctly using the estimation model. For the vest-type harness, 7 participants wore a size different from the current sizing chart recommendation, and for the overhead-type harness there were 14 such participants (see *Best-fitting size of harness* at the beginning of the Results section). These participants were intentionally assigned to the estimation groups for the best development of prediction models. The remaining participants were randomly assigned to either the estimation or validation subset while maintaining an equal number of total participants between the two subsets.

Using the six most influential independent

TABLE 1: Fit Ratings by Type of Harness and Gender With Failures Broken Into Categories

	Overhead			Vest		
Fit Ratings	Men	Women	Total	Men	Women	Total
Pass	87 (81%)	78 (62%)	165 (76%)	78 (72%)	70 (65%)	148 (69%)
Fail total	21 (19%)	30 (28%)	51 (24%)	30 (28%)	38 (35%)	68 (31%)
Suspension angle (SA)	16	15	31	19	28	47
Hip ring (HR)	0	2	2	1	0	1
Chest ring (CR)	5	2	7	7	1	8
Back ring (BR)	0	3	3	2	2	4
SA + HR	0	1	1	0	1	1
SA + CR	0	2	2	1	3	4
SA + BR	0	4	4	0	3	3
CR + BR	0	1	1	0	0	0
Totals	108	108	216	108	108	216
Size XS						
Pass	6	51	59	8	46	54
Fail	3 (33%)	18 (26%)	21 (27%)	5 (38%)	25 (35%)	30 (36%)
Totals	9	69	78	13	71	84
Size STD						
Pass	69	27	96	60	24	84
Fail	18 (21%)	10 (27%)	28 (23%)	22 (27%)	12 (33%)	34 (29%)
Totals	87	37	124	82	36	118
Size XL						
Pass	12	0	12	10	0	10
Fail	0	2	2 (14%)	3	1	4 (29%)
Totals	12	2	14	13	1	14

variables, we derived logistic regression models to predict the best-fitting size; STD was set as the reference size. The resulting probability for choosing a specific size over STD fell between 0 and 1. The logistic regression models for overhead-type harness are described as Equations 1, 2, 3, and 4. The probability of wearing XS instead of STD for men is

$$1/[1 + \exp(-681.075 + 3.894\mathit{breadth}_{up} - 3.66\mathit{depth}_{low} + 3.164\mathit{depth}_{up} + 1.854\mathit{stature} + 2.441\mathit{weight} + 2.001\mathit{breadth}_{low})] \quad (1)$$

and for women is

$$1/[1 + \exp(-657.348 + 3.894\mathit{breadth}_{up} - 3.66\mathit{depth}_{low} + 3.164\mathit{depth}_{up} + 1.854\mathit{stature} + 2.441\mathit{weight} + 2.001\mathit{breadth}_{low})]. \quad (2)$$

in which $\mathit{breadth}_{low}$ is the breadth of the lower torso bounding box, $\mathit{breadth}_{up}$ is the breadth of the upper torso bounding box, depth_{low} is the depth of the lower torso bounding box, and depth_{up} is the depth of the upper torso bounding box. The probability of .5 is the determining point for size selection. For instance, after the bounding box parameters, stature, and weight are input using the men's probability formula (i.e., Equation 1) for the overhead-type harness, if the resulting value is .51 or greater, the participant will fit into XS.

