Ergonomics

ISSN: 0014-0139 (Print) 1366-5847 (Online) Journal homepage: http://www.tandfonline.com/loi/terg20

Development of sizing structure for fall arrest harness design

Hongwei Hsiao , Martin Friess , Bruce Bradtmiller & F. James Rohlf

To cite this article: Hongwei Hsiao , Martin Friess , Bruce Bradtmiller & F. James Rohlf (2009) Development of sizing structure for fall arrest harness design, Ergonomics, 52:9, 1128-1143, DOI: 10.1080/00140130902919105

To link to this article: http://dx.doi.org/10.1080/00140130902919105

Published online: 04 Jan 2011.

Ergonomics
Vol. 52, No. 9, September 2009, 1128–1143

Development of sizing structure for fall arrest harness design

Hongwei Hsiao[a]*, Martin Friess[b], Bruce Bradtmiller[c] and F. James Rohlf[d]

[a]*Division of Safety Research, National Institute for Occupational Safety and Health (NIOSH), Morgantown, West Virginia, USA;* [b]*Musée de l'Homme, Paris, France;* [c]*Anthrotech, Inc., Yellow Springs, Ohio, USA;* [d]*Department of Ecology and Evolution, Stony Brook University, New York, USA*

Updated harness designs are needed to accommodate diverse populations in the current workforce. This paper determined an improved fall-arrest harness sizing scheme and strap-length configurations for harness design. A 3-D elliptic Fourier analysis (EFA) procedure with 123 coefficients was developed to quantify torso-shape effect on harness fit, based on 3-D data of 108 women and 108 men. The EFA coefficients were then applied to 600 representative body scans from a national database of 2382 participants to establish an improved sizing system. Study outcomes suggested a more upward back D-ring location for women than current unisex designs to accommodate female torso form and mitigate their fit problem. Results also suggested an improved system of three sizes for women and three sizes for men. New harness sizing charts for women and men were proposed accordingly. Using the most current 3-D whole-body digital scanning technology, this study assembled data from a US workforce to establish an improved fall-arrest harness sizing system and strap configurations for men and women. The information is useful for new generation harness designs to reduce the risk of worker injury.

Keywords: construction; falls; torso shape; Fourier; anthropometry

1. Introduction

Personal fall-arrest systems (PFAS) provide the last line of defence to 7.4 million US construction workers in areas where fall hazards cannot be completely eliminated (US Department of Labor 2008) and full-body harnesses are the standard body support component of the PFAS used in the United States (Ellis 2001). The successful design of efficient full-body harnesses relies on quantitative data of human body shape variation. In a previous study on full-body harness fit, Hsiao *et al*. (2003) reported that existing traditional anthropometric data were not satisfactory in establishing good and up-to-date harness design. First, the best available body measurements from the military populations in the 1970s and 1980s do not represent the current civilian worker population due to relatively strict anthropometric entry requirements, which were imposed in the armed forces (Bradtmiller *et al*. 2000). In addition, population anthropometry evolves over time (Hertzberg 1972, Bodzsar 2000); large changes have taken place over the last decades in body dimensions among the US civilian population (US Department of Health and Human Services 2001). Moreover, diverse workforces in the current construction industry by gender and ethnicity showed a greater variation in their range of body dimensions and shapes compared to that in the 70s and 80s (Hsiao *et al*. 2007). Finally, harness assemblies are 3-D in nature; the traditional linear anthropometric data do not correspond well to the harness strap components and thus are not informative in harness design practice.

This research quantified body shape information for harness design applications with three objectives: (1) identify body shape factors that associated with harness-fit problems; (2) determine the most favourable number of harness sizes and define the adjustable range for each harness component; (3) provide a sizing chart associated with the newly defined sizes. The results have a direct impact on harness design and have a potential impact on the development of national and international standards for fall-arrest harness sizing configurations.

2. Method

2.1. *Research outline*

A series of four experiments were conducted to address the harness sizing and fit issues. The first experiment determined the optimal number of coefficients of the elliptic Fourier analysis (EFA) method to effectively quantify human torso shape, using 95 participants. The second experiment obtained the relationship

*Corresponding author. Email: hxh4@cdc.gov

ISSN 0014-0139 print/ISSN 1366-5847 online

DOI: 10.1080/00140130902919105
http://www.informaworld.com

between body shapes and harness fit using 216 participants and developed equations for predicting the best-fit harness size per any given 3-D torso scan. The third experiment established an improved harness sizing system based on the equations developed in the second experiment using 600 3-D torso scans. The last experiment developed gender-based sizing charts for assigning the best-fit size to a person in a fast and accurate manner, based on the 600 torso-scan data and the predicted size distributions derived from the third experiment. This paper reports the results of the second experiment (referred to as study I hereafter) and the combined outcomes of the third and fourth experiments (referred to as study II hereafter).

2.2. Participants

2.2.1. General information

Two groups of people participated in two studies, respectively. In total, 108 men and 108 women participated in study I. The sample covered 27 participants from each of the four racial categories of white, black, Hispanic and other (including multi-racial). Their average height was 175.7 (SD 6.5) cm and mass was 85.5 (SD 14.2) kg for men and 162.6 (SD 6.6) cm and 66.2 (SD 12.4) kg for women. Participants were reimbursed for time and inconvenience. In study II, which was a retrospective study, 298 men and 302 women were included. They were representative samples drawn from the Civilian American and European Surface Anthropometry Resource (CAESAR) project of 2382 participants (Society of Automotive Engineers International 2008). Their average height was 177.4 (SD 8.2) cm and mass was 86.0 (SD 18.0) kg for men and 163.4 (SD 7.6) cm and 69.0 (SD 18.7) kg for women. The protocol was approved by the Institutional Review Board of the National Institute for Occupational Safety and Health (NIOSH).

2.2.2. Sampling strategy for study I

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 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: $\left|\overline{X} - \upsilon\right| = \frac{\delta * \sigma}{\sqrt{n}}$, where $\left|\overline{X} - \upsilon\right|$ is within-cell accuracy, $\overline{X}$ the sample mean of the subgroup, υ the true mean of the subgroup, n the sample size, σ the standard deviation of the subgroup and δ the eccentricity (1.96 for 5% two-sided probability). Based on the standard deviation of stature from the CAESAR-US database (73 for women and 79 mm for men) and the desired cell accuracy of 17 mm for this study, the estimated sample size is 71 for women and 83 for men. Namely, at a 95% confidence level the sample sizes of 71–83 would have sufficient power for the sample mean to be within 17 mm of the true mean of the gender group. Since study I was to investigate the effect of anthropometry on the fit of fall-arrest harnesses, the full range of anthropometric variation is more important than just the number of subjects. The sample size was set at 108 for each gender and covered the four racial categories of white – non-Hispanic, black – non-Hispanic, Hispanic and other (including multi-racial), 27 participants for each category for each gender group. This sample size is small enough to be cost-effective, while large enough to contain the human variation needed to allow investigators to examine a full range of body sizes and thus to develop sizing prediction equations.

2.2.3. Subsampling the CAESAR database for study II

Given that the ultimate goal of this research was to develop an enhanced sizing system to accommodate the current US worker population, the findings and methods of determining the variation of torso size and shape from the 216 scans in study I may continue to be conservative in making a definitive recommendation of proper fit. However, it is plainly impractical to conduct the same fit and scan study for a larger population group or even the national population. Use of larger human 3-D scan databases to obtain a better assessment of the physical variation of the US workforce presents a potential solution to this tractability issue. One such large database is CAESAR, which contains 3-D scan data of 2382 participants that were collected throughout the USA in 1998 to 2001, of which NIOSH was a contributing partner. In order to maximise the potential gain from this data source without having to process every single scan (for cost reasons), a random sub-sample was needed to represent the physical variability of the US work force. This sub-sample was set at about 600 cases.

Given the physical differences between males and females, and the previously demonstrated importance of gender differences for harness sizing (Hsiao *et al.* 2007), a balanced representation with regard to gender was preferable. Furthermore, the ethnic mix of the US population needed to be taken into consideration. This can be achieved in two ways. The first option is to have a balanced sample containing the same number of males, females, whites, African-Americans, Hispanics and 'others'. Such a sample is suitable for testing between-group differences, such as sexual dimorphism described in study I. An alternative is to replicate the demographic profile of the US population, so that minorities are represented at their actual percentage relative to the entire population. The advantage of the latter approach is that it allows for a more accurate estimate of the population parameters, which, in turn, is relevant for manufacturers. Study II used this option.

