

Firefighter Hand Anthropometry and Structural Glove Sizing: A New Perspective

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Objective: We evaluated the current use and fit of structural firefighting gloves and developed an improved sizing scheme that better accommodates the U.S. firefighter population.

Background: Among surveys, 24% to 30% of men and 31% to 62% of women reported experiencing problems with the fit or bulkiness of their structural firefighting gloves.

Method: An age-, race/ethnicity-, and gender-stratified sample of 863 male and 88 female firefighters across the United States participated in the study. Fourteen hand dimensions relevant to glove design were measured. A cluster analysis of the hand dimensions was performed to explore options for an improved sizing scheme.

Results: The current national standard structural firefighting glove-sizing scheme underrepresents firefighter hand size range and shape variation. In addition, mismatch between existing sizing specifications and hand characteristics, such as hand dimensions, user selection of glove size, and the existing glove sizing specifications, is significant. An improved glove-sizing plan based on clusters of overall hand size and hand/finger breadth-to-length contrast has been developed.

Conclusion: This study presents the most up-to-date firefighter hand anthropometry and a new perspective on glove accommodation. The new seven-size system contains narrower variations (standard deviations) for almost all dimensions for each glove size than the current sizing practices.

Application: The proposed science-based sizing plan for structural firefighting gloves provides a step-forward perspective (i.e., including two women hand model-based sizes and two wide-palm sizes for men) for glove manufacturers to advance firefighter hand protection.

Keywords: finger, shape, sizing, cluster, fit

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INTRODUCTION

Structural firefighting gloves provide a delicate balance for adequate hand protection while allowing firefighters to effectively conduct essential firefighting operations. The National Fire Protection Association (NFPA) 1971 Standard 2013 edition on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting stipulates that the gloves meet performance requirements as an outer shell, moisture barrier, and thermal barrier (NFPA, 2012). These integrated gloves must adequately fit the firefighters' multifaceted hand dimensions and shapes and provide firefighters with protection from sharp objects, fluids, flame, and heat. The construction of glove materials is essential to glove protection characteristics and is tested as glove body composite samples or as whole gloves. Glove fit to firefighters, additionally, plays a critical role on the effectiveness of gloves; it affects material property engagement and ultimately impacts firefighter grip performance and dexterity and thus requires extra attention.

A key issue for glove fit for protection and performance is the sizing. The NFPA standard lists glove sizes as XXS, XS, S, M, L, XL, and XXL, defined mainly by hand length and circumference with finger lengths and circumferences as supplements (NFPA, 2012). A tight-fitting glove can constrict finger circulation and may increase the risk of burn and frostbite injuries. On the other hand, gloves that fit too loosely hinder accomplishment of finer dexterity and grip tasks. Glove sizing charts are commonly organized by hand circumference or length, but a few guidelines use index finger length and palm breadth as the criteria. Firefighters often have to use best judgment for their choice. More often, a firefighter will simply try on gloves that are available and pick one pair that is the most

comfortable. The availability of adequate glove sizes and sizing systems is therefore important to firefighters.

A recent National Institute for Occupational Safety and Health (NIOSH) national firefighter anthropometry study (Hsiao et al., 2014) reported that of the 951 participating firefighters from four U.S. geographic locations, 30% of men and 62% of women experienced problems with the fitting or bulkiness of their gloves. The International Association of Women in Fire and Emergency Services (IAWFES) survey on women firefighters and protective gear in 1995 also reported that 31% of female firefighters encountered fit issues with their gloves (IAWFES, 2004). Plotting hand length as specified by the NFPA 1971 standard versus the defined glove sizes showed that the NFPA 1971 sizing scheme was organized around hand length (coefficient of determination $r^2 = 1$) for five sizes (XS, S, M, L, and XL). An XXS size and an XXL size were also included in the sizing system with no dimensional specifications (NFPA, 2012). Although there were overlaps on hand circumference and finger lengths among different sizes of gloves, manufacturers have found the need to supplement additional sizes, such as XXXL or Jumbo, in an attempt to accommodate the firefighting communities. In fact, manufacturers offer as many as three to six styles and seven to 10 sizes for each style of gloves, yet the NFPA 1971 Technical Committee Task Group on Gloves found that firefighters often remove their gloves to perform tasks, exposing their hands to thermal or chemical damage (McKenna, 2009; Watkins, 2011).

In the past few years, tool manufacturers have improved operating equipment controls for firefighters, and glove manufacturers have enhanced gloves with finer dexterity. This is the right time to systematically assess hand dimensions of the current firefighter population, evaluate glove use and fit, and possibly update the current glove sizing system.

Objectives

In this study we reported the most up-to-date firefighter hand anthropometry through a national firefighter anthropometric study and evaluated the current use and fit of structural

firefighting gloves to the firefighter population. A new perspective for enhancing glove sizing scheme was proposed accordingly. Four hypotheses were tested: (a) Firefighter hand dimensions were different among gender, race/ethnicity, and age groups; (b) current firefighter hand dimension ranges are greater than the specifications outlined in the NFPA 1971 glove-sizing scheme; (c) there is no association between choosing an NFPA-matched size and the fit of the gloves reported by firefighters; and (d) glove fit is multidimensional and is associated with hand shape (hand and finger breadth-to-length contrast) aside from the overall hand size.

METHOD

Anthropometric Measurements Associated With Firefighting Glove Specifications

Fourteen dimensions relevant to the design of gloves were measured in this study. They were hand length, hand breadth, palm length, palm breadth, thumb and finger lengths, and thumb and finger breadths. The graphical descriptions and definitions of these dimensions are presented in Figure 1 and Appendix A, respectively. The NFPA 1971 standard on gloves contains additional information on hand and finger circumferences; this present study did not collect these data. The Hand Anthropometry of U.S. Army Personnel data provided two equations for converting the NFPA hand circumference ranges to hand/palm breadth ranges, which were employed in this study to evaluate the NFPA sizing system. The equations are Hand/Palm Breadth (males) = $4.93 + 0.4 \times$ Hand Circumference (coefficient of determination $r^2 = .93$; Greiner, 1991, p. 432) and Hand/Palm Breadth (females) = $0.62 + 0.42 \times$ Hand Circumference ($r^2 = .937$; Greiner, 1991, p. 434).

Participants

A stratified sample of 863 male firefighters (three age by three race/ethnicity combinations) and 88 female firefighters (three age groups) for a total of 951 firefighters participated in the study. Their right-hand scans were recorded using a flatbed scanner (Epson Perfection 1260; $10,200 \times 14,040$ pixels at 1,200 dpi) as part of a national firefighter anthropometry survey (Hsiao et al., 2014).