The probability of wearing XL instead of STD for men is

$$1/[1 + \exp(79.220 - 0.386\mathit{breadth}_{up} - 2.464\mathit{depth}_{low} + 1.77\mathit{depth}_{up} + 0.035\mathit{stature} - 0.409\mathit{weight} - 0.038\mathit{breadth}_{low})] \quad (3)$$

whereas for women it is

$$1/(1 + \exp(81.315 - 0.386\mathit{breadth}_{up} - 2.464\mathit{depth}_{low} + 1.77\mathit{depth}_{up} + 0.035\mathit{stature} - 0.409\mathit{weight} - 0.038\mathit{breadth}_{low})]. \quad (4)$$

These four models (Equations 1–4) for the overhead-style harness successfully classified

TABLE 2: Population Estimates for Torso Box Data for Men and Women Between Ages 18 and 56

Torso Box	Mean	Min.	Max.	SD	Percentile 5th	Percentile 95th
			Men			
Upper						
Breadth	39.4	32.2	48.1	3.20	35.2	47.3
Depth	30.5	23.3	37.4	3.65	24.6	37.2
Height	40.0	34.0	53.6	3.38	35.6	48.4
Lower						
Breadth	38.7	33.8	47.3	2.26	35.5	42.2
Depth	.3	23.1	42.5	4.36	25.1	38.1
Height	36.6	25.6	45.6	3.65	31.2	43.2
			Women			
Upper						
Breadth	35.3	29.8	45.1	2.84	31.7	41.4
Depth	27.0	21.2	40.2	3.30	22.3	32.3
Height	34.1	28.4	40.8	2.45	30.4	37.6
Lower						
Breadth	39.2	33.5	49.4	2.83	34.6	44.3
Depth	28.8	22.8	44.1	3.55	23.7	34.4
Height	31.9	25.6	39.6	2.36	28.4	36.4

Note. Distances are in centimeters.

99% of the classification subset and 100% of the validation subset.

The logistic regression models for the vest-type harness are described in Equations 5, 6, 7, and 8. The probability of wearing XS instead of STD for men is

$$1/[1 + \exp(-386.137 + 2.874 breadth_{low} + 2.837 breadth_{up} - 2.111 depth_{low} + 0.675 stature + 1.157 weight + 1.756 depth_{up})] \tag{5}$$

and for women is

$$1/[1 + \exp(-385.676 + 2.874 breadth_{low} + 2.837 breadth_{up} - 2.111 depth_{low} + 0.675 stature + 1.157 weight + 1.756 depth_{up})], \tag{6}$$

The probability equation of wearing XL instead of STD for men is

$$1/[1 + \exp(287.430 - 7.9 breadth_{low} - 6.007 breadth_{up} - 6.557 depth_{low} + 1.119 stature + 1.7349 weight + 4.6849 depth_{up})], \tag{7}$$

and for women is

$$1/[1 + \exp(353.459 - 7.9 breadth_{low} - 6.007 breadth_{up} - 6.557 depth_{low} + 1.119 stature + 1.734 weight + 4.684 depth_{up})]. \tag{8}$$

These models for the vest-type harness successfully classified 100% of the classification subset and 96% of the validation subset.

Size selection. These eight models (equations) provided unique 3-D anthropometric information for better defining harness size groups. This grouping will help harness designers to restructure current harness sizing plans (and thus the adjustment range of each harness component) to accommodate at least 96% of the population. The process of harness sizing plans is further explained in the Discussion section. For practical purposes, any size-selection chart must be based on dimensions that are readily known or easily measured by the consumer. To explore the possibility that there could be simpler models for harness end users, we used only gender, weight, and stature in generating logistic regression models. These models successfully classified 90% of the classification subset and 94% of the validation subset for the overhead-style harness for men and women combined, as well as 93% of the classification subset and 96%

of the validation subset for the vest-type harness. The estimated logistic regression models for determining sizing among XS, STD, and XL for overhead-style harnesses are illustrated in Figures 6 and 7. The estimated logistic regression models for determining sizing among XS, STD, and XL for vest-type harnesses are illustrated in Figures 8 and 9.

Predicting Postfall Harness Fit From Static Harness Fit

Two goodness-of-fit parameters (fit of shoulder strap and thigh strap angle) were evaluated for possible use of these static test data in predicting results for dynamic tests (i.e., suspension angles). In addition, the back D ring location during standing may be a good predictor of suspension angle and thus was statistically tested as well.