During the sub-sampling process, the authors encountered the problem that the Hispanic segment of the population could not be properly represented, because of overall shortcomings in the CAESAR database. Furthermore, the 'other' sub-sample had only 18 men and 19 women, which is very small for obtaining meaningful statistics. The underlying question was whether or not group differences are significant enough to require a weighted sample. An analysis of harness-related anthropometric dimensions among the various groups was performed and the results suggested that this Hispanic segment is not the most critical in terms of the anthropometric range. They are relatively similar to 'whites' with regard to harness-related dimensions. Consequently, the full Hispanic subset of CAESAR was included in study II and the missing numbers to achieve US workforce representativeness were filled with 'white' participants through a random sampling. The final working samples are 210 whites, 37 African-Americans, 36 Hispanic (17 Hispanic plus 19 whites) and 19 others for the female group, and 208 whites, 33 African-Americans, 39 Hispanic (30 Hispanic plus nine whites) and 18 others for the male group; no weighting for the samples is needed.

2.3. Independent variables

2.3.1. *Harness fit rating*

A broad category of vest-type harness was used in the research (Figure 1). In study I, the harness was tested for fit while participants were both standing and suspended. A pass or fail rating was assigned based on four criteria that are in use in the harness manufacturing industry to minimise any potential biomechanical stress and suspension trauma (Brinkley 1988, Turner *et al.* 2008). The pass criteria were that: (1) the harness back D-ring was positioned between the inferior and superior borders of the scapula while the participant was standing; (2) the suspension angle had to be equal to or less than 35° during the suspension condition; (3) the chest strap should not make contact with the neck while the participant was suspended; (4) the centre of gravity (COG) of the body had to be behind the hip rings during the suspension condition. These criteria were evaluated 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. A harness fit rating of pass was assigned if all four criteria were met.

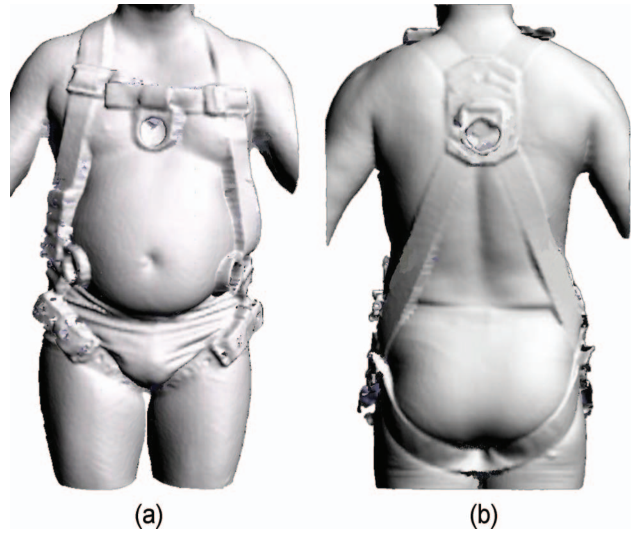


Figure 1. The vest-type harness used in the study – (a) front view and (b) back view.

2.3.2. *Gender*

New roles for women in the construction workforce make it necessary that their body dimensions and shapes be considered in the re-design of harnesses that were traditionally designed for men. There were 108 female participants in study I and 302 women in study II. Gender is therefore a testable independent variable.

2.3.3. *Elliptic Fourier coefficients of torso outlines*

A 3-D extension to the EFA approach (Kuhl and Giardina 1980, Lestrel 1997, Rohlf 2003) was used to quantify body shape variation and to determine the correlation between body shape and harness size and fit. The EFA approach is based on the mathematical decomposition of a curve into a series of ellipses that can be described by coefficients and constants. These coefficients and constants, in turn, can be treated as ordinary variables that describe the original curve of the shape of a human torso (Figure 2), for statistical analyses. The constants are defined as:

$$x(t) = A_0 + \sum_{n=1}^{N} a_n \cos nt + \sum_{n=1}^{N} b_n \sin nt \qquad (1)$$

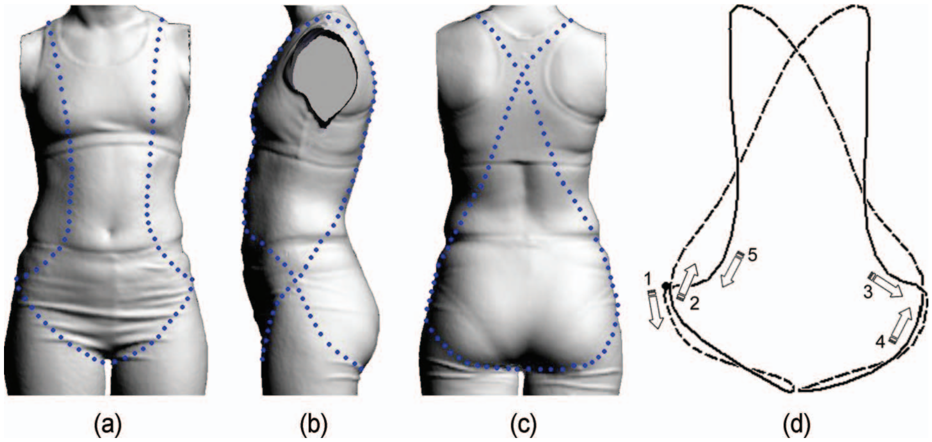


Figure 2. The outline that describes the curve of the shape of a human torso corresponds to the form of a vest type harness; the outline is presented in (a) front; (b) side; (c) back views. The outline (d) started with (1) the right thigh strap at the right trochanter, then (2) the right side of the back strap, (3) the left side of the front strap, (4) the left thigh strap and the left side of the back strap and (5) finally the right side of the front strap; the dotted line in (d) represents the outline of the back side while the solid line describes the front side of the outline. Starting and end point of the outline is the right trochanter; the anterior iliac spines, shoulder blade point at midsagittal plan, nipple and two abdominal points were the landmarks that the outline was to pass through. Note that the cross-chest strap shown in Figure 1a was not part of the extracted outline (i.e. Figure 2d) or elliptic Fourier analysis computations, since it was easily done with a two-point digitisation.

$$\mathrm{y(t)} = \mathrm{C}_0 + \sum_{n=1}^{N} c_n \cos nt + \sum_{n=1}^{N} d_n \sin nt \qquad (2)$$

$$\mathrm{z(t)} = \mathrm{E}_0 + \sum_{n=1}^{N} e_n \cos nt + \sum_{n=1}^{N} f_n \sin nt \qquad (3)$$

where A_0, C_0, and E_0 are the coordinates of the first harmonic (centroid); a_n, b_n, c_n, d_n, e_n and f_n are the six coefficients of the nth elliptic harmonic; n is the harmonic number, N is the maximum number of harmonics and the variable t is the position along the curve scaled to range from 0 to 2π.

The coefficients are defined as:

$$\mathrm{a_n} = \frac{1}{n^2\pi} \sum_{p=1}^{q} \frac{\Delta x_p}{\Delta t_p} \left[\cos(nt_p) - \cos(nt_{p-1})\right] \qquad (4)$$

$$\mathrm{b_n} = \frac{1}{n^2\pi} \sum_{p=1}^{q} \frac{\Delta x_p}{\Delta t_p} \left[\sin(nt_p) - \sin(nt_{p-1})\right] \qquad (5)$$

for the x projection,

$$\mathrm{c_n} = \frac{1}{n^2\pi} \sum_{p=1}^{q} \frac{\Delta y_p}{\Delta t_p} \left[\cos(nt_p) - \cos(nt_{p-1})\right] \qquad (6)$$

$$\mathrm{d_n} = \frac{1}{n^2\pi} \sum_{p=1}^{q} \frac{\Delta y_p}{\Delta t_p} \left[\sin(nt_p) - \sin(nt_{p-1})\right] \qquad (7)$$

for the y projection and

$$\mathrm{e_n} = \frac{1}{n^2\pi} \sum_{p=1}^{q} \frac{\Delta z_p}{\Delta t_p} \left[\cos(nt_p) - \cos(nt_{p-1})\right] \qquad (8)$$

$$\mathrm{f_n} = \frac{1}{n^2\pi} \sum_{p=1}^{q} \frac{\Delta z_p}{\Delta t_p} \left[\sin(nt_p) - \sin(nt_{p-1})\right] \qquad (9)$$

for the z projection, where q is the number of points in the outline, Δt_p is the distance between point p and $p + 1$ along the outline, and Δx_p, Δy_p, and Δz_p are the x, y, and z components of the line segment from $p-1$ to p.