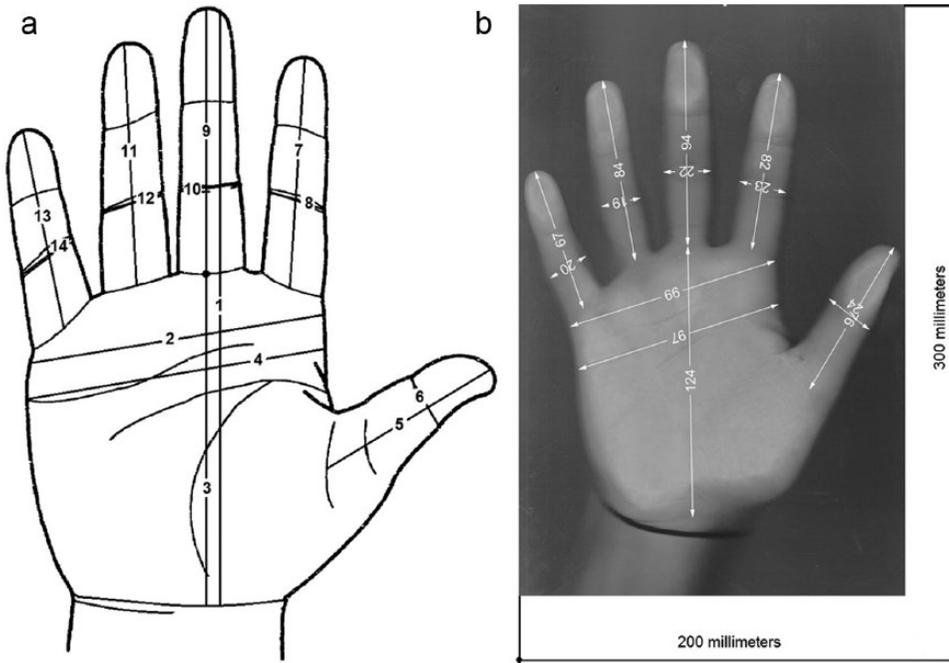


Figure 1. (a) Hand dimensions: 1 = hand length, 2 = hand breadth, 3 = palm length, 4 = palm breadth, 5 = thumb length, 6 = thumb breadth, 7 = index finger length, 8 = index finger breadth, 9 = middle finger length, 10 = middle finger breadth, 11 = ring finger length, 12 = ring finger breadth, 13 = pinky length, and 14 = pinky breadth. Hand Length = Middle Finger Length + Palm Length. (b) The measured dimensions, along with the hand scan image, are displayed.

The sampling plan was based on a statistical power estimation for an assessment of differences in anthropometry among gender, race, and age groups who represented the 1,136,650 firefighters documented in the U.S. Fire Department Profile Through 2005 (Karter, 2006). Data collection was conducted in four geographic locations (Rockville, Maryland; Phoenix, Arizona; Philadelphia, Pennsylvania; and Fort Worth, Texas; Table 1). The number of participants in each region was assigned based on the size of the population in that region in the 2000 U.S. Census (U.S. Census Bureau, 2001a, 2001b, 2001c) with an assumption that the number of firefighters was proportional to the size of the population they serve. The detailed sampling plan, accounting for geographic density of racial/ethnic distributions, was presented in Hsiao et al. (2014). These firefighter profiles represented the best available and most up-to-date firefighter population distribution data at the study-planning stage in 2007. An oversampling of female firefighters (88/951 = 9.3%) was necessary, in lieu of 4.2% per

the Household Data Survey (U.S. Department of Labor, 2006), to address some issues (i.e., hand and finger shape associated with glove design) that were critical to females.

Data Collection Procedure and Data Process

The data collection stations consisted of a briefing table, a changing area, and a space with sufficient lighting for measurements. Participants were approached through leaders of regional fire stations at four data collection sites. Data collection was performed during 2009 to 2012. Upon arrival at the NIOSH field laboratory that was established at a fire station, the firefighters were given a brief overview of the study. Participants then signed a consent form and completed a questionnaire related to experience with fire apparatus and protective gear. As part of the National Firefighter Anthropometry Survey (Hsiao et al., 2014), a two-dimensional (2-D) hand scan of the right hand was recorded for each participant.

TABLE 1: The Stratified Sample (3 [Age] × 3 [Race/Ethnicity] × 2 [Gender]) in the Study

Data Collection Site	Male												Total
	White			Black			Hispanic/Other			Female			
	18–32 Years	33–44 Years	45–65 Years	18–32 Years	33–44 Years	45–65 Years	18–32 Years	33–44 Years	45–65 Years	18–32 Years	33–44 Years	45–65 Years	
Phoenix, Arizona	46	47	43	3	3	3	13	17	13	7	7	8	210
Philadelphia, Pennsylvania	49	55	52	6	5	11	4	5	2	7	8	5	209
Rockville, Maryland	63	62	63	10	8	9	8	9	6	8	13	5	264
Fort Worth, Texas	55	72	59	7	14	14	9	9	9	5	10	5	268
Total measured	213	236	217	26	30	37	34	40	30	27	38	23	951

Fourteen dimensions were then extracted using image digitizing software CorelDraw. Participants' biographical information (e.g., gender, race/ethnicity, and age), the size of gloves used, and the self-assessment of glove fit (too tight, acceptable, or too loose) were also logged. The self-assessment of glove fit was based on the gloves that the participant has used and brought to the study. A "good fit" of a glove was defined as that the glove was not too tight or too loose at any finger and hand area for which a firefighter performed tasks during regular operations.

Literature has shown no significant difference in finger and hand length measurements between using the 2-D scanning method and the traditional caliper-based measurement method; additionally, the scanning method took considerably less time than the traditional measurement method (Yu, Yick, Ng, & Yip, 2013, p. 389). Hand/palm breadth obtained from image digitization in a hand abduction posture (fingers open), on average, is 5 mm greater for men and 3.6 mm greater for women than that of a traditional measurement in a fingers-closed pose (Greiner, 1991).

RESULTS

Summary Statistics of the Measured Hand Dimensions

Statistical analyses on the 14 hand measurements were performed for their arithmetic means

and standard deviations (Tables 2 through 4). A previous publication has verified that the raw data from the NIOSH National Firefighter Anthropometry Survey can be employed directly into protective gear design applications without major weighting or abnormality concerns (Hsiao et al., 2014). Data from eight participants were excluded in the analyses because three of them have a partial amputation on one of their fingers and five participants' hand scans were missing due to a scanner malfunction. Analysis results show significant differences in means of the dimensions by gender (14 dimensions), race/ethnicity (14 dimensions), and age group (all except four finger lengths).

Coverage of NFPA 1971 Glove Sizing Scheme

The NFPA standard on gloves categorizes glove sizes mainly by hand length and circumference. In this current study, hand length and palm breadth from the 14 collected hand dimensions were selected for the sizing coverage analysis because they were compatible with the dimensions used in the NFPA standard (Table 5). The hand length is defined as the combined palm length and middle finger length. The hand circumference range for each glove size outlined in the NFPA 1971 standard was converted to a palm breadth range, using Hand/Palm Breadth

TABLE 2: Summary Statistics for Hand Dimensions by Gender (in millimeters)

Hand Dimension (mm)	Men			Women			Significant Difference
	<i>n</i>	<i>M</i>	<i>SD</i>	<i>n</i>	<i>M</i>	<i>SD</i>	
Hand length	855	197.6	9.3	88	182.7	8.7	*
Hand breadth	855	97.2	4.6	88	87.4	4.2	*
Palm length	855	113.8	5.8	88	104.0	5.7	*
Palm breadth	855	96.0	4.6	88	85.3	4.2	*
Thumb length	855	70.8	4.3	88	64.8	4.1	*
Thumb breadth	855	24.4	1.6	88	21.5	1.5	*
Index finger length	855	75.8	4.4	88	71.3	4.2	*
Index finger breadth	855	22.7	1.6	88	20.5	1.2	*
Middle finger length	855	83.8	4.6	88	78.6	4.5	*
Middle finger breadth	855	22.4	1.7	88	20.3	1.3	*
Ring finger length	855	79.6	4.5	88	74.0	4.5	*
Ring finger breadth	855	21.7	1.6	88	19.4	1.2	*
Pinky length	855	65.2	4.3	88	60.4	4.3	*
Pinky breadth	855	19.8	1.5	88	17.5	1.2	*