Landmarks used to evaluate the position of the shoulder strap location were exterior and interior edges of the shoulder strap, neck lateral base, and right acromion. Their *x* coordinates (horizontal) were used to calculate the distances between neck lateral base and the interior shoulder strap point as well as between the acromion and the exterior shoulder strap point. The results showed that all harness shoulder straps were properly positioned along the shoulder relative to the acromion. A correlation test indicated a positive correlation between the distance from shoulder strap to neck base and suspension angle (Spearman correlation $r = .185, p < .01$) for overhead-style harness; when the shoulder strap is too close to the acromion, the postfall suspension angle is more likely to fall beyond the safe range. The correlation was not significant for the vest-type harness. It is worth noting that harness shoulder straps are too close to the neck for a significant portion of participants, which could result in discomfort to the harness wearer. This is more of an issue for women than for men. The overhead-style harness had a higher rate of "misfit" than did the vest style, $\chi^2(1) = 42.602, p < .001$. There were 17 misfits for women and 6 for men for the vest-style harness; the misfit numbers were 58 for women and 23 for men for the overhead-style harness.

The front thigh strap angle at the static posture varied from 5° to 48° among participants. Female participants demonstrated a "flatter" thigh strap angle, with a mean of 21.3° for both the overhead and vest harnesses. Men wore the thigh strap a bit differently, with a mean of 30.4° for the overhead-style harness and 31.9° for the vest-type harness.

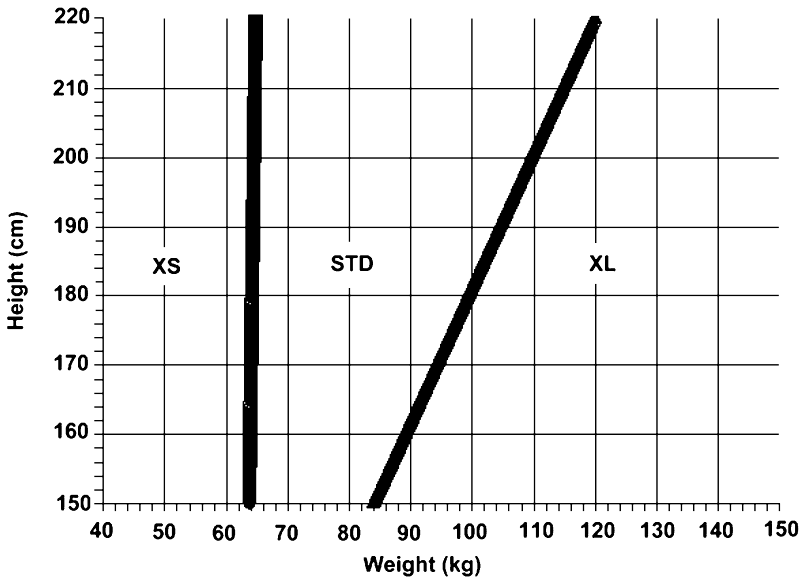


Figure 6. Proposed simplified sizing chart for men for the overhead-style harness. These models successfully classify 97.6% of the estimation subset and 94.3% of the validation subset in this study. The comprehensive logistic regression models, from which this simplified chart was derived, successfully classified 99% of the estimation subset and 100% of the validation subset.

