

CONSTRUCTING NEW HARNESS FIT CHARTS USING 3D ANTHROPOMETRIC INFORMATION

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The harness manufacturing industry has a pressing need to update harness fit charts to accommodate diverse workforces in the construction industry as well as in supporting new roles for women in the workforce. This paper presents an improved harness sizing system for vest-type harness-design applications. Three dimensional (3D) torso-scan data from 108 women and 108 men were obtained using a 3D whole-body scanning system. Human-harness interfaces, both in static and suspended forms, were digitally captured. A combination of weight, height, gender, and 3D information for upper and lower torso regions yielded a logistic regression model that correctly classified 96% of the participants to their best fit size in a validation test. The outcomes suggested the replacement of the current 4-size system with a new system that contains 2 sizes for females and 3 sizes for males. Two approaches to determine the adjustment range for each critical harness component for each harness size were proposed for harness designers to consider.

Introduction

A review of the historical anthropometric sources for commercial harness sizing revealed that they are based on dimensions which were derived from U.S. military population databases collected in the 1970's and 1980's (Bradtmiller et al., 2000). Population anthropometry evolves over time (Bodzsar, 2000); large variations exist over the last decades in body dimensions among the U.S. civilian population (HHS, 2001). In addition, 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 range of body dimensions and shapes as compared to that in the 70s and 80s. The harness manufacturing industry has a pressing need to reassess the current sizing schemes. The goals of this study were to identify anthropometric characteristics that affect the fit of vest type fall-protection harnesses to workers and to correspondingly develop an enhanced sizing scheme. The results should have a direct impact on practical design consideration for harnesses and have a potential impact on the development of standards for harness sizing systems.

Method

Participants

One hundred and eight males and 108 females participated in this study. Their ages ranged from 18 to 56. The average height was 175.7 cm (6.5 cm S.D.) and mass was

85.5 kg (14.2 kg S.D.) for males, and 162.6 cm (6.6 cm S.D.) and 66.2 kg (12.4 kg S.D.) for females.

Independent variable

Harness fit rating

Harnesses were tested while the participant was both standing and suspended, and a pass or fail rating was assigned based on 4 criteria. 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, 3 criteria needed to be met to receive a pass rating: the suspension angle had to be equal to or less than 35 degrees; the chest strap should not make contact with the neck; and the center of gravity (COG) of body had to be behind the hip rings. These criteria were evaluated by examining the interface between the harness and the human torso through 3D scan images. A harness fit rating of pass was assigned if all 4 criteria were met.

Body dimensions

The maximum breadth, depth, and height of the upper-torso volume space and the lower-torso volume space were extracted from 3D scan images. The breadth measure refers to side-to-side distance, depth to front-to-back, and height to top-to-bottom distance of the two torso regions (also known as “torso bounding boxes”). The 10th rib landmark was used to separate the torso images into the upper and lower torso regions. These dimensions were used to explore the interaction of the general body shape and dimensions with harness fit, based on the “bounding box” concept in the computer graphics field. Body weight, stature, and 17 other body dimensions that may be associated with harness sizing were also measured.

Dependent variable

Best-fit size

Four available harness sizes (XSM, STD, XLG, and SXL) were fitted for each participant. The investigator adjusted the harness to achieve the best possible fit and asked the participant about the comfort/discomfort of the harness and recorded the best-fit size.

Apparatus

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. The accuracy of the scanning system was tested to an average error of 2.9 mm. A Toledo scale (Mettler-Toledo Inc., Worthington, OH) was used to measure body weight, and a custom-made suspension system was developed to suspend the participants safely.