EFA coefficients were calculated using the program EFA3-D (Rohlf 2003). They served as independent variables in study II to predict the best-fit harness size for each participant while acting as dependent variables in study I to identify the potential body shape factor responsible for fit-test failure. The input to an EFA3-D was a series of Cartesian coordinates that represent an individual's torso outline in three dimensions. In this study, 49 data points on the torso outline (i.e. $q = 49$) were used. The output was a series of coefficients (weighted sums of the ellipses) that mathematically describe the outline and that are used like any continuous variable for statistical purposes. In this study, the maximum number of harmonics (N) was set at 20, which yielded 123 EFA variables (20 $\times$ six coefficients + three constants). The optimal number of data points ($q = 49$) on the torso outline and the number of harmonics (N = 20) for adequate description of torso shape were tested through a separate pilot study using 95 participants (Friess *et al.* 2004).

2.4. Dependent variable

2.4.1. Harness size assignment through live fit evaluation

In study I, four sizes of harness were available – extra small (XSM; or size 1), standard (STD; or size 2), extra large (XLG; or size 3) and super extra large (SXL; or size 4). Each of the 216 participants was fitted in the harness for all sizes. The investigator adjusted the harness to achieve the best possible fit and asked participants about the comfort/discomfort of the harness and recorded the best-fit size.

2.4.2. Predicted best-fit harness size

In study II, the predicted best-fit harness size, based on the elliptic Fourier coefficients of torso outlines, was treated as a continuous rather than an ordinal variable. The predicted sizes can then be grouped by using certain cut-off points to establish an ordinal scale based on any proposed adjustment range of harness straps.

2.5. Apparatus

An anthropometer (GPM Instruments Inc., Zurich, Switzerland) and a Toledo scale (Mettler-Toledo Inc., Worthington, OH, USA) were used to measure stature and body weight. A Cyberware WB4 3-D full-body scanner (Cyberware Inc., Monterey, CA, USA) was used to register the interface between the harness and participant during both normal standing and suspended conditions for study I (Figure 3). The same model of scanner was used in study II to register torso images of 600 participants while standing without a harness. The accuracy of the scanning system was tested to an average error of 2.9 mm, ranging from +6 mm to –6 mm (Hsiao *et al.* 2003).

2.6. Procedure

In study I, 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.

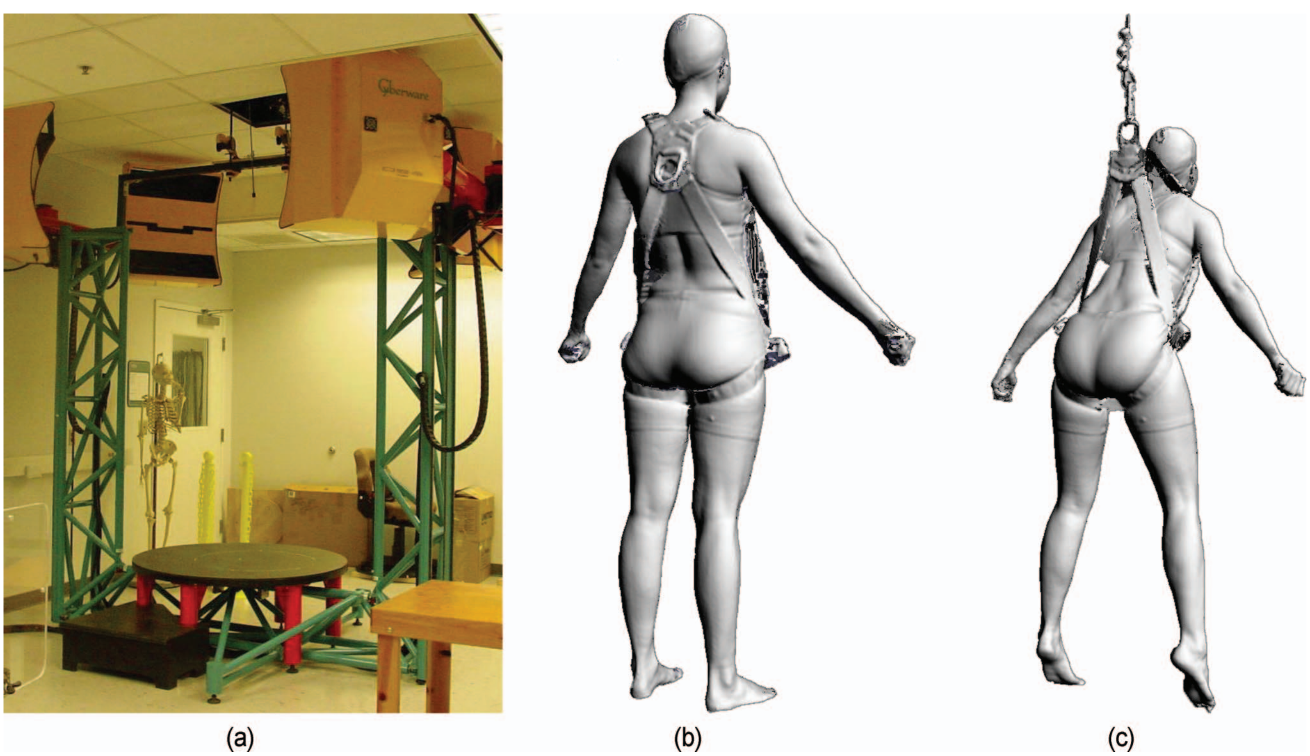


Figure 3. Equipment and positions used to evaluate the torso-harness interface. (a) The Cyberware WB4 3-D full-body scanner; (b) standing posture (referred to as A scan when with harness donned and C scan when without harness); (c) suspended position (B scan).

Using standard anthropometric techniques, 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, mid-point 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 non-permanent cosmetic marker. Another investigator then measured stature and body weight. The participant tried on four sizes of the harness. The investigators performed the fit test with feedback from the participant and recorded the fitting result. The 'best-fitting' size was then selected for a subsequent fit assessment. During the subsequent fit assessment, the landmarks were covered with adhesive white labelling dots (1.3 cm diameter) for 3-D scanning. The participant was scanned with the Cyberware full-body scanner in an erect standing posture with a harness (Figure 3b). The participant lined up his or her feet with the pre-marked footprints on the scanner platform. The participant's arms were held 45° laterally 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 scan). Although the effect of human sway on image fidelity in Cyberware whole-body scans is minimal (Corner and Hu 1998), a device to minimise sway was placed on top of the participant's head (Brunsman *et al*. 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 *et al*. 1997). The scans were visually inspected for quality. After the first scan, investigators attached the steel cable of a suspension system above the scanner in the laboratory to the back D-ring of the harness and raised the participant until the participant's toes were off the floor to simulate a post fall condition. While the participant was off the floor, he or she was scanned a second time (referred to as the B scan; Figure 3c). After the second scan, the participant was lowered to the floor and the fall-arrest harness was removed. The participant was then scanned for the third time without the harness (referred to as the C scan). 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.

In study II, participants were scanned for only the standing condition without a harness (i.e. C scan), using the same procedure as study I. To be more precise about this experimental design procedure, it should be noted that this component used existing scans from the CAESAR project database collected in 1998–2001 (Society of Automotive Engineers International 2008).

3. Data extraction and analysis

3.1. Alignment of standing (C scans) and standing-with-harness scans (A scans)

In study I, body landmarks from surface scans with the harness donned (i.e. A scans) were sometimes hidden by the placement of the harness. For instance, the suprasternale might disappear behind the chest ring. Alignment of the A and C scans allowed the hidden landmarks in the A scans to be copied from C scans so that the evaluations of the interface between the harness components and the body were possible. Alignment of the A and C scans was performed using landmarks common and visible to both scans; the right and left PSIS and C7 served the alignment process well (Hsiao *et al*. 2007).

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 *et al.* 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.

3.2. Alignment of suspended (B scans) and standing-with-harness scans (A scans)

One of the harness fit tests in study I was meant to determine whether the body's COG fell 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 (Hsiao *et al*. 2007).

3.3. Outline data extraction

For both study I and study II, a continuous outline with 49 landmarks following the position of a harness on a human torso, as illustrated in Figure 2, was developed using C scans. The anterior iliac spines, shoulder blade point at midsagittal plan, nipple, trochanters and two abdominal points were the landmarks that the outline was to pass through.

Prior to determining the outline and landmarks, the polygon meshes of C scans were prepared to ensure data quality. Using Cyslice software (Cyberware Inc.), all holes left by the scanning process were filled. These gaps are particularly common on top of the shoulders, under the arms and between the thighs. In addition, the area between the thighs is usually connected through triangulation noise in the range data. The area was cleaned out and reconstructed as naturally as was possible. The harness outline was extracted using Cyslice and the B-spline feature of the software was used to place 49 landmarks (data points) spread approximately evenly onto the outline to complete a 3-D curve (Figure 2b). The xyz coordinates were written out in ASCII text and then used for further analyses.