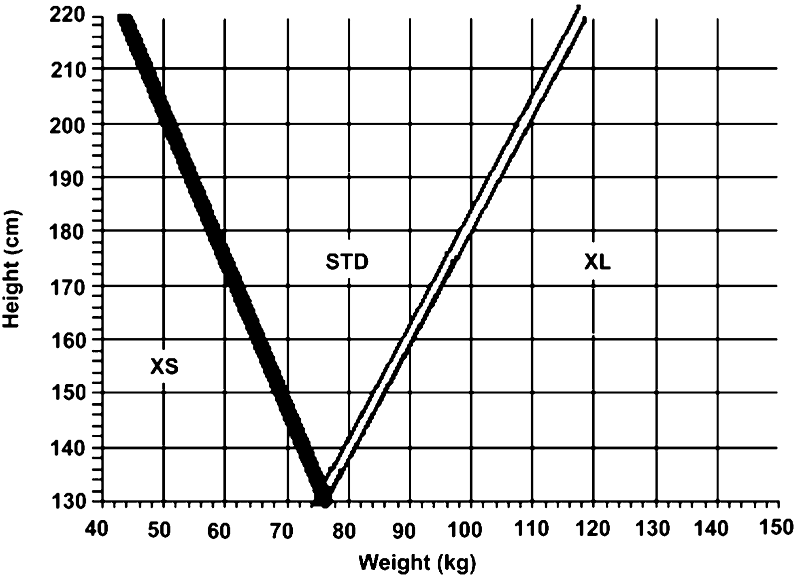


Figure 7. Proposed sizing chart for women for the overhead-style harness in XS and STD sizes (solid line), with an expanded component for the XL size (hollow line; very few women would be expected to use this size) that was derived from combined data for men and women. This model successfully classifies 89.7% of the estimation subset and 94% of the validation subset. The comprehensive logistic regression models, from which this simplified chart was derived, successfully classified 99% of the estimation subset and 100% of the validation subset.

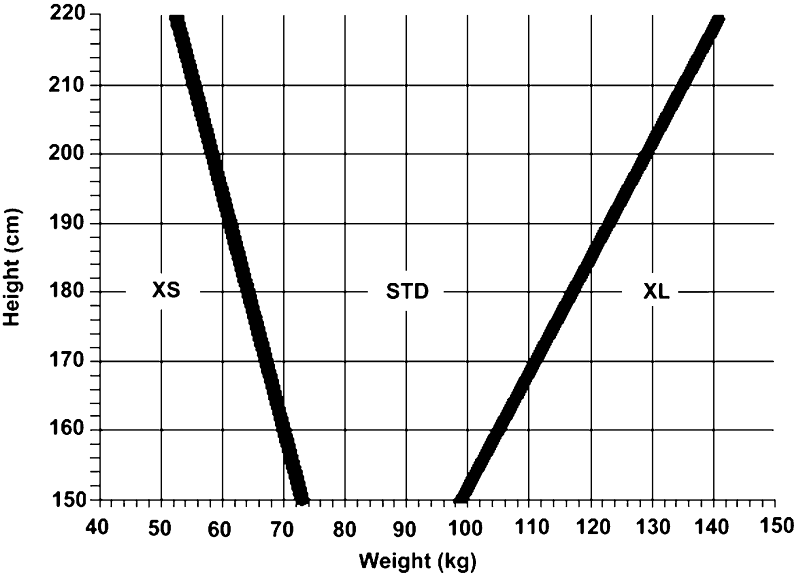


Figure 8. Proposed sizing chart for men for the vest-type harness; this model successfully classifies 96.5% of the estimation subset and 96.4% of the validation subset. The comprehensive logistic regression models, from which this simplified chart was derived, successfully classified 100% of the estimation subset and 95% of the validation subset.