**p* = .05 for two-tailed independent *t* test where pooled test was applied.

TABLE 3: Summary Statistics for Hand Dimensions by Race/Ethnicity (in millimeters)

Hand Dimension (mm)	White			Black			Hispanic/Other			Significant Difference
	<i>n</i>	<i>M</i>	<i>SD</i>	<i>n</i>	<i>M</i>	<i>SD</i>	<i>n</i>	<i>M</i>	<i>SD</i>	
Hand length	735	195.4	9.8	99	203.5	11.4	109	195.0	9.5	*
Hand breadth	735	96.6	5.4	99	94.8	5.1	109	95.7	5.1	*
Palm length	735	112.3	6.1	99	117.6	7.3	109	112.2	5.7	*
Palm breadth	735	95.2	5.5	99	93.8	5.5	109	94.7	5.4	*
Thumb length	735	70.2	4.5	99	71.9	5.1	109	68.7	4.3	*
Thumb breadth	735	24.3	1.8	99	22.8	1.9	109	23.9	1.7	*
Index finger length	735	75.3	4.5	99	77.1	5.1	109	74.5	4.2	*
Index finger breadth	735	22.7	1.6	99	21.1	1.8	109	22.2	1.5	*
Middle finger length	735	83.1	4.7	99	85.9	5.2	109	82.8	4.9	*
Middle finger breadth	735	22.5	1.6	99	20.4	1.8	109	22.1	1.6	*
Ring finger length	735	78.8	4.7	99	81.6	5.5	109	78.8	4.7	*
Ring finger breadth	735	21.8	1.6	99	20.0	1.8	109	21.2	1.7	*
Pinky length	735	64.7	4.5	99	66.1	4.8	109	64.1	4.6	*
Pinky breadth	735	19.7	1.5	99	18.7	1.7	109	19.4	1.6	*

**p* = .05 for *F* tests from the ANOVA to determine whether the means are all equal.

(mm; males) = 4.93 + 0.4 × Hand Circumference as the upper boundary and Hand/Palm Breadth (mm; females) = 0.62 + 0.42 × Hand Circumference as the lower boundary (Greiner,

1991) as reported in the Method section. In this study, both palm breadth and hand breadth were collected with fingers open naturally. These two measurements are highly correlated (*r*² = .93).

TABLE 4: Summary Statistics for Hand Dimensions by Age (in millimeters)

Hand Dimension (mm)	<40 Years			≥40 Years			Significant Difference
	<i>n</i>	<i>M</i>	<i>SD</i>	<i>n</i>	<i>M</i>	<i>SD</i>	
Hand length	498	195.5	10.4	445	197.0	9.9	*
Hand breadth	498	95.8	5.3	445	96.8	5.3	*
Palm length	498	112.2	6.4	445	113.6	6.3	*
Palm breadth	498	94.6	5.5	445	95.4	5.4	*
Thumb length	498	69.9	4.6	445	70.6	4.7	*
Thumb breadth	498	23.6	1.7	445	24.6	1.8	*
Index finger length	498	75.2	4.7	445	75.5	4.5	
Index finger breadth	498	22.1	1.6	445	22.8	1.7	*
Middle finger length	498	83.3	5.0	445	83.4	4.7	
Middle finger breadth	498	22.0	1.7	445	22.5	1.8	*
Ring finger length	498	79.1	4.9	445	79.2	4.7	
Ring finger breadth	498	21.3	1.6	445	21.8	1.8	*
Pinky length	498	64.3	4.8	445	64.8	4.2	
Pinky breadth	498	19.3	1.5	445	19.9	1.6	*

**p* = .05 for two-tailed independent *t* test where pooled test was applied.

TABLE 5: A Display of National Fire Protection Association (NFPA) 1971 Standard on Glove Sizes, Using Hand Length, Palm Breadth, and Hand Circumference as the Indices (in millimeters)

NFPA Glove Size	NFPA Sizing Range (mm)					
	Hand Length (Lower)	Hand Length (Upper)	Palm Breadth (Lower)	Palm Breadth (Upper)	Hand Circumference (Lower)	Hand Circumference (Upper)
XXS	"Size XXS shall be smaller than the sizes indicated below."					
XS	162.5	172.5	68.9	85.9	162.5	202.5
S	172.5	182.5	73.1	89.9	172.5	212.5
M	182.5	192.5	77.3	93.9	182.5	222.5
L	192.5	202.5	81.5	97.9	192.5	232.5
XL	202.5	212.5	85.7	101.9	202.5	242.5
XXL	"Size XXL shall be larger than the sizes indicated above."					

The hand breadth data were slightly affected by the level of opening of fingers. Palm breadth measurements were less affected and thus were used without adjustment in this assessment.

A comparison of the hand length and palm breadth data of the sampled firefighter population against those of the NFPA 1971 glove sizing scheme revealed that 72% (617/855) of men and 96% (84/88) of women are covered by the current NFPA 1971 glove-sizing chart (Table 5). Women

had a higher coverage rate than men, $\chi^2 = 22.69 > \chi^2(1, .05) = 3.840$, $p < .001$. The hand dimension ranges outlined in the NFPA 1971 glove standard in general underrepresented national firefighter hand size variation (Figure 2a). An adjustment of the palm breadth data from fingers-open posture to fingers-closed pose showed that 91% (777/855) of men and 97% (85/88) of women are covered under the current NFPA 1971 glove-sizing map. The coverage rates were not statistically different