3.4. *Outline data process and size prediction*

Participants in study I with a passing test result were analysed further to develop the prediction equations (to be used in study II) of the best-fit harness size using the EFA coefficients. With the statistical analysis of shape-and-size variation as a main goal, the outline data must be standardised in order to remove the effects of non-shape variation such as the location (starting point) and orientation (i.e. clockwise or counterclockwise) of the data in raw space. Various procedures, such as major axes orientation method (Kuhl and Giardina 1980) and multiple homologous landmarks approach (Friess and Baylac 2003), have been proposed to normalise outlines prior to Fourier analysis. The authors used the latter technique, because it has been shown to provide more consistent results (Bookstein 1991, Rohlf 2000).

In study II, EFA coefficients of 298 men and 302 women were used to determine the harness sizes for them based on the prediction procedure developed in study I. It should be noted that while the participants with a pass test result in study I had their original best-fit harness sizes reported as integers, in the standard EFA process the best-fit harness size is treated as a continuous rather than an ordinal variable. Once predicted, sizes can be rounded to the nearest integer or set at any cut-off point, based on the adjustment ranges of harness components defined in order to re-establish an ordinal scale. The approach can, in theory, lead to predicting any number of sizes, depending entirely on the range of the predictor variables (body shape), unlike other techniques, such as discriminant analysis, which assigns subjects to an existing category no matter how distant they are from the average of that category. In study II, sizes were set at cut-off points through a reiterative process based on the goal that adjustment ranges of the front, back, chest and cross-chest straps were within the 17 cm expectation range and that the thigh and hip straps were in the 23 cm range criteria. These ranges were supplied by industry partners and reflect current practice in harness sizing.

4. Results

4.1. *Body shape factors associated with harness-fit problems*

4.1.1. *Harness fit rate*

Table 1 presents the fit rates by gender and harness size as well as by gender and race for the best-fitting-size

Table 1. Fit ratings by harness gender and size.

Fit ratings	Men	Women	Total
Pass	78	70	148
Fail total	30	38	68
Suspension angle (SA)	19	28	47
Hip ring (HR)	1	0	1
Chest ring (CR)	7	1	8
Back ring (BR)	2	2	4
SA + HR	0	1	1
SA + CR	1	3	4
SA + BR	0	3	3
Totals	108	108	216

	Harness size			
Fit ratings	XSM	STD	XLG	Total
Men				
Pass	8	60	10	78
Fail	5 (38%)	22 (27%)	3 (23%)	30 (28%)
Subtotal	13	82	13	108
Women				
Pass	46	24	0	70
Fail	25 (35%)	12 (33%)	1 (100%)	38 (35%)
Subtotal	71	36	1	108
All				
Pass	54	84	10	148
Fail	30 (36%)	34 (29%)	4 (29%)	68 (31%)
Subtotal	84	118	14	216

	Race			
Fit ratings	Black	Hispanic	White	Other
Men				
Pass	22	20	14	22
Fail	5 (19%)	7 (26%)	13 (48%)	5 (19%)
Subtotal	27	27	27	27
Women				
Pass	14	15	23	18
Fail	13 (48%)	12 (44%)	4 (15%)	9 (33%)
Subtotal	27	27	27	27
All				
Pass	36	35	37	30
Fail	18 (50%)	19 (54%)	17 (46%)	14 (26%)
Subtotal	54	54	54	54

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

harnesses when the four fit criteria were employed. Overall, 31% of participants failed to obtain a proper fit; all sizes have the failure rate in the range of 29% to 36%. In most failed cases only one criterion was not satisfied, typically the suspension angle; about 32% of women ((28 + 1 + 3 + 3)/108 = 0.32) and 19% of men ((19 + 1)/108 = 0.19) exceeded the maximum 35° angular deviation during suspension (statistically significant, $X^2(1) = 5.49$, $p = 0.02$). More than one fit criterion failed for some individuals. Although women faced a higher fit challenge than did men at the 35% vs. 28% overall fail rates, the difference was not statistically significant ($X^2(1) = 1.37$, $p = 0.24$). The gender-by-harness-size fit rating analysis revealed that the fit failure rate of a harness size is dependent upon gender ($X^2(1) = 15.08$, $p < 0.001$; discounting the XLG size, which has small cell numbers). Failure to pass the test criteria did not occur more often in one race/ethnic group than others ($X^2(3) = 0.82$, $p > 0.25$).

4.1.2. *Body shape factors*

In order to identify potential body shape factors responsible for fit-test pass/failure, a multivariate analysis of covariance was computed, with the EFA coefficients as dependent variables and the inclination angle as predictor. This made it possible to quantify and visualise shape differences between subjects who had a successful fit and those who failed. The statistically significant link between the angle of inclination and the body shape (EFA coefficients) can be visualised by an inverse EFA that estimates the 3-D curves for a given angle. This angle ranged from 11 to 55°, with 35° being the threshold for passing. Note that the mean angle of all participants was 30.4°. An analysis of the predicted outlines for 15, 30 and 45° of inclination showed that the only apparent changes in torso shape that occur with increasing inclination (hence failure) are a reduction in torso length (from shoulders to crotch) as well as a deeper, more developed chest, suggesting that a relatively long, flat upper body improves the chance of passing the fit test. Figure 4 illustrates how increased torso length shifts the COG downward relative to the suspension point between the shoulder blades and therefore reduces the angle off the vertical. Chest flatness accentuates this shift by reducing the leverage effect of the upper end of the torso. In the opposite case, a deep, bulky chest combined with a short torso imparts increased leverage that forces the upper body further down, thereby increasing the angle of inclination.

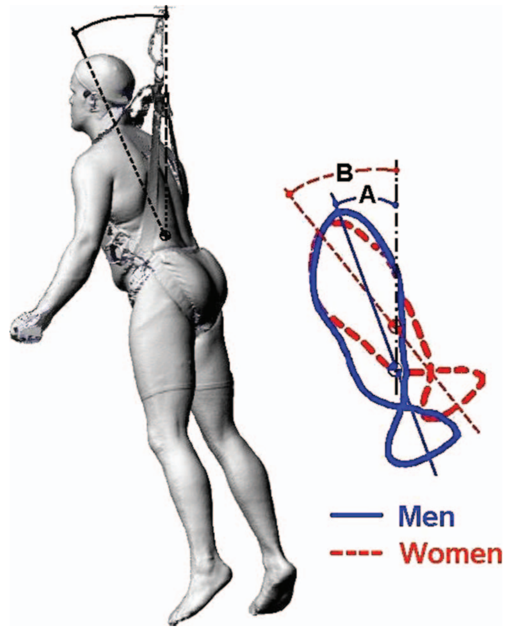


Figure 4. Application of inverse Fourier analysis to visualise torso shape differences associated with angle of inclination. A relatively long, flat upper body is associated with a reduced torso inclination angle (angle A as compared to angle B), which improves the chance to pass the fit test.

In order to identify anthropometric factors related to the other three fit criteria (relative position of the various rings), discriminant analyses were performed between the two groups of who passed or failed the fit test, separately for each gender. The result of these analyses yielded no significant differences in body shape, which suggests that fit test failure due to the relative position of the various rings had no significant association with anthropometric measurements.

4.2. *Harness sizing and adjustable range of harness components*

4.2.1. *Sizing prediction*

Those participants in study I who received a pass fit rating (i.e. 78 men and 70 women) were used to establish harness sizing prediction equations for use in study II. Given the known contribution of gender to physical variation in torso shape, gender-specific regressions were computed. In order to maintain observation numbers (i.e. 78 men and 70 women) above variable numbers, the EFA coefficients (123 coefficients) were reduced by principal component analysis (PCA) of the covariance matrix. In total, 20 components, accounting for over 96% (96.1% for men and 96.4% for women) of the total variance were retained. The sizing prediction equations were:

$$\begin{aligned}\text{mensize} = {} & 1.99786 + 0.30848 \times PC1 - 0.24474 \\ & \times PC2 - 0.05685 \times PC3 + 0.03922 \\ & \times PC4 - 0.01651 \times PC5 - 0.06822 \\ & \times PC6 + 0.03060 \times PC7 - 0.01629 \\ & \times PC8 - 0.00683 \times PC9 + 0.04194 \\ & \times PC10 + 0.06007 \times PC11 + 0.04930 \\ & \times PC12 + 0.05077 \times PC13 + 0.11445 \\ & \times PC14 - 0.01287 \times PC15 + 0.02308 \\ & \times PC16 - 0.00094 \times PC17 - 0.01062 \\ & \times PC18 + 0.02750 \times PC19 - 0.00297 \times PC20 \end{aligned} \tag{10}$$

$$\begin{aligned}\text{women size} = {} & 1.31288 + 0.16952 \\ & \times PC1 - 0.31094 \times PC2 + 0.08114 \\ & \times PC3 + 0.04800 \times PC4 + 0.08927 \\ & \times PC5 + 0.07112 \times PC6 - 0.00486 \\ & \times PC7 + 0.01060 \times PC8 + 0.03756 \\ & \times PC9 - 0.00433 \times PC10 - 0.01335 \\ & \times PC11 - 0.00921 \times PC12 - 0.00855 \\ & \times PC13 - 0.04256 \times PC14 + 0.03733 \\ & \times PC15 - 0.03648 \times PC16 - 0.13320 \\ & \times PC17 + 0.00363 \times PC18 - 0.03925 \\ & \times PC19 - 0.06134 \times PC20 \end{aligned} \tag{11}$$

where PC1, PC2, ..., PC20 are the 20 principal component factors.