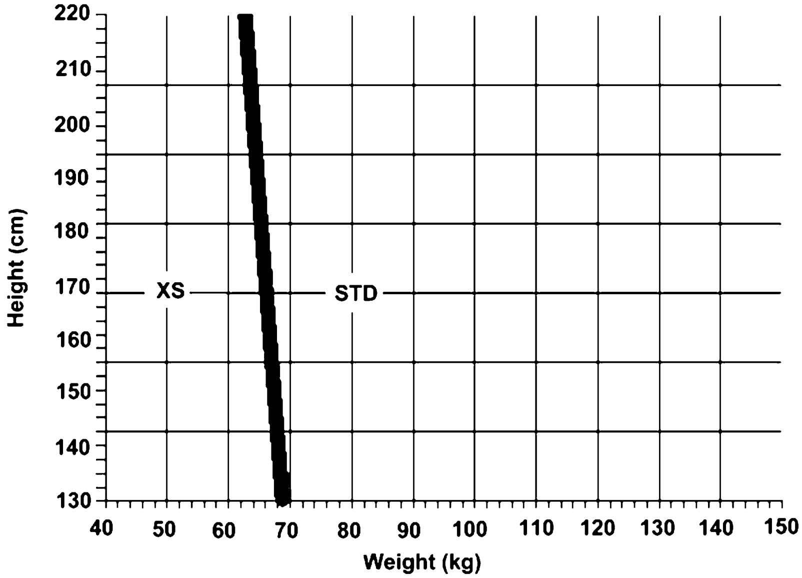


Figure 9. Proposed sizing chart for women for the vest-type harness; this model successfully classifies 84.2% of the estimation subset and 96.4% of the validation subset. The comprehensive logistic regression models, from which this simplified chart was derived, successfully classified 100% of the estimation subset and 96% of the validation subset.

A two-sample *t* test was used to compare the overhead-style harness thigh strap angle between the group of participants who received a pass fit rating and those who received a fail fit rating. There was a significant difference ($t = -3.22, p = .0015$) in the thigh strap angles between those two groups. The pass group ($n = 165$) had a mean thigh strap angle of 26.9° with a standard deviation of 8.2°, and the fail group ($n = 50$; 1 missing) had a mean thigh strap angle of 22.6° with a standard deviation of 8.3°. A Pearson correlation test of the relation between thigh strap angle and the angle of inclination during suspension for the overhead-style harness indicated that the flatter angle of the thigh strap is coincident with the increased angle of the participant during suspension (Pearson correlation $r = -.202, p = .003$).

For the vest-style harness, we performed a two-sample Wilcoxon rank-sum test to compare the thigh strap angle between the group of participants who received a pass fit rating and those who received a fail fit rating. The nonparametric Wilcoxon rank-sum test for this analysis on the vest-style harness was used because the data were not distributed normally. There was a significant difference ($z = -2.78, p = .005$) in the thigh strap angles between these two groups. The pass group ($n = 148$) had a mean thigh strap angle of 27.7° with a standard deviation of 7.6°, and the fail group ($n = 68$) had a mean thigh strap angle of 24.1° with a standard deviation of 8.9°. Spearman correlation tests showed a significant negative correlation between thigh strap angle and angle of inclination for the vest-style harness (Spearman correlation $r = -.237$, $p < .001$). Clearly, adequate thigh strap angle is a precursor to suspension angle; it can be considered as an additional criterion along with the current static fit criteria to possibly minimize the need for a suspension test.

A Spearman correlation test of the relation between back D ring position (relative to the lower shoulder blade point) and the angle of torso inclination during suspension for the overhead-style harness indicated that the lower the back D ring, the higher the suspension angle (Spearman correlation $r = -.317, p < .001$). The correlation between back D ring position and the angle of torso inclination during suspension for the vest-style harness was similar to that of the overhead-style harness (Spearman correlation $r = -.318, p < .001$). The back D ring location can be explored during static fit tests to minimize the need for a suspension test.

DISCUSSION

Sampling Strategy and Weighting Factors

A good sampling strategy is necessary to make sure that the anthropometric statistics resulting from a survey accurately represent the population of interest. For anthropometric surveys good sampling involves determining the sample size as well as the sample structure in terms of age, sex, and race. Because this particular study was to investigate the effect of anthropometry on the fit of fall arrest harnesses, the full range of anthropometric variation is more important than the number of participants. It was estimated that 72 to 80 participants would be needed to investigate the anthropometric effect (i.e., body weight and stature) on harness sizing schemes with a risk of 10% for Type I error and 5% for Type II error. The sample size was set at 108 for each gender. The sample was planned to cover the four racial categories of White non-Hispanic, Black non-Hispanic, Hispanic, and other (including multiracial); 27 participants were recruited for each category for each gender group. This sample size is small enough to be cost effective but large enough to contain the human variation needed to allow investigators to examine a full range of body sizes.