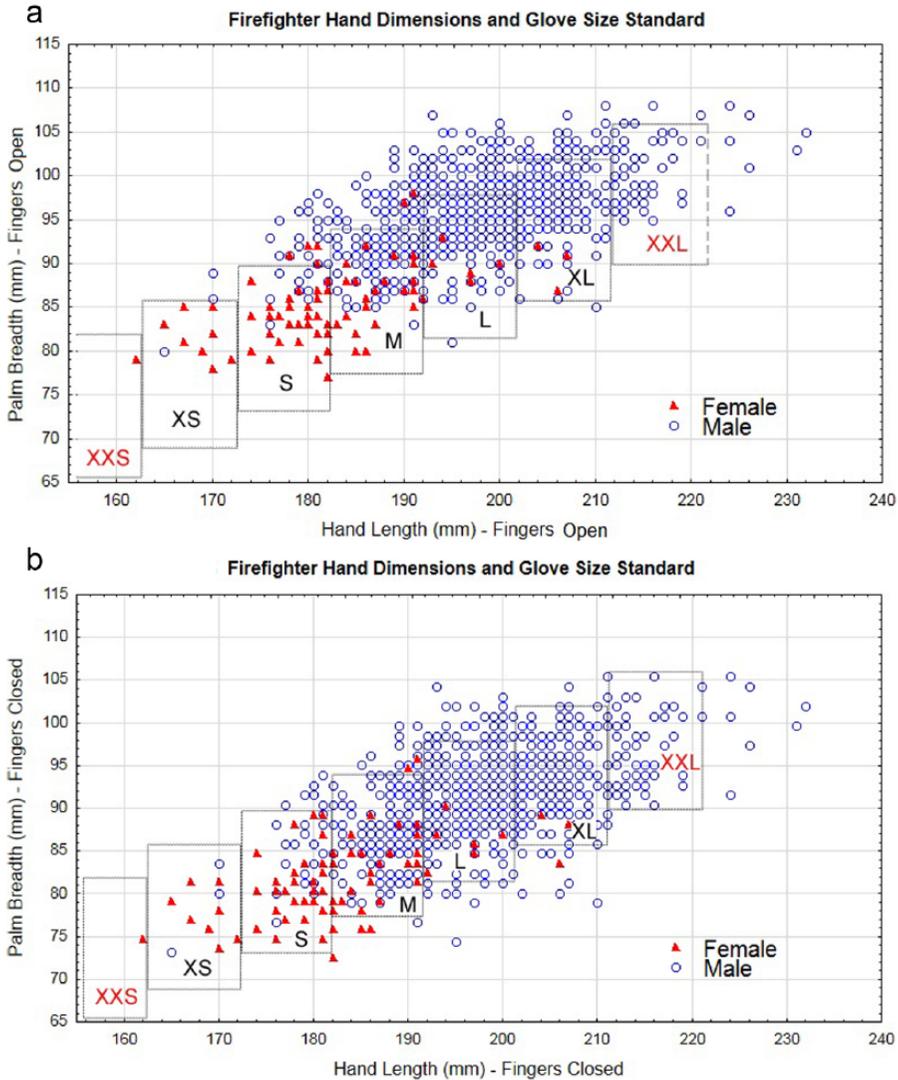


Figure 2. Matching firefighter hand dimensions with National Fire Protection Association 1971 glove-sizing scheme. (a) Data distribution in fingers-open posture. (b) Data distribution in fingers-closed posture. The rectangles represent the hand length and palm breadth ranges corresponding to the glove sizes.

between genders, $\chi^2 = 3.32 < \chi^2(1, .05) = 3.840$, $p = .07$. The NFPA sizing scheme still understated hand size distribution of the firefighter population (Figure 2b).

Association Between Choosing an NFPA-Matched Size and the Fit of the Gloves

Of the 943 participants who had the complete hand dimension measurements, 586 reported the

glove sizes they used. Of the 586 responses, 434 (74%) indicated that their gloves fit their hands well, whereas 152 (26%) reported that the gloves they used did not fit them adequately (Table 6). For men, there was 76% (415/547) fit and 24% (132/547) nonfit. For women, the ratio was 49% (19/39) fit and 51% (20/39) nonfit. The difference in glove-fit distribution is significant between men and women, $\chi^2 = 15.55 > \chi^2(1, .05) = 3.840$, $p < .001$.

TABLE 6: Participants' Glove Size Use Versus National Fire Protection Association (NFPA) 1971 Glove-Sizing Standard

Fit Assessment	Participants Who Reported Glove Size They Used (<i>N</i> = 586)		Glove Size Used Matches NFPA's (Fingers Open)		Glove Size Used Matches NFPA's (Fingers Closed)	
	Male	Female	Yes	No	Yes	No
Gloves fit well (<i>n</i> = 434)	415	19	160	274	163	271
Gloves fit poorly (<i>n</i> = 152)	132	20	59	93	65	87

Also, of the 434 participants who had well-fitting gloves, 160 (37%) used glove sizes that matched the NFPA 1971 standard sizing scheme according to their hand dimensions (Table 6). In contrast, of the 152 participants who had poor-fitting gloves, 59 (39%) used glove sizes that matched the NFPA 1971 standard sizing scheme according to their hand length and palm breadth. No association was found between choosing an NFPA-matched size and the fit of the gloves, $\chi^2 = 0.18 < \chi^2(1, .05) = 3.840, p = .67$.

While firefighter gloves are designed and used for operation with fingers open and closed, traditional hand measurement approaches and existing standards tended to report hand data in a fingers-closed posture (like mittens). Two equations were available for converting the raw data between the two postures: Hand/Palm Breadth Digitized (mm; fingers open; males) = $16.3 + 0.87 \times \text{Hand Breadth Measured (fingers closed; Greiner, 1991, page 279)}$, and Hand/Palm Breadth Digitized (mm; fingers open; females) = $11.74 + 0.90 \times \text{Hand Breadth Measured (fingers closed; Greiner, 1991, p. 285)}$. Using the converted data (fingers-closed posture), we again found no association between choosing an NFPA-matched size and the fit of the gloves, $\chi^2 = 1.28 < \chi^2(1, .05) = 3.840, p = .26$ (Table 6).

Features of Firefighter Hand/Finger Size and Shape

A principal component analysis (PCA), based on 12 hand dimensions (lengths and breadths of palm, thumb, and fingers) was performed to explore the most distinguishable features of hand and fingers in defining hand sizes and shapes among firefighters to identify the direction for an improved glove-sizing plan (Table 7). Since multivariate normality assumptions are of

secondary importance in this application (Jackson, 1997; Jolliffe, 2002), data of men and women were combined in this PCA analysis for its simplicity. Hand length and hand breadth were excluded in this PCA because of their high correlation with palm length and palm breadth, respectively ($r = .93$; see Hsiao et al., 2005, pp. 346–347). The result shows that the first two principal components are critical factors with eigenvalues of 6.74 and 2.42, respectively (Kaiser, 1960). They accounted for 56.2% and 20.1% of the total hand anthropometry variations (Table 7). The first principal component (PC1) represents the overall hand size (all dimensions as a group), and the second component (PC2) represents hand/finger breadth-to-length contrast as a whole.

Palm breadth and index finger length accounted for more variance of overall hand size (10.7% and 9.7%, respectively) than that of other dimensions. Middle finger breadth and index finger breadth accounted for more variance in hand shape (i.e., breadth-to-length contrast; 13.9% and 12.5%, respectively) than that of other dimensions. Using a weighted approach (i.e., 56.2% for PC1 and 20.1% for PC2) to calculate the influence of the 12 hand dimensions revealed that the middle finger length is the most contributory factor in defining hand sizes and shapes among firefighters ($9.3\% \times 56.2 + 10.4\% \times 20.1 = 7.32$; Table 7). Palm breadth, middle finger (length and breadth), and index finger (length and breadth) are the most distinguishable features of hand and fingers in defining hand sizes and shapes among firefighters and are therefore advantageous parameters for inclusion in future glove-sizing charts.