The predicted best-fit sizes for the 600 participants in study II, based on 20 rank-ordered PCA estimators using EFA coefficients, were in the range of 0.92 to 3.49 for men and 0.32 to 2.96 for women.

4.2.2. *Sizing structure and strap lengths (study II)*

Following standard manufacturing and design practices, a 17-cm range for back strap, chest strap, front cross-chest strap and front strap, as well as a 23-cm range for gluteal furrow arc, thigh flat strap (thigh circumference) and trochanter-crotch circumference were assumed as cost-effective designs, which have the additional value of not being cumbersome. An iterative process of grouping of the predicted sizes was performed to identify the smallest number of sizes while meeting the above criteria on the adjustable ranges of the harness components. Three sizes for men and three sizes for women were the outcome. The sizes were defined by four cut-off points (i.e. sizes 0.9, 1.6, 2.515 and 3.5) for men and four (i.e. sizes 0.31, 0.916, 2.0613 and 3.0) for women. The adjustment ranges to cover 95% size-specific subpopulation for seven harness-strap dimensions for men were 98 mm, 67 mm, 97 mm, 101 mm, 183 mm, 140 mm and 132 mm for back strap, chest strap, front cross-chest strap, front strap, gluteal furrow arc, thigh circumference and trochanter-crotch circumference, respectively, for size S. The ranges were 139 mm, 80 mm, 150 mm, 142 mm, 157 mm, 186 mm and 203 mm for size M and 154 mm, 113 mm, 175 mm, 146 mm, 229 mm, 218 mm and 228 mm for size L. Similarly, the adjustment ranges for seven harness-strap dimensions for women were 116 mm, 58 mm, 115 mm, 94 mm, 157 mm, 179 mm and 201 mm for back strap, chest strap, front cross-chest strap, front strap, gluteal furrow arc, thigh circumference and trochanter-crotch circumference, respectively, for size S. The ranges were 142 mm, 71 mm, 143 mm, 122 mm, 184 mm, 211 mm and 232 mm for size M and 175 mm, 112 mm, 206 mm, 172 mm, 170 mm, 283 mm and 269 mm for size L. The adjustment ranges of women's size L were slightly greater than 17 cm for the torso straps and slightly greater than 23 cm for the thigh and hip straps.

Harness manufacturers can use the 97.5th percentile values of the back strap, chest strap, front cross-chest strap, front strap, gluteal furrow arc, thigh circumference and trochanter-crotch circumference presented in Table 2 as the basis to determine strap cut lengths. They can also use the 2.5th percentile value of the strap length in Table 2 to define the tightest position for each harness component.

4.3. *Anthropometric sizing chart*

An anthropometric sizing chart 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 consumer. Relatively accurate weight and stature are known by individual workers and thus were utilised in presenting the new sizing charts (Figure 5). In Figure 5a for female sizes, the two size boundaries (solid lines) were defined by two logistic regression models: (1) probability of wearing size S instead of size M = $1/(1 + \exp(-9.714 + 0.156\,weight + 0.011\,stature))$; (2) probability of wearing size L instead of size M = $1/(1 + \exp(16.807 - 0.654\,weight + 0.292\,stature))$, where the probabilities were set both at 0.5. Similarly, in Figure 5b for male sizes, the two size

Table 2. Proposed sizing plan for the vest-type harness and the adjustment ranges for seven harness-strap dimensions. Three sizes were defined by four sizing scores (men 0.9–1.6–2.515–3.5; women: 0.3–0.916–2.016–3.0).

Male size 1 (S) – 0.90 = < predicted size < 1.60

Variable (mm)	N	Mean	SD	Min	Max	1%	2.5%	97.5%	99%	95%RG*	98%RG*
Back strap	55	693	25	650	758	650	653	750	758	98	108
Chest strap	55	215	19	173	252	173	180	247	252	67	79
Front cross-chest strap	55	676	25	619	728	619	629	726	728	97	109
Front strap	55	586	25	520	635	520	532	633	635	101	115
Gluteal furrow arc	55	582	39	472	675	472	488	671	675	183	204
Thigh circumference	55	565	36	455	651	455	507	647	651	140	196
Trochanter-crotch circumference	55	691	39	563	780	563	630	762	780	132	217

Male size 2 (M) – 1.60 = < predicted size < 2.515

Variable (mm)	N	Mean	SD	Min	Max	1%tile	2.5%	97.5%	99%	95%RG	98%RG
Back strap	210	737	36	635	842	656	679	818	829	139	173
Chest strap	210	239	21	193	302	194	200	280	289	80	95
Front cross-chest strap	210	734	37	647	839	657	661	811	819	150	161
Front strap	210	630	33	549	724	555	557	699	707	142	153
Gluteal furrow arc	210	624	39	546	749	554	558	715	722	157	168
Thigh circumference	210	617	47	522	796	543	546	732	762	186	219
Trochanter-crotch circumference	210	767	50	672	942	677	688	891	920	203	243

Male size 3 (L) – 2.515 = < predicted size < 3.5

Variable (mm)	N	Mean	SD	Min	Max	1%tile	2.5%	97.5%	99%	95% RG	98% RG
Back strap	31	794	37	746	900	746	746	900	900	154	154
Chest strap	31	267	28	213	326	213	213	326	326	113	113
Front cross-chest strap	31	820	43	756	930	756	756	930	930	175	175
Front strap	31	692	33	641	787	641	641	787	787	146	146
Gluteal furrow arc	31	656	54	556	785	556	556	785	785	229	229
Thigh circumference	31	675	59	601	819	601	601	819	819	218	218
Trochanter-Crotch circumference	31	854	67	764	992	764	764	992	992	228	228

Two outliers (#2277 and #2712) were excluded from men's size L; they need customized designs. Therefore, 296 participants were used to set the harness adjustment ranges for men. *95%RG: 95% range, 98%RG: 98% range,

Female size 1 (S) – 0.31 = < predicted size < 0.916

Variable (mm)	N	Mean	SD	Min	Max	1%	2.5%	97.5%	99%	95%RG	98%RG
Back strap	54	637	31	572	711	572	574	691	711	116	139
Chest strap	54	171	15	140	206	140	143	200	206	58	66
Front cross-chest strap	54	629	30	575	707	575	582	696	707	115	131
Front strap	54	562	27	517	636	517	518	612	636	94	118
Gluteal furrow arc	54	615	43	532	733	532	543	700	733	157	202
Thigh circumference	54	561	46	470	667	470	486	665	667	179	196
Trochanter-crotch circumference	54	669	53	577	791	577	580	781	791	201	214

Female size 2 (M) – 0.916 = < predicted size < 2.0613

Variable (Unit: mm)	N	Mean	SD	Min	Max	1%	2.5%	97.5%	99%	95%RG	98%RG
Back strap	229	674	37	575	767	587	603	745	752	142	165
Chest strap	229	190	18	148	239	154	157	228	232	71	78
Front cross-chest strap	229	676	36	577	768	604	610	754	762	143	158
Front strap	229	613	32	527	711	544	553	675	686	122	142
Gluteal furrow arc	229	644	46	533	797	551	568	753	768	184	216
Thigh circumference	229	614	57	514	803	522	525	736	740	211	219
Trochanter-crotch circumference	229	720	61	606	882	611	617	849	867	232	256