Procedure

Upon arrival, the participant viewed a web page, which described the details of the study and the tasks that the participant was to perform. Each participant signed an informed consent form and then changed from street clothes into bicycle shorts for men and bicycle shorts with halter top for women. The participant tried on 4 sizes of a vest-style harness. One investigator performed the fit test with feedback from the participant and recorded the fitting result for each size. The “best-fit” size was then selected for a subsequent fit assessment. The participant was scanned with the Cyberaware full-body scanner in an erect standing posture with a harness (referred to as A scan, Figure 1). The scan took 17 seconds. After the first scan, an investigator attached the steel cable of the suspension system to the back D-ring of the harness, and

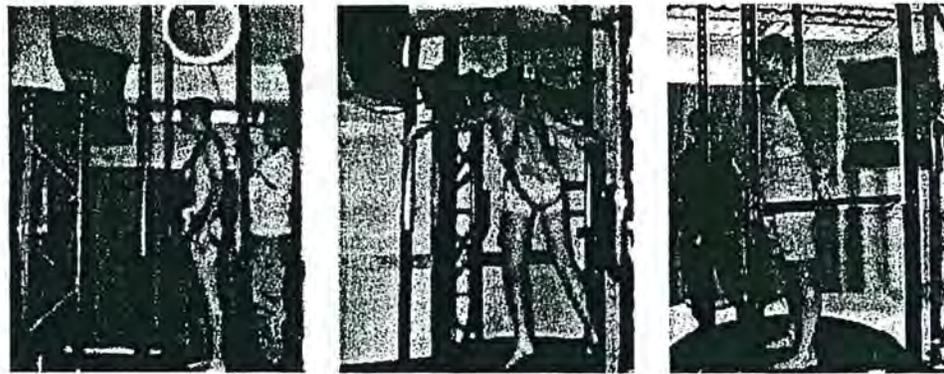


Figure 1. A standing posture with harness donned (A scan; 1a), a suspended position (B scan; 1b), and a standing posture without a harness (C scan; 1c) were used to evaluate human-harness interface.

raised the participant until the participant's toes were off the floor to simulate a post-fall condition. The participant was scanned a second time (referred to as B scan). The participant was lowered to the floor and was then scanned the third time without a harness (referred to as C scan). Finally, the participant changed back into street clothes and was compensated for his/her time, and then was dismissed.

Data extraction

Body landmarks from surface scans with the harness donned (A scans) were sometimes hidden by the placement of the harness. Alignment of the A and C scans allowed the hidden landmarks in A scans to be copied from C scans so that the evaluations of the interface between the harness components and the body were possible. One of the harness-fit tests was to determine whether the body's COG fell behind the harness hip rings during suspension. To assign the COG within the suspended conditions (B scans), an alignment of A and B scans was performed based on crotch and right and left anterior superior iliac spines.

Results

A multinomial logistic regression with forward hierarchical approach was used to search for the most influential factors on sizes. The dependent variable was the best-fit size of the harness, and potential independent variables included gender, height, weight, traditional anthropometry, and torso bounding box data. Only those participants who received a "pass" fit rating were used to construct the new sizing chart. These participants were randomly assigned to either the estimation or validation subset of data. The estimation subset was used to create a harness-sizing-classification model while the validation subset gave a post estimate (i.e., validation) of the percentage of the user population that could be fit correctly using the estimation model. Upper and lower torso box breadth and depth, gender, body height, and weight were found to be most influential. Four logistic regression models were derived to predict the best fit size. The "Standard Size (STD)" was set as the reference size and the resulting probability factor fell between 0 and 1, with 0.51 or above as a measure of favor of tested size over the reference size. The probability of wearing small size (XSM) instead of STD for