The latest NHANES study data (1999–2000) were used to define the population gender and racial composition and thus their weights for the population estimates. Each White non-Hispanic man, Black non-Hispanic man, Hispanic man, and other racial makeup man represented 331,990, 54,679, 76,951, and 23,751 men of each racial/ethnic group, respectively. Each White woman, Black woman, Hispanic woman, and other racial origin woman represented 341,523, 64,775, 85,421, and 20,910 women of each racial/ethnic group, respectively.

Harness Fit Test Methods

Some criteria are commonly used in the harness manufacturing industry to indicate whether a harness fits well (see the *Harness fit rating* subsection in the Independent Variables section). During the course of this investigation, the industrial criteria and human 3-D information were integrated to create a comprehensive test for assessing the overall fit of the harnesses. In addition, this study established the correlations between static thigh strap angle and dynamic suspension angle as well as between static back D ring location and dynamic suspension angle. The results shed light on the possible use of static fit assessment scores for predicting the dynamic suspension outcomes. The finding would have a special meaning in that performing a dynamic suspension test is costly and presents a potential risk of suspension trauma to the participant. Harness manufacturers and harness users could add these enhanced practical criteria to improve or evaluate harness fit.

It is worth noting that there was a positive correlation of thigh strap angle with lower torso box height (Spearman $r = .431$, $p < .001$) and gluteal furrow arc length (Spearman $r = .163$, $p = .017$) in the overhead-style harness tests. Similar results existed for the vest-type harness. There was a significant positive correlation between thigh strap angle and thigh circumference (Spearman $r = .318$, $p < .001$), lower torso box depth (Spearman $r = .188$, $p = .006$), lower torso box height (Spearman $r = .567$; $p < .001$), and gluteal furrow arc length (Spearman $r = .371$, $p < .001$). These results suggest that the thigh strap range, as represented by these two harness systems, can be adjusted or increased to accommodate harness users with small lower bounding box dimensions, which in turn will improve the postfall fit of the human-harness interface.

Adjustment Range of Each Harness Component

With the alternative sizing scheme presented in the Constructing an Enhanced Sizing Scheme section, it can be expected that harness manufacturers would be interested in knowing the adjustment range of each harness component for harness redesign (e.g., in determining the cut length of each harness component). There are several ways to determine the adjustment range. First, all the participants (including those in the fail group for the harness fit test) can be classified into their predicted best fit sizes for vest- and overhead-style harnesses using prediction Equations 1 through 8. Table 3 describes the distribution of predicted best fit sizes for each gender within each harness type.

Using descriptive statistics, the adjustment range of a harness component of each harness size for each gender can be determined. For instance, 62 female participants were predicted to use the women XS size of overhead-style harness. Their front strap length measurements have a mean of 58.2 cm (the 95% confidence interval range for mean = 57.4–59.1 cm) with a standard deviation of 3.3 cm. The adjustment range of the front strap can be estimated as 50.5 to 65.9 cm for 98% of XS-size female users.

The second approach would also classify all the participants (including those in the fail group for the harness fit test) into predicted best fit size groups as the first step for vest and overhead harness size assignment using Equations 1 through 8. A principal component analysis then would identify representative body models that consider multiple harness component dimensions at the same time (Meindl, Hudson, & Zehner, 1993). This approach would accommodate individuals with unique ratios among torso dimensions, such as a short torso length with a large belly depth or a long torso with a wide chest width and median belly depth. The adjustment range for each harness component is likely to be slightly smaller and more realistic than the range that was computed by the first approach. A separate paper will report the subject of adjustment range using this approach in detail. It 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, one would need to take into account the additional clothing that workers wear in the wintertime; harness users usually want one harness for all seasons. An additional 5-cm range for each major harness component would therefore be necessary.