Female size 3 (L) – 2.0613 = < predicted size < 3.0

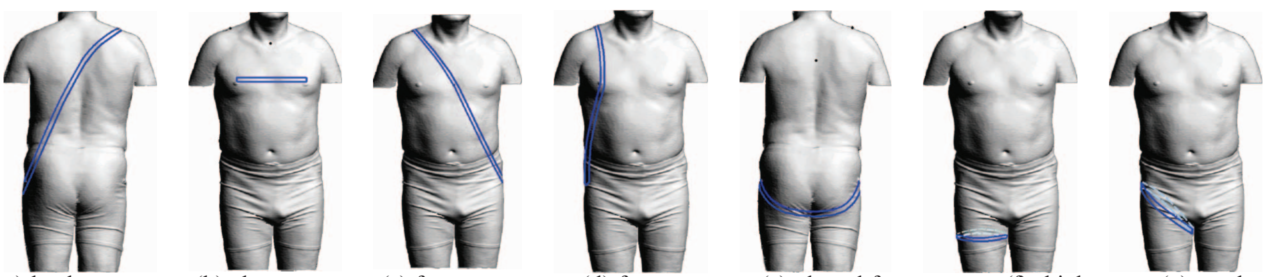
Variable (mm)	N	Mean	SD	Min	Max	1%	2.5%	97.5%	99%	95%RG	98%RG
Back strap	18	773	51	677	852	677	677	852	852	175	175
Chest strap	18	235	26	186	298	186	186	298	298	112	112
Front cross-chest strap	18	812	55	724	931	724	724	931	931	206	206
Front strap	18	723	48	631	802	631	631	802	802	172	172
Gluteal furrow arc	18	734	50	655	825	655	655	825	825	170	170
Thigh circumference	18	802	78	690	974	690	690	974	974	283	283
Trochanter-crotch circumference	18	929	66	806	1075	806	806	1075	1075	269	269

Eight M outliers were added to size S due to extreme small thigh circumference or torso length; three S outliers were moved to M due to large thigh circumference. Two L outliers were added to size M due to small thigh circumference; eight M outliers were moved to L due to large thigh circumference or torso length. One outlier (subject #2603) is excluded from female size L; she needs a customised design. 301subjects were used to set the harness adjustment range.

(*continued*)

Table 2. (*Continued*).

Male	Male S				Male M				Male L			
Harness component	Lower	Mean	Upper	Range	Lower	Mean	Upper	Range	Lower	Mean	Upper	Range
Back strap (a)	650	693	750	101	679	737	818	139	746	794	900	154
Chest strap (b)	173	215	247	74	200	239	280	80	213	267	326	113
Front cross-chest strap (c)	619	676	726	107	661	734	811	150	756	820	930	175
Front strap (d)	520	586	633	114	557	630	699	142	641	692	787	146
Gluteal furrow arc (e)	472	582	671	199	558	624	715	157	556	656	785	229
Thigh circumference (f)	455	565	647	192	546	617	732	186	601	675	819	218
Trochanter-crotch circumference (g)	563	691	762	199	688	767	891	203	764	854	992	228
Female	Female S				Female M				Female L			
Harness component	Lower	Mean	Upper	Range	Lower	Mean	Upper	Range	Lower	Mean	Upper	Range
Back strap (a)	572	637	691	119	603	674	745	142	677	773	852	175
Chest strap (b)	140	171	200	60	157	190	228	71	186	235	298	112
Front cross-chest strap (c)	575	629	696	121	610	676	754	143	724	812	931	206
Front strap (d)	517	562	612	95	553	613	675	122	631	723	802	172
Gluteal furrow arc (e)	532	615	700	168	568	644	753	184	655	734	825	170
Thigh circumference (f)	470	561	665	195	525	614	736	211	690	802	974	283
Trochanter-crotch circumference (g)	577	669	781	204	617	720	849	232	806	929	1075	269



a) back strap (b) chest strap (c) front cross-chest strap (d) front strap (e) gluteal furrow arc (f) thigh circumference (g) trochanter-crotch circumference

The strap adjustment ranges were set to accommodate at least 95% of the estimated population within the specified size categories. The small size was set at 96.5% level (adjustable range = percentile 97.5 – percentile 1.0). The medium size was set at 95% level (adjustable range = percentile 97.5 – percentile 2.5), and the large size was set at 96.5% level (adjustable range = percentile 99 – percentile 2.5). The overall arrangement provides an opportunity to accommodate 98% of the estimated overall population.

boundaries were defined by two logistic regression models: (1) probability of wearing size S instead of size M = 1/(1 + exp(–22.427 + 0.239*weight* + 0.033 *stature*)); (2) probability of wearing size L instead of size M = 1/(1 + exp(25.249 – 0.117*weight* – 0.065 *stature*)).

5. Discussion

5.1. *Quantifying body shape factors*

Using inverse EFA, it is possible to approximate the original torso outline for evaluating shape factors associated with harness fit failure. The more harmonics that are used, the more accurately the original curve will be fitted. This becomes critical in areas where the curve changes more abruptly, e.g. in the chest or the crotch. However, increasing the number of harmonics automatically increases the number of coefficients, as there are six coefficients per harmonic. Any over-sampling can easily lead to analyses with more variables than subjects within each group. Several trials were made in order to determine the optimal number of harmonics for the human torso. It was found in the pilot study of 95 participants that 10 to 20 harmonics, resulting in 63 to 123 coefficients, yielded a satisfying fit of the original curve for harness-design applications (Friess *et al.* 2004).

5.2. *Sizing structure and strap lengths*

5.2.1. *Harness sizing development*

By subjecting representative CAESAR scans (gender–ethnicity stratified random sample of 600 out of the

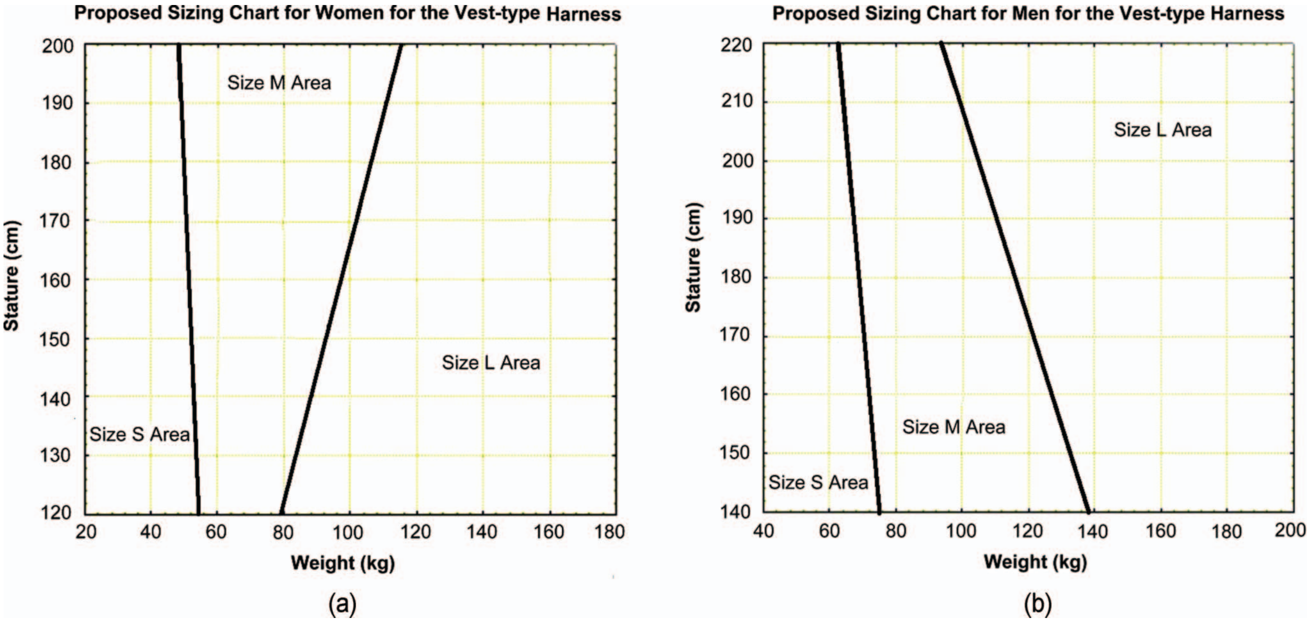


Figure 5. Proposed sizing charts for vest-type harness for (a) women and (b) men. (a) The two size boundaries (solid lines) are defined by two logistic regression models: (1) probability of wearing size S instead of size M (set as 0.5) = $1/(1 + \exp(-9.714 + 0.156 weight + 0.011 stature))$; (2) probability of wearing size L instead of size M (also set as 0.5) = $1/(1 + \exp(16.807 - 0.654 weight + 0.292 stature))$; (b) the two size boundaries (solid lines) are defined by two logistic regression models: (1) probability of wearing size S instead of size M (set as 0.5) = $1/(1 + \exp(-22.427 + 0.239 weight + 0.033 stature))$; (2) probability of wearing size L instead of size M (also set as 0.5) = $1/(1 + \exp(25.249 - 0.117 weight - 0.065 stature))$.