A further analysis of PC1 and PC2 indicated a significant mean difference of PC1 scores by gender (−1.59 for women and 0.16 for men,

TABLE 7: Principal Component (PC) Loading Factors, Based on 12 Hand Dimensions (N = 943)

Principal Components	Eigen-values	% of Total Variance	Hand/Finger Dimension	Eigen Vectors: PC1	Variance Accounted for PC1	Eigen Vectors: PC2	Variance Accounted for PC2	Weighted Influence
Factor 1	6.74	56.2	Palm length	.285	8.1%	-.153	2.3%	5.01
Factor 2	2.42	20.1	Palm breadth	.327	1.7%	.117	1.4%	6.29
Factor 3	0.54	4.5	Thumb length	.287	8.2%	-.239	5.7%	5.75
Factor 4	0.43	3.6	Thumb breadth	.264	7.0%	.302	9.1%	5.76
Factor 5	0.37	3.1	Index length	.312	9.7%	-.288	8.3%	7.12
Factor 6	0.35	2.9	Index breadth	.268	7.2%	.353	12.5%	6.56
Factor 7	0.28	2.4	Middle length	.305	9.3%	-.322	10.4%	7.32
Factor 8	0.23	1.9	Middle breadth	.26	6.8%	.373	13.9%	6.62
Factor 9	0.22	1.9	Ring length	.307	9.4%	-.307	9.4%	7.17
Factor 10	0.20	1.7	Ring breadth	.277	7.7%	.327	10.7%	6.48
Factor 11	0.14	1.2	Pinky length	.286	8.2%	-.290	8.4%	6.30
Factor 12	0.07	0.6	Pinky breadth	.278	7.7%	.280	7.8%	5.90

$p < .001$), and so did PC2 scores by gender (-0.35 for women and 0.04 for men, $p < .001$), which have practical implications in glove sizing and design. Men have a wider spread in hand/finger breadth-to-length contrast than women, and women may benefit from one or two gender-specific glove sizes for their smaller overall hand size and narrower hand/finger breadth-to-length contrast (i.e., elongated) as compared to those of men (Figure 3a). PC1 and PC2 are orthogonal and uncorrelated by definition when overall data are used (i.e., men and women are combined; Figure 3a). Scatter plots of PC1 against PC2 by gender show different trends between men and women for correlation between PC1 and PC2 (Figure 3b). PC1 and PC2 remain uncorrelated for men (correlation coefficient $r = -.056$); a negative correlation was observed for women ($r = -.228$, $p < .05$). Although this finding is likely due to the fact that men dominate the sample, so the two PC factors will be orthogonal to each other for them, the data trend revealed that women with a larger overall hand size tend to have smaller hand/finger breadth-to-length ratio.

Direction for an Improved Glove Sizing System

In traditional protective gear fit research and design improvement, a practical and commonly

used approach is to utilize the data from the groups who had good fit of their gear and apply the sizing strategy to the nonfit groups or the whole intended group. Given the significant mismatch between existing glove-sizing specifications and hand characteristics, such as the hand dimensions, user selection of glove size, and the existing glove-sizing specifications described in the current study, the same strategy would not yield a satisfactory result (Table 6). A revamping of the current sizing system by incorporating both an overall hand/fingers size and breadth-to-length contrast in the sizing scheme would be advisable. In light of the need for improved coverage (for men and women) and accommodation (for multiple finger dimensions), a cluster approach was employed. Clustering is a process that is used to group a set of objects in such a way that objects in the same group (a cluster) are more similar to each other than to those in other groups (clusters).

Although women have different distinct features in hand size and shape from men (Figure 3a), the naturally formed clusters of factor scores (i.e., PC1 and PC2 coordinates) of women pointed to the simplicity of an overall-group cluster analysis (Figure 4) over a combination of results from two gender-specific cluster analyses (Figure 3b). We propose a seven-size system to cover 97.5% of the sampled population. This system would not overburden the glove

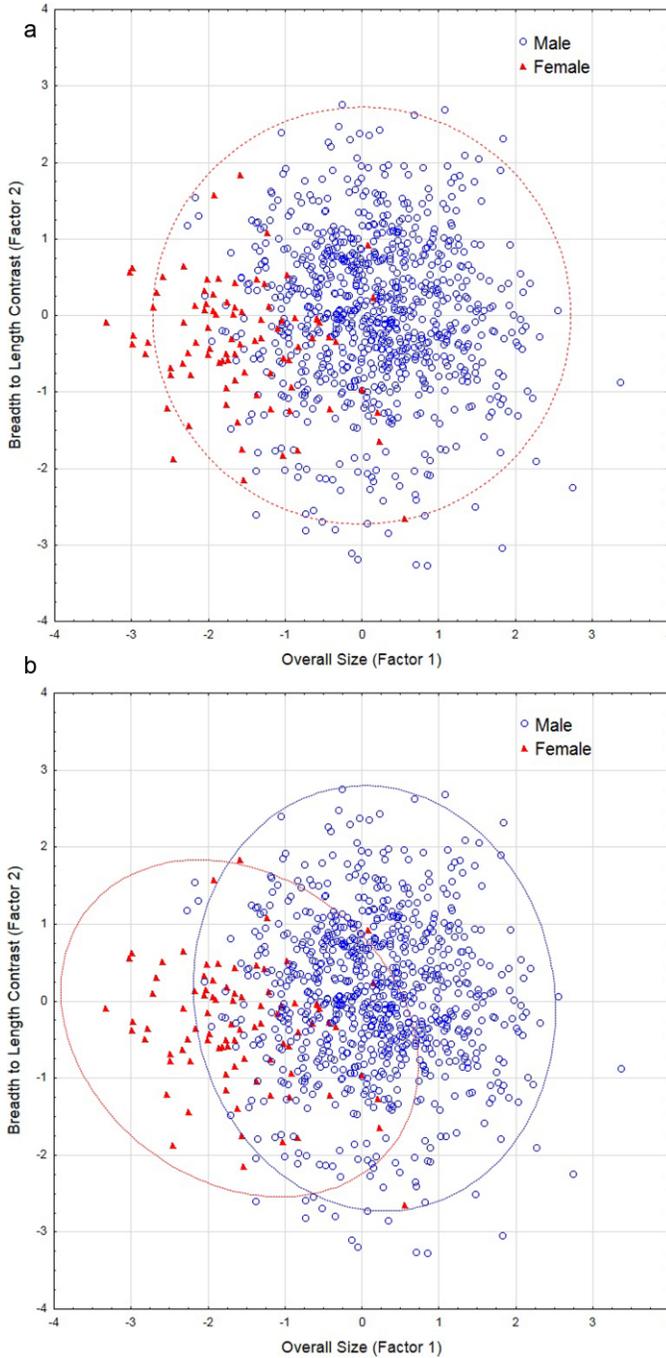


Figure 3. (a) Scatter plots of Principal Component 1 (PC1) and Principal Component 2 (PC2) scores by gender show that women (triangles) have smaller overall hand size and narrower hand/finger breadth-to-length contrast as compared to men (small circles). (b) Gender-specific scatter plots of PC1 against PC2 show no association between PC1 and PC2 for men. In contrast, women with a larger overall hand size tend to have smaller hand/finger breadth-to-length ratio. The large circle in Figure 3a and two ellipses in Figure 3b represent the 97.5th-percentile boundary of PC1 and PC2 coordinates.