Limitations of the Study and Directions for Future Harness Design

The study used participants mainly in the West Virginia area. This worker database should be used in designing harnesses with this understanding. However, it is worth mentioning that the average stature and weight of our study participants were very close to those of the general civilian populations that were described in the 1999 to 2000 NHANES (Centers for Disease Control and Prevention, 2004; Hsiao, Long, & Snyder, 2002). In this study, the weighted average height was 175.7 cm (*SD* = 6.5 cm) and mass was 85.5 kg (*SD* = 14.2 kg) for men and 162.6 cm (*SD* = 6.6 cm) and 66.2 kg (*SD* = 12.4 kg) for women. The 1999 to 2000 NHANES data showed that the national average height was 175.7 cm and mass was 81.8 kg for men and 162.0 cm and 68.9 kg for women. In addition, the participants in this study do represent a variety of body types, which demonstrates the usefulness of this modeling procedure for harness fit testing. The study outcomes can serve as an initial model for testing harness fit as well as for harness design applications.

The research team is exploring the use of a national 3-D database of 2,384 participants from the Civilian American and European Surface Anthropometric Resource (CAESAR) project (Robinette, 2000; Society of Automotive Engineers International, 1998) to establish an extended harness sizing system based on this study for the national civilian population. This step is especially useful in finalizing the adjustment range of harness components for harness redesign to match the proposed alternative sizing scheme; there were limited predicted counts for the XS size for men and the XL size for women from this study, which may compromise the quality of using a principal component analysis approach in identifying representative body models for harness design and testing. With the larger 3-D body scan database from CAESAR, this constraint can be adequately relieved.

TABLE 3: Distribution of Predicted Best-Fit Sizes for Each Gender Within Each Harness Type, Based on the Equations 1–8.

	Overhead Style			Vest Style		
Best Fit Size	Count	Unweighted Proportion of Population	Weighted Proportion of Population	Count	Weighted Proportion of Population	Unweighted Proportion of Population
			Men			
XS	10	9.3%	6.2%	12	11.1%	6.5%
STD	77	71.3%	70.5%	79	73.2%	74.1%
XL	21	19.4%	23.3%	17	15.7%	19.4%
			Women			
XS	62	57.4%	51.8%	66	61.1%	59.8%
STD	42	38.9%	44.2%	42	38.9%	40.2%
XL	4	3.7%	4.0%	0	0%	0%

CONCLUSION

Updated harness sizing systems are needed to accommodate diverse workforces and new roles for women in the construction industry. This study estimated that at least 24% of men and 31% of women would not be able to find a well-fitting harness based on their body dimensions and the current harness sizing scheme. An alternative scheme model with eight equations was developed and validated to successfully classify 96% to 100% of tested participants to their best fit size for two types of harnesses. This model is a combination of weight, height, gender, and 3-D information for upper and lower torso regions; it predicts which size an individual (including the 24% of men and 31% of women for whom one or more fit criteria failed) should use, which in turn provides information for harness designers to better define harness sizing groups to accommodate at least 96% of the population. The alternative scheme contains two sizes for women and three sizes for men in lieu of the current four-size unisex system. The new sizing charts were graphed by gender, body weight, and body height for manufacturers' consideration in redesigning harnesses as well as for harness users in selecting an optimal harness size.

In addition, this study found that human-harness interfaces in suspended forms (i.e., suspension angle) are correlated to static fit parameters: thigh strap angle and back D ring location. The result shed light on the possible use of static fit assessment scores for predicting the dynamic suspension outcomes. Harness manufacturers and users could utilize these additional parameters along with current criteria during static fit tests to better "predict" suspension test results, which would help the construction industry to reduce the risk of injury that results from poor user fit, improper size selection, and the failure to don the protective equipment properly.

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