2382 CAESAR participants) to the same procedure (i.e. extracting outline data, computing EFA coefficients and using the estimators as input to the best-fit size regression models that were developed in study I), the predicted optimal sizing range was revealed to be 0.92 to 3.49 for men and 0.32 to 2.96 for women. Therefore, four sizes for men and three sizes for women can be proposed by rounding the ranges to the nearest integers, or four sizes for men and four sizes for women can be proposed by rounding the ranges to the nearest 0.5.

However, given current design and production practices and constraints, neither of these proposals may necessarily represent the optimal choice. The allowable or tolerable adjustable range of each harness component and the cost to stock uncommon sizes can effect user adoption and acceptance significantly. The study result determined that three sizes for men (defined by four scores: 0.9; 1.6; 2.515; 3.5) and three sizes for women (defined by four scores: 0.3; 0.916; 2.016; 3.0) were the smallest number of sizes that met the design constraint that the adjustment length of the front, back, chest and cross-chest straps was no more than 17 cm, and the thigh and hip strap adjustment range was no more than 23 cm. The cross-chest strap, thigh circumference and trochanter-crotch strap (circumference) for the female large size turned out to be slightly over the preset range criteria (see Table 2, female size L). Since this size covers a wide combination of body dimensions and the extra 3–5 cm adjustment range is not extreme, the size is not further divided into two sizes.

It must be noted that an adjustment for clothing or other equipment is necessary in anthropometry research and practices (Hsiao and Halperin 1998). In the harness design application, one would need to take into account the additional clothing that workers wear in the winter time; harness users usually want one harness for all seasons. An additional 2.5-cm range for back strap, 2.5 cm for front cross-chest strap and 7.5 cm for thigh-hip strap (i.e. gluteal furrow arc, thigh circumference and trochanter-crotch in combination) would therefore be necessary. Some designs may even require an additional 7 cm for the thigh–hip area for better mobility. No additions would be needed for the chest strap and front strap.

5.2.2. *Harness sizing by gender*

During the sizing grouping process in study II, the authors noticed that thigh dimensions correlated fairly with body weight ($r = 0.86$–0.88) and torso dimensions with stature ($r = 0.32$–0.65) in men; this was not the case in women. In women, thigh dimensions correlated well with body weight ($r = 0.91$–0.93) but weakly for torso dimensions with stature ($r = 0.18$–0.46), which made determining a women's size a very challenging task. A few outliers had to be reassigned to the adjacent groups after their EFA-based harness sizing prediction, due to their extreme dimensions in chest or thigh. The reassignment had some effects on the outcome of adjustment range for some harness components. Dropping these outliers was not a sound solution as they 'represented' those whose torsos fit one size while thighs fit the other size better. A follow-up study to test the effectiveness of the new sizing scheme and thus for refinement of the sizing system for women is desirable.

5.2.3. *Sizing structure for harness design and manufacturing*

In harness design and manufacturing practices, torso straps and thigh/hip straps may be fabricated on different production runs or equipment, using standardised machine settings. Adjusting manufacturing tolerances for strap-production machinery to increments below 5 cm may be cost ineffective or technically impractical. Recognising these design constraints and considering just hip and thigh dimensions without the torso component (i.e. gluteal furrow arc and thigh circumference, Table 2), it may be concluded that there are four recommended hip/thigh strap sizes: universal small (47.2–70 cm for both genders combined for gluteal furrow arc, where 47.2–67.1 cm for men and 53.2–70 cm for women, and 45.5–66.5 cm for both genders combined for thigh circumference, where 45.5–64.7 cm for men and 47–66.5 cm for women); universal medium (55.8–75.3 cm for gluteal furrow arc and 52.5–73.6 cm for thigh circumference); male large (55.6–78.5 cm for gluteal furrow arc and 60.1–81.9 cm for thigh circumference); female large (65.5–82.5 cm for gluteal furrow arc and 69–97.4 cm for thigh circumference). Similarly, five combined torso-strap sizes can be suggested: universal small; female medium; male medium; female large; male large. A harness manufacturer may also consider merging the female small size with male small size to become a universal small size (along with a small size thigh/hip strap) and possibly utilising a universal medium size thigh/hip strap for both the female medium (torso) size and the male medium (torso) size. The male large size will have a large thigh strap and the female large size will go with an extra large thigh strap. This suggestion was made solely based on existing practices in the harness manufacturing process.

Merging a female size with a male size, however, can complicate a harness design in mitigating the harness fit problem. This study has shown 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. female torso shape); a more upward design of back D-ring for women than the current unisex design is desirable to minimise the fit problem. Furthermore, due to differences in pelvic structure, women have demonstrated a 'flatter' thigh strap angle than men and a flatter thigh strap angle is correlated to the increase of torso suspension angle, hence fit failure (Hsiao *et al.* 2007). Finding a balance between designs and manufacturing process here may be more of an art than a science.

5.2.4. *Differences in cut lengths between the current and newly proposed sizing structures*

Table 3 presents the differences in cut lengths between the current and newly proposed sizing structures for two selected harness components – chest strap and thigh strap (trochanter-crotch circumference). It is clear that the chest strap length of the current harnesses can be reduced from 35 cm to 25 cm for size XSM, from 35.5 cm to 28 cm for size STD and from 39.5 cm to 33 cm to save some materials. The thigh strap, however, needs to be significantly enlarged for all sizes to accommodate the current worker population. For instant, the adjustment range for

Table 3. Differences in cut lengths between the current and newly proposed sizing structures (mm).

Harness		Proposed for Men			Proposed for Women			Current Unisex		
Size	Harness component	Lower	Upper	Range	Lower	Upper	Range	Lower	Upper	Range
XSM	Chest strap (b)*	173	247	74	140	200	60	120	350	230
	Trochanter-crotch circumference (g)**	563	762	199	577	781	204	390	660	270
STD	Chest strap (b)*	200	280	80	157	228	71	125	355	230
	Trochanter-crotch circumference (g)**	688	891	203	617	849	232	490	750	260
XLG	Chest strap (b)*	213	326	113	186	298	112	125	395	230
	Trochanter-crotch circumference (g)**	764	992	228	806	1075	269	660	930	270
SXL	Chest strap (b)*	–	–	–	–	–	–	125	425	300
	Trochanter-crotch circumference (g)**	–	–	–	–	–	–	730	1145	415

* and ** Please see figures in Table 2 for the definitions of chest strap and trochanter-crotch circumference.

men's size XSM would be 56.3 cm to 76.2 cm (plus 7.5 cm for clothing) and women's size XSM 57.7 cm to 78.1 cm (plus 7.5 cm for clothing); the thigh trap range of current unisex size XSM of 39 cm to 66 cm seems to be too tight for harness users. Detailed information on other harness component cut lengths, sewing points and connector locations are not presented here since they are associated with some manufacturer-specific proprietary materials.

5.3. Anthropometric sizing chart

Figure 5a,b shows the sizing charts associated with the newly defined sizes for women and men respectively. It must be noted that some harness users (approximately 15%) would need to try on more than one size to determine their best choice because the combination of their body dimensions dictates the size; body weight and stature only partially explain the variation of torso–harness interfaces among individuals. The new sizing charts can be used to streamline the process. They reflect the most updated information on human torso size and shape variation to further fall-arrest harness design and represent a practical guide for harness users to make a proper size selection.

In the case that a construction company needs to order a large number of harnesses (say thousands) for their employees, an assessment of their employees' body weight by body height may still take a major effort. A quick and cost-effective alternative is to use body weight as a reference. Based on the logistic regression technique with body weight as the sole determining factor, 51 kg and 97 kg would be the two sizing boundaries to separate small and large sizes from medium size respectively for women. Similarly, 70 kg and 113 kg would be the boundaries to separate small and large sizes from medium size respectively for men.

5.4. Limitation of the study and direction for future harness design

Study I used participants mainly in the West Virginia area; the prediction equations were derived with this understanding. However, it is worth mentioning that the average stature and weight of study I participants were very close to those of the general civilian populations that were described in the 1999–2000 NHANES (Hsiao *et al*. 2002, Centers for Disease Control and Prevention 2004). In this study, the average height was 175.7 (SD 6.5) cm and mass was 85.5 (SD 14.2) kg for men and 162.6 (SD 6.6) cm and 66.2 (SD 12.4) kg for women. The 1999–2000 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. Study II used a stratified random sample of 600 participants of the 2382 CAESAR database (Robinette 2000, Society of Automotive Engineers International 2008) to establish an extended harness sizing system for the national civilian population. Their average height was 163.4 (SD 7.6) cm and mass was 69.0 (SD 18.7) kg for women and 177.4 (SD 8.2) cm and 86.0 (SD 18.0) kg for men. The average stature and weight were very close to the 1999–2000 NHANES data for women as well and were slightly larger for men. With the larger 3-D body scan database from CAESAR, the constraint on determining the adjustment range of harness components for the small size for men and the large size for women (due to small counts for these two sizes in study I; see the larger standard deviations of weight and stature in study II than in study I) was adequately satisfied.