males is $1/(1 + \exp(-681.075 + 3.894 * \text{BreadthUp} - 3.66 * \text{DepthLow} + 3.164 * \text{DepthUp} + 1.854 * \text{Stature} + 2.441 * \text{Weight} + 2.001 * \text{BreadthLow}))$... [Equation 1]. For females, the equation is: $1/(1 + \exp(-657.348 + 3.894 * \text{BreadthUp} - 3.66 * \text{DepthLow} + 3.164 * \text{DepthUp} + 1.854 * \text{Stature} + 2.441 * \text{Weight} + 2.001 * \text{BreadthLow}))$... [Equation 2]. The probability equation of wearing XLG instead of STD for males is: $1/(1 + \exp(79.220 - 0.386 * \text{BreadthUp} - 2.464 * \text{DepthLow} + 1.77 * \text{DepthUp} + 0.035 * \text{Stature} - 0.409 * \text{Weight} - 0.038 * \text{BreadthLow}))$... [Equation 3]; and for females the equation is $1/(1 + \exp(81.315 - 0.386 * \text{BreadthUp} - 2.464 * \text{DepthLow} + 1.77 * \text{DepthUp} + 0.035 * \text{Stature} - 0.409 * \text{Weight} - 0.038 * \text{BreadthLow}))$... [Equation 4]. These models accurately classified 96% of the validation subset and thus provided unique information for harness designers to restructure current harness sizing plans to accommodate an estimated 96% of the population. 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, only gender, weight, and stature were involved in generating logistic regression models. These models accurately classified 93% of the classification subset and 96% of the validation subset. The simplified models are illustrated in two charts in Figure 2.

With the new sizing scheme, harness manufacturers would be interested in knowing the adjustment range of each harness component for harness redesign use (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 of harness fit test) can be classified into their predicted best-fit sizes, using the prediction equations 1–4. Using descriptive statistics, the adjustment range of a harness component for each harness size for each gender can be determined. For instance, 66 female participants were predicted to use a Female-XSM harness. Their Front Strap Length measurements have a population-weighted mean of 57.5 cm with a standard deviation of 2.9 cm. The adjustment range of the front strap for 98% of the population in this body-height-weight category can be estimated as 50.9 cm to 64.2 cm. The second approach would also classify all the participants into predicted best-fit size groups, using equations 1–4. A principal component analysis (PCA) (Meindl et al., 1993) would identify representative body models that consider multi-harness component dimensions at the same time. This approach would accommodate individuals with unique ratios among torso dimensions, such as a short torso with large belly depth as well as a long torso with wide chest width and median belly depth. Therefore, the adjustment

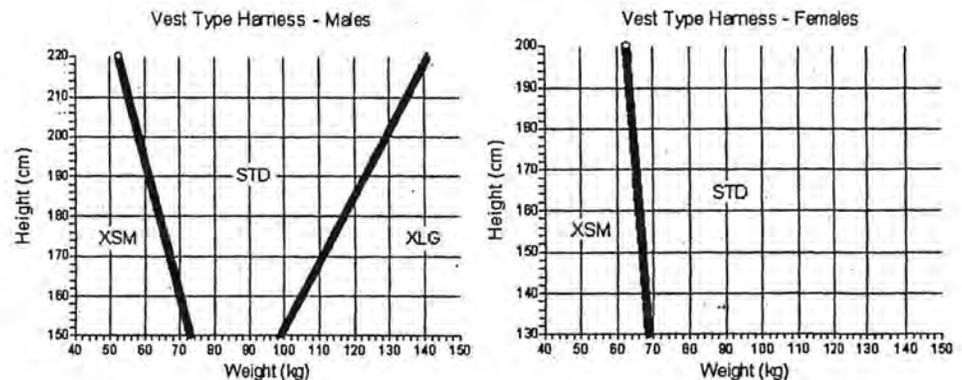


Figure 2. Proposed sizing charts for males (left) and females (right) for vest type harnesses; the possibility for males to use a SXL size and females to use a XLG or SXL size is remote.

range for each harness component is likely to be slightly smaller and more close to the reality than that computed from the first approach.

Conclusion

Updated harness sizing systems are needed to accommodate diverse workforces and new roles for women in the construction industry. This study developed a logistic regression model that correctly classified 96% of the participants to their best fit sizes, i.e., 2 sizes for females and 3 sizes for males. The model is a combination of weight, height, gender, and 3D information for upper and lower torso regions. The new sizing charts were graphed by gender, body weight and body height for harness manufacturers to consider for redesigning harnesses as well as for harness users to consider for selecting an optimal size of harness.

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