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Female firefighters' increased risk of occupational exposure due to ill-fitting personal protective clothing

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Despite the growing female firefighter population, firefighting gear was originally designed with only the male human form in mind. As a result, women in the fire service experience issues of improper fit and injuries at rates exponentially higher than their male counterparts. Areas of ill-fit, specifically in interfaces, can increase the risk of occupational exposure for women in the fire service. The purpose of this research was to determine fit and sizing issues of personal protective clothing (PPC) to improve female firefighters' comfort, mobility, and safety. A mixed methods approach was adopted including a nationwide questionnaire, end-user focus groups, and remote three-dimensional body scanning of 189 female structural and wildland firefighters. Between 15%–21% of female firefighters were found to intentionally leave off a part of their PPC at least "sometimes," if not "nearly always," with the coat and pants being the primary items not donned. 100% of participants had wrist and ankle circumferences smaller than the smallest size garment's wrist and pant leg openings per the wildland sizing system, indicating interface areas and wildland PPC have the greatest opportunities for design and fit improvement. This study gathered and created the first and largest U.S. female firefighter anthropometric database. Overall results indicate female firefighters are wearing PPC with significant fit issues that not only reduce their comfort and restrict their mobility but pose increased safety risks related to occupational exposure.

KEYWORDS

female firefighter, personal protective clothing, turnout gear, wildland, protection, fit, sizing

1 Introduction

As of 2020, there were over 89,000 female firefighters in the United States making up 9% of the fire service (Fahy et al., 2022), a statistic that has continued to increase over the past several years. With more and more females entering the fire service, they must be properly outfitted with appropriate personal protective equipment (PPE) to ensure they are as protected as their male counterparts. Despite the growing female firefighter population, structural firefighting turnout gear was originally designed with only the male human form in mind (Boorady, Barker, Lin, et al., 2013). Previous research has shown 80% of female firefighters experience issues with ill-fitting PPE, a rate four times greater than their male counterparts' self-reported fit issues (Hulett et al., 2008). In turn, female firefighters

experience a 33% greater risk of injury due to ill-fitting PPE (Liao et al., 2001; Boorady, Barker, Lin, et al., 2013; Andersen et al., 2016; Hollerbach et al., 2017; 2020). A lack of available and properly designed PPE for women in the fire service leads to a lack of protection, an increased risk of onsite injury, a reduction in mobility, and poor wear comfort due to areas of improper fit (McQuerry et al., 2019).

Improper fit can have severe consequences, especially in interface areas (e.g., sleeve/glove, neck/hood, coat/pant, and boot/pant) that allow for greater opportunity for liquid, chemical, and heat exposure. Firefighters' risk of hazardous exposure is evident in the recent uptick in awareness of firefighter cancer (Daniels et al., 2014; Lee et al., 2020; Ma et al., 2005; 2006; U.S. Fire Administration (USFA, 2019). As the International Association of Fire Fighters (IAFF) reports, occupational cancer is the leading cause of line-of-duty deaths in the fire service, especially when tracked longitudinally across their long service careers (International Association of Fire Fighters, 2023). Recent research into interface testing of PPE has exposed these vulnerable areas, as seen by the visual assessments from the Fluorescent Aerosol Screening Test (FAST) (Ormond et al., 2019). Based on the conditions of the emergency scene, smoke and particulates can seep through gaps and spaces at the neck, waist, wrists, and ankles. This is of particular concern for female firefighters as female turnout coats are often smaller, shortened versions of jackets made from patterns designed for men. Women in the fire service have reported lower satisfaction with the fit and functionality of their turnout ensemble in multiple areas as compared to their male counterparts (Park & Hahn, 2014). Specifically, female firefighters have reported oversized necklines and sleeve cuffs with too wide of openings (Jahnke et al., 2012; Park and Hahn, 2014).

A study by McQuerry (2020) demonstrated differences in male *versus* female firefighter turnout suit fit and the consequential impact on ergonomic range of motion (McQuerry, 2020). This study body scanned female (n = 6) and male (n = 10) firefighters in a stationary three-dimensional body scanner while wearing loose-fitting base layers and department-issued turnout suits. Differences in circumferential measurements between clothing configurations and sex were analyzed. Indeed, female firefighters experienced issues of improper fit and limited mobility in areas different from male firefighter participants (McQuerry, 2020). This study was limited, however, by the small sample size of female firefighter participants and the lack of tight-fitting base layers which prohibited the gathering of true body anthropometric measurements.

Few studies have collected the body measurements of United States (U.S.) female firefighters. Up until recently, PPE manufacturers have been forced to assume that female firefighters are the same anthropometrically as the general U.S. population female (Mcdowell et al., 2008; SizeUSA, 2003; Kuebler et al., 2019). The widely used SIZE United States® study was the first and only U.S. apparel-focused anthropometric database, however, it only included the general U.S. female population and is now considered by some to be outdated (SizeUSA, 2003). Recent general U.S. population databases have been