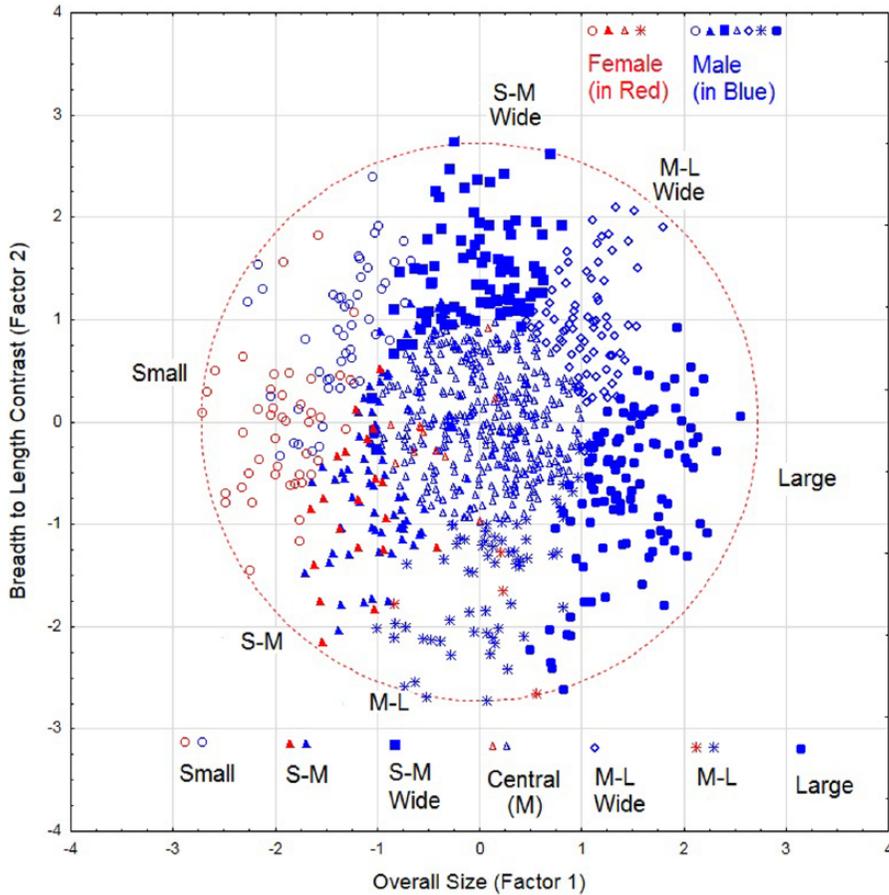


Figure 4. A proposed cluster-based seven-size system contains Small, S-M, S-M Wide, Central (Medium), M-L Wide, M-L, and Large sizes for men and women, in which the central size is predetermined for principal component factors' scores which are less or equal to 1, and the remaining six sizes are defined through an iterative process where the sum of distances among the center of the six clusters (based on 12 hand dimensions: lengths and breadths of palm, thumb, and fingers) is maximized. The dotted circle represents the boundary of 97.5% coverage of the sampled population.

manufacturing industry in glove production or national firefighter stations in stocking gloves, while providing firefighters with a good chance of finding a well-fitting glove size. A cluster analysis was employed to identify the best clustering, in which the central size was predetermined for factors scores less than or equal to 1 (i.e., the distance from PC1 and PC2 coordinates to the center of PC1-PC2 plot is less than or equal to 1; Figure 4), and the remaining six sizes were defined through an iterative process where the sum of distances among the center of the six clusters was maximized.

There were two options to determine the six noncentral clusters. The first option was to use PC1 and PC2 scores. The second option was to cluster the 12 hand dimensions (lengths and breadths of palm, thumb, and fingers) that were used to derive PC1 and PC2. The first option has an advantage of having near-even clusters since only two variables (i.e., PC1 and PC2) were employed. The second option has a potential advantage of having a smaller standard deviation within each cluster as compared to the first option and thus was used in this paper. The final seven-cluster system contains Small, S-M, S-M

Wide, Central/Medium, M-L Wide, M-L, and Large sizes (Figure 4) and the hand dimensions of the sizes (i.e., the clusters) are tabulated in Table 8.

DISCUSSION

Differences in Hand Dimensions Among Gender, Race/Ethnicity, and Age Groups

This study reports significant differences in means of firefighter hand dimensions by gender, race/ethnicity, and age groups. The results on gender and race/ethnicity effects are generally in line with existing literature. Men, on average, have greater hand length and hand breadth than women (Gordon et al., 1989; Greiner, 1991; Pheasant & Haslegrave, 2006; Poston, 2000). Blacks have more elongated hands than other race/ethnicity groups (Courtney, 1984; Greiner, 1991; Martin et al., 1975; White, 1980). Information on age effect on hand dimensions of adults is lacking in the literature. This current study shows that the older firefighter group (≥ 40 years old) has larger hands than the younger group. The outcomes reaffirmed the importance of stratified sampling that adequately represents gender, race/ethnicity, and age distribution in the target population. It directly affects the level of accommodation of gloves to firefighters and glove design applications.

Differences in Hand Dimensions Between Firefighters and Other Occupational Groups

Several databases of hand anthropometry, mostly from military personnel, are available for exploring the differences in hand dimensions between firefighters and other occupational groups (Churchill, Churchill, McConville, & White, 1977; Clauser et al., 1972; Donelson & Gordon, 1996; Garrett, 1970a, 1970b; Gordon et al., 1989; Greiner, 1991; White & Churchill, 1971; Table 9). Male firefighters have larger mean hand length (196.6 mm) than Army and Marine Corps men (190.3–194.1 mm) but not Air Force men (197.2 mm). Female firefighters also have larger mean hand length (182.7 mm) than Army and Marine Corps women and Air Force nurses (177.4–180.7 mm) but not Air Force women as a group (183.8 mm). Literature

has shown no difference in finger/hand length measurements between using 2-D flatbed scanning and traditional measurement methods (Yu et al., 2013). These hand dimension differences reflect occupational variances.

From the same surveys, firefighters have larger hand breadth (97.2 mm for men and 87.4 mm for women) than military personnel (89.0–90.4 mm for men and 75.5–79.5 mm for women). It is worth noting that a fingers-open hand posture was used for scanning in this study, and the hand breadth was extracted through a digitization process. Greiner (1991) reported an average 5-mm increase for men and 3.6-mm for women in hand breadth measurement when comparing a digitization approach with fingers open to the traditional measurement method (fingers closed). After adjusting for these additions, firefighters still have greater hand breadth than other groups (Table 9). Moreover, a comparison of finger dimensions between firefighters from this study and the best available Army finger anthropometry data (Greiner, 1991) showed significant differences for all finger dimensions for women and thumb dimensions and ring and pinky breadths for men. These results reaffirmed that general population statements on anthropometry may not be drawn from population-specific surveys and vice versa (Hsiao, Long, & Snyder, 2002) because anthropometric differences exist among specialized occupational groups, such as pianists (Wagner, 1988), truck drivers (Guan et al., 2012), and firefighters (Hsiao et al., 2014).

Glove Fit and Gender-Specific Sizes

Structural firefighting glove fit is multidimensional, and hand/fingers size and breadth-to-length contrast are different in clusters by gender. Some manufacturers have included firefighter glove sizes designated for women in their product line. This current study demonstrated a need to include at least one or two glove sizes based on female hand models (i.e., Small and S-M sizes; Figure 4). Moreover, although literature has reported poor correlation between hand length and hand breadth (Gooderson, Knowles, & Gooderson, 1982; Vicinus, 1962), female firefighters who have a larger hand size tend to have a smaller hand/finger breadth-to-length ratio (Figure 3b). This study

TABLE 8: A Sizing Plan Based on Cluster Analysis of Overall Hand Size and Fingers and Palm Width-to-Length Contrast (in millimeters)