It also should be noted that in study I the failure criterion of harness angle was evaluated while participants were suspended in slow motion in lieu of an actual drop of the participants for safety reasons. In a real fall event, the plastic back pad along with the back D-ring may slide up the back of the user, which, in turn, would reduce the torso inclination angle and thus can ease the harness misfit problem associated with the torso inclination. Additional tests can be done to validate the benefit of sliding back pads and their optimal sliding range, especially for women.

Individuals might reasonably wonder how someone doing sizing of other garments or designing sizing structures of harnesses in other countries could benefit from this work without having to have a scanner and conducting a massive amount of data processing. It is worth noting that Hsiao *et al*. (2003) reported that traditional anthropometric data were not satisfactory in addressing the harness fit issue. In addition, the traditional linear anthropometric data did not correspond well to the harness strap components and thus were not informative in harness design practice (Hsiao *et al*. 2007). Studies I and II filled these gaps by introducing the torso shape and size information for improved harness design. In retrospect, the research team is exploring a couple of approaches, such as cluster procedures, with the goal of achieving more or less the same results by choosing a resizing based on some combined standard anthropometric measurements (such as shoulder to crotch back curve, chest depth and body weight). If successful, the procedures would be an invaluable reference to the national and international consensus standard committees on protective equipment and garments. They can cost-effectively update national and international consensus standards every decade or two.

6. Conclusion

Updated harness sizing systems and designs are needed to accommodate diverse workforces in the construction industry. This study identified that increased inclination of torso suspension angle (hence fit failure) was associated with a reduction in torso length and a more developed chest; harnesses for women can be designed with a more upward back D-ring than that of the current unisex design to mitigate this problem. The study outcomes suggested an improved sizing scheme containing three sizes for women and three sizes for men in lieu of the current 4- and 7-size unisex systems. The new sizing charts were graphed by gender, body weight and body height for manufacturers' use to revise or develop new designs. The adjustment ranges of the front, back, chest and cross-chest straps were within the industry common practice length of 17 cm expectations and the thigh and hip straps were in the 23 cm adjustment range, except for the female large size, which has a slightly wider range. Harness manufacturers can utilise the parameters in Table 2 plus the adjustment for clothing (2.5–7.5 cm) to set harness cut lengths for improved harness assemblies and workers can use the new sizing charts in Figure 5 to select an optimal harness size, 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 put on the harness properly.

Acknowledgements

The authors gratefully acknowledge the support of the entire research team, including Joyce Zweiner, Richard Whisler, Jinhua Guan, Christopher Lafferty, Jennifer Whitestone, Paul Keane and James Spahr. Many thanks to Joseph Feldstein and Rich Reynolds of MSA Fall Protection and Tom Wolner of Capital Safety for providing a critical industrial perspective of harness design and use. We are also appreciative of Mary Godby of Anthrotech for her technical input with data processing and Matthew Reed of UMTRI and Brian Corner of the US Army for their insightful technical suggestions. The findings and conclusions in this report are those of the authors and do not necessarily represent the views of NIOSH. Mention of any product in this report does not constitute an endorsement of the product by NIOSH or the authors.

References

Bodzsar, E.B., 2000. A review of Hungarian studies on growth and physique of children. *Acta Biological Szegediensis*, 44 (1–4), 139–153.

Bookstein, F.L., 1991. *Morphometric tools for landmark data*. Cambridge, UK: Cambridge University Press.

Bradtmiller, B., *et al*., 2000. Improving fall protection harness safety: contributions of 3-D scanning. *In*: *Proceedings of Scanning 2000: The European meeting point for scanning*. Paris, France, NUMERISATION 3D, 117–128.

Brinkley, J.W., 1988. Experimental studies of fall protection equipment. *In*: *Proceedings of international fall protection symposium*. Toronto, Canada, International Society for Fall Protection, 51–65.

Brunsman, M., Daanen, H., and Files, P., 1996. Earthquake in anthropometry: the view from the epicenter. *Gateway*, VII (2), 1–6.

Centers for Disease Control and Prevention, 2004. *1999–2000 National Health and Nutrition Examination Survey (NHANES) data file* [online]. Atlanta, GA: Centers for Disease Control and Prevention. Available from: http://www.cdc.gov/nchs/about/major/ nhanes/datalink.htm [Accessed 23 August 2004].

Corner, B.D. and Hu, A., 1998. Effect of sway on image fidelity in whole-body digitizing. *In*: *SPIE Proceedings: three-dimensional image capture and applications*, vol. 3313. Bellingham, WashingtonThe International Society for Optical Engineering, 90–99.

Daanen, H., Brunsman, M., and Robinette, M., 1997. Reducing movement artifacts in whole body scanning. *In*: *Proceedings of international conference on recent advances in 3-D digital imaging and modeling*. Ontario, Canada. IEEE Computer Society Press, 262–265.

Ellis, J.N., 2001. *Introduction to fall protection*. 3rd ed. Des Plaines, IL: American Society of Safety Engineers.

Friess, M. and Baylac, M., 2003. Exploring artificial cranial deformation using elliptic Fourier analysis of procrustes aligned outlines. *American Journal of Physical Anthropology*, 122, 11–22.

Friess, M., Rohlf, F.J., and Hsiao, H., 2004. Quantitative assessment of human body shape using Fourier analysis. *In*: B.D. Corner, P. Li, and R.P. Pargas, eds. *Three-dimensional image capture and applications VI, Proceedings of SPIE*, 117–124.

Hertzberg, T.H.E., 1972. Engineering anthropology. *In*: H.P van Cott and R.G Kincade, eds. *Human engineering guide to equipment design,* revised edition. Washington, DC: US Government Printing Office, 468–584.

Hsiao, H., Bradtmiller, B., and Whitestone, J., 2003. Sizing and fit of fall-protection harnesses. *Ergonomics*, 46 (12), 1233–1258.

Hsiao, H. and Halperin, W., 1998. Occupational safety and human factors. *In*: W.N. Rom, ed. *Environmental and occupational medicine,* chapter 64, third edition. Philadelphia, PA: Lippincott-Raven Publishers, 919–932.

Hsiao, H., Long, D., and Snyder, K., 2002. Anthropometric differences among occupational groups. *Ergonomics*, 45 (2), 136–152.

Hsiao, H., Whitestone, J., and Kau, T., 2007. Evaluation of fall-arrest harness sizing scheme. *Human Factors*, 49 (3), 447–464.

Kuhl, F.P. and Giardina, C.R., 1980. Elliptic Fourier features of a closed contour. *Computer Graphics and Image Processing*, 18, 236–258.

Lestrel, P.E., 1997. *Fourier descriptors and their applications*. Cambridge, UK: Cambridge University Press.

McConville, J.T., *et al*., 1980. *Anthropometric relationships of body and body segment moments of inertia*. Technical Report, AFAMRL-TR-80–119. AD A097 238. Wright-Patterson Air Force Base, OH: Aerospace Medical Research Laboratory.

Robinette, K.M., 2000. CAESAR measures up. *Ergonomics in Design*, 8, 17–23.

Rohlf, F.J., 2000. Statistical power comparisons among alternative morphometric methods. *American Journal of Physical Anthropology*, 111, 463–478.

Rohlf, F.J., 2003. *EFA3D*. v. 1.0. Stony Brook, NY: Department of Ecology and Evolution, State University of New York at Stony Brook.

Society of Automotive Engineers International, 2008. *Civilian American and European surface anthropometry resource project—CAESAR*^{TM} [online]. Warrendale, PA: Society of Automotive Engineers, Inc. Available from: http://store.sae.org/caesar/ [Accessed 18 March 2008].

Turner, N.L., *et al.*, 2008. Suspension tolerance in a full-body safety harness, and a prototype harness accessory. *Journal of Occupational and Environmental Hygiene*, 5 (4), 227–231.

US Department of Health and Human Services, 2001. *The surgeon general's call to action to prevent and decrease overweight and obesity,* VI-VII. Washington DC: US Government Printing Office.

US Department of Labor, 2008. *The employment situation: February 2008*. US Department of Labor News, USDL 08–0294 [online]. Washington, DC: US Department of Labor. Available from: http://www.bls.gov/news.release/pdf/empsit.pdf [Accessed 18 March 2008].