Hand Dimension	Small (n = 94)	S-M (n = 87)	S-M Wide (n = 91)	Central (Medium) (n = 393)	M-L Wide (n = 78)	M-L (n = 71)	Large (n = 105)
Hand length							
Mean	180	190	191	196	203	204	211
2.5th percentile	169	181	181	185	195	195	202
97.5th percentile	187	198	198	207	211	213	224
Hand breadth							
Mean	89	91	99	97	101	95	102
2.5th percentile	82	84	94	90	94	87	96
97.5th percentile	96	95	105	103	109	102	108
Palm length							
Mean	104	109	111	113	118	117	120
2.5th percentile	94	102	105	104	111	107	112
97.5th percentile	112	117	117	121	126	125	129
Palm breadth (fingers open)							
Mean	87	89	97	95	100	94	101
2.5th percentile	80	83	93	89	94	86	96
97.5th percentile	95	94	103	102	106	99	108
Palm breadth (fingers closed)							
Mean	82	84	93	91	97	89	98
2.5th percentile	76	78	88	82	89	80	92
97.5th percentile	90	89	100	99	103	95	105
Thumb length							
Mean	63	68	67	70	72	74	76
2.5th percentile	58	63	63	64	66	68	70
97.5th percentile	68	73	72	76	79	79	83
Thumb breadth							
Mean	22	22	25	24	26	23	25
2.5th percentile	19	20	23	22	25	21	21
97.5th percentile	25	25	28	27	30	26	28
Index finger length							
Mean	69	73	72	75	78	78	82
2.5th percentile	64	68	68	70	74	73	78
97.5th percentile	73	78	76	81	82	83	88
Index finger breadth							
Mean	21	21	24	23	25	21	24
2.5th percentile	19	18	21	21	22	19	21
97.5th percentile	23	24	25	24	27	24	26
Middle finger length							
Mean	76	81	80	83	85	87	91
2.5th percentile	71	77	75	78	81	81	86

(continued)

TABLE 8: (continued)

Hand Dimension	Small (<i>n</i> = 94)	S-M (<i>n</i> = 87)	S-M Wide (<i>n</i> = 91)	Central (Medium) (<i>n</i> = 393)	M-L Wide (<i>n</i> = 78)	M-L (<i>n</i> = 71)	Large (<i>n</i> = 105)
97.5th percentile	81	86	84	89	89	93	95
Middle finger breadth							
Mean	21	20	24	22	24	21	23
2.5th percentile	19	18	20	20	22	18	20
97.5th percentile	23	23	26	24	27	24	26
Ring finger length							
Mean	72	76	76	79	81	83	86
2.5th percentile	67	72	70	74	77	77	82
97.5th percentile	76	81	81	85	85	89	93
Ring finger breadth							
Mean	20	20	23	22	24	20	23
2.5th percentile	18	17	21	20	21	17	20
97.5th percentile	23	22	24	24	26	24	25
Pinky length							
Mean	58	62	61	65	66	68	71
2.5th percentile	54	56	56	60	60	62	65
97.5th percentile	63	67	65	71	70	76	76
Pinky breadth							
Mean	18	18	20	20	21	19	21
2.5th percentile	16	16	18	18	19	16	18
97.5th percentile	21	20	23	22	23	22	23

provides a step forward (i.e., including women hand model-based sizes and wide-palm sizes for men) for developing an improved glove sizing system for firefighters.

Improvement of the Proposed Glove Sizing System Over the Current Practice

As presented in the Results section, there are discrepancies among existing firefighter glove size specifications, firefighter hand dimensions, and firefighter glove selection. The discrepancies may lead to several research questions. What are the acceptable tolerance ranges for palm and each finger for a single glove size? What is the most practical and accurate way to select the correct glove size? Although additional efforts are needed to address these questions, it is clear that firefighter hand dimensions and shape variations are greater than

the corresponding ranges of the current sizing systems (Figures 2a, 2b, and 3b). The proposed seven-cluster system from this study contains Small, S-M, S-M Wide, Central/Medium, M-L Wide, M-L, and Large sizes. The Small size is more for female firefighters, whereas the S-M size can fit both female and male firefighters who have an elongated and small-to-median size hand. The remaining five sizes are in general for men with an understanding that some female firefighters will likely need the S-M Wide and Central (medium) sizes based on their hand size and shape (Figure 4). A comparison of the size ranges of each size between the proposed seven-size system ($N = 919$) and the sizes used by firefighters who reported that their gloves fit well ($n = 434$) shows that the proposed seven-size system has smaller ranges of standard deviation for almost all hand/finger dimensions for each size, except for a few dimensions in

TABLE 9: Differences in Hand Dimensions Between Firefighters and Other Occupational Groups (in millimeters)

Hand Dimension	n	Hand Length			Hand Breadth		
		M	SD	SE	M	SD	SE
Occupational group (men)							
Firefighters (Hsiao et al., 2014), fingers open ^a	855	197.6	9.3	0.3	97.2	4.6	0.2
Air Force (Garrett, 1970a)	148	197.2	9.3	0.8	89.6*	4.0	0.3
Army 1966 (White & Churchill 1971)	6682	190.3*	9.6	0.1	89.0*	4.9	0.1
Army (Gordon et al., 1989)	1774	193.8*	9.8	0.2	90.4*	3.8	0.0
Army (Greiner, 1991)	1003	194.1*	9.9	0.3	90.4*	4.2	0.1
Marine Corps (Donelson & Gordon, 1996)	4444	193.0*	9.3	0.5	90.0*	4.1	0.2
Army (Greiner, 1991), fingers open ^a	1003	194.1*	10.3	0.3	95.3*	5.8	0.2
Occupational group (women)							
Firefighters (Hsiao et al., 2014), fingers open ^a	88	182.7	8.7	0.9	87.4	4.2	0.4
Air Force (Clauser et al., 1972)	1905	183.8	9.6	0.2	75.5*	3.9	0.1
Army (Churchill et al., 1977)	1331	174.4*	9.0	0.2	78.2*	3.9	0.1
Army (Gordon et al., 1989)	2208	180.5*	9.7	0.2	79.4*	3.8	0.0
Army (Greiner, 1991)	1304	180.7*	9.8	0.3	79.5*	3.8	0.1
Air Force women/nurses (Garrett, 1970b)	211	179.3*	8.6	0.6	77.1*	3.8	0.3
Marine Corps (Donelson & Gordon, 1996)	2888	179.0*	9.4	0.5	79.0*	3.8	0.2
Army (Greiner, 1991), fingers open ^a	1304	177.9*	9.8	0.3	83.1*	4.4	0.1

^aMeasured when fingers are open naturally.

*p < .05 for two-tailed independent t test between means of the identified group and firefighters.

XS and XXXL sizes in which the sample sizes of three and five in the old/current system are too small for a meaningful comparison (Table 10). The proposed seven-cluster system offers a resolution for better accommodation and business value.

Practical Implication, Study Limitations, and Direction for Future Studies

In this study we proposed a seven-cluster system as a step-forward resolution to improve the current firefighter glove sizing structure. This perspective assumed that each single glove size can accommodate a specific cluster of firefighters. There are at least three merits from this study. First, the method incorporated both hand/finger overall size and breadth-to-length contrast in the process (in lieu of a single dimension

at a time), which is useful in lessening one of the primary problems with the current NFPA standard, that the accommodation ranges seem unrealistically large. Second, the number of sizes is less than or equal to the current practices, which does not create additional manufacturing and stocking burdens to the glove industry. Third, a representative hand model or a series of hand models from each cluster can be selected to make solid or digital hand prototypes for glove design and testing applications. The limitation of this study is that we do not know whether these new dimensional ranges for each cluster are the narrowest acceptable ranges. We are conducting studies on the acceptable tolerance ranges for palm and each finger for selected glove sizes. This effort will provide additional data for refining glove sizing schemes. A further

TABLE 10: A Comparison of the Size Ranges Between the Cluster-Based Seven-Size System and the Current System Used by Firefighters (in millimeters)

Hand Dimension	New		Small (n = 94)		S-M (n = 87)		S-M Wide (n = 91)		Central (n = 393)		M-L Wide (n = 78)		M-L (n = 71)		Large (n = 105)		
	Old	XS (n = 3)	S (n = 16)	M	SD	M	SD	M (n = 84)	L (n = 188)	M	SD	XL (n = 100)	M	SD	XXL (n = 38)	M	SD
Hand length	New	180	4.8	190	4.5	191	4.5	196	5.8	203	3.9	204	5.0	211	5.2		
	Old	171	5.1	184	9.2	193	7.7	197	8.6	201	8.7	205	8.6	206	7.3		
Hand breadth	New	89	4.1	91	3.0	99	3.3	97	3.4	101	3.1	95	3.3	102	3.1		
	Old	84	0.6	90	4.8	95	4.3	97	4.2	99	4.3	99	4.2	101	1.6		
Palm length	New	104	4.4	109	3.9	111	3.4	113	4.5	118	3.7	117	4.7	120	4.2		
	Old	97	3.1	105	6.1	111	5.1	113	5.3	115	5.7	117	4.9	118	4.1		
Palm breadth	New	87	4.4	89	2.9	97	3.2	95	3.4	100	3.0	94	3.3	101	2.9		
	Old	81	3.0	87	4.2	94	4.3	96	4.2	98	4.3	98	4.3	101	2.1		
Palm breadth (finger closed)	New	82	4.2	84	3.1	93	3.6	91	3.8	97	3.4	89	3.7	98	3.3		
	Old	77	3.3	83	4.2	89	4.6	91	4.8	93	4.9	94	4.9	98	2.4		
Thumb length	New	63	2.5	68	2.8	67	2.6	70	3.1	72	3.1	74	3.0	76	3.2		
	Old	60	0.6	65	5.0	69	4.0	71	3.7	72	3.5	74	3.8	70	4.4		
Thumb breadth	New	22	1.6	22	1.3	25	1.4	24	1.2	26	1.2	23	1.3	25	1.5		
	Old	20	0.6	22	1.0	24	1.5	24	1.7	25	1.5	25	1.5	25	1.2		
Index length	New	69	2.3	73	2.5	72	2.3	75	2.8	78	2.1	78	2.4	82	2.6		
	Old	69	2.5	71	3.3	74	4.0	76	3.9	77	3.9	79	4.4	79	5.8		
Index breadth	New	21	1.2	21	1.4	24	1.1	23	1.0	25	1.1	21	1.3	24	1.4		
	Old	19	0.6	21	1.0	22	1.5	23	1.6	23	1.7	23	1.5	24	1.1		
Middle length	New	76	2.5	81	2.6	80	2.6	83	2.8	85	2.1	87	2.5	91	2.3		
	Old	75	2.1	78	3.9	82	3.9	84	4.5	86	4.1	87	4.8	87	4.9		
Middle breadth	New	21	1.3	20	1.2	24	1.3	22	1.1	24	1.1	21	1.6	23	1.4		
	Old	19	0.6	21	1.2	22	1.5	22	1.7	23	1.8	23	1.7	24	0.7		
Ring length	New	72	2.4	76	2.4	76	2.7	79	2.9	81	2.2	83	2.8	86	2.5		
	Old	71	2.0	75	4.4	78	3.8	80	4.5	82	4.1	82	5.1	83	6.3		
Ring breadth	New	20	1.3	20	1.2	23	1.2	22	1.1	24	1.1	20	1.6	23	1.4		
	Old	18	0.6	20	1.4	21	1.6	22	1.6	22	1.8	22	1.5	23	1.1		
Pinky length	New	58	2.4	62	2.6	61	2.6	65	2.8	66	2.8	68	3.0	71	3.3		
	Old	55	2.6	61	3.8	64	4.0	65	4.1	67	4.4	68	4.6	66	5.0		
Pinky breadth	New	18	1.3	18	1.1	20	1.2	20	1.0	21	1.1	19	1.5	21	1.3		
	Old	16	1.0	18	1.2	19	1.6	20	1.5	20	1.4	20	1.2	21	0.9		

cluster analysis using more or fewer clusters then can be performed iteratively to identify the best matched sizing plan. Until then, the proposed sizing modification represents the furthest advancement in structural firefighting glove-sizing practices.

CONCLUSION

This study reports the most up-to-date U.S. firefighter hand anthropometry data for structural firefighting glove-sizing applications. Firefighter hand dimensions vary by gender, race/ethnicity, and age groups and in general differ from those of military populations. The current NFPA firefighter glove-sizing specification ranges cover 72% of male firefighters and 96% of female firefighters. But no clear association was found between choosing an NFPA-matched size and the good fit of gloves. On variation of hand dimensions, palm breadth and middle and

index fingers have the most distinguishable features. On glove-sizing planning, a cluster-based seven-size system was proposed to address the mismatch problem among hand size, glove use, and glove size specifications, by utilizing the most up-to-date firefighter-specific hand dimensions and considering both overall hand size and hand and fingers breadth-to-length contrast. The new system in general has smaller hand and finger dimensional ranges for each size as compared to the current sizes classified and used by firefighters. The multivariate cluster-based results will enhance size matching and accommodate users substantially better than the old system, which relied on a linear sizing structure and had a size-matching rate of 39%. The next important step is to continue partnership with industry to build glove prototypes using the proposed sizing specifications and then test new gloves with firefighters.

APPENDIX A

Dimensions Relevant to the Design of Firefighter Structure Gloves

Dimension	Figure	Definition
Hand length		The distance from the base of the hand at the wrist crease to the tip of the middle finger, measured along the long axis of the hand.
Hand breadth		Hand breadth is drawn by connecting the point of the left side of the joint connecting the little finger to the palm and the point of the right side of the joint connecting the index finger to the palm (metacarpal-phalangeal joints).
Palm length		The distance from the base of the hand at the wrist crease to the furrow at the base of the middle finger.
Palm breadth		Palm breadth is drawn by connecting the point of the left of the distal transverse crease to the point of the right of the proximal transverse crease.
Thumb and finger lengths		Thumb and finger lengths are defined as the distance from the tip to the base of the finger for thumb, index, middle, ring, and little fingers.
Thumb and finger widths		Thumb and finger widths are defined as the width of the specific finger at the first (proximity) knuckle from the base of the finger for thumb, index, middle, ring, and little fingers.

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KEY POINTS

- Firefighter hand dimensions are different among gender, race/ethnicity, and age groups; their hand size and shape also are different from those of military personnel.
- Firefighter hand variations are greater than the current National Fire Protection Association (NFPA)

1971 standard glove-sizing specifications. Although the specification ranges are very large to cover the hand sizes of 72% of male and 96% of female firefighters, no association was found in this study between choosing an NFPA 1971 matched size and the good fit of gloves.

- Firefighter glove fit is multidimensional. Hand/fingers overall size and hand/fingers breadth-to-length contrast play a role, and palm breadth and middle and index fingers have distinguishable features in describing hand sizes and shapes.
- A cluster-based seven-size glove system is proposed. It has an overall advantage of having smaller hand and finger dimensional ranges for each size as compared to the current system and thus has a business and practical value of better size matching and accommodation to firefighters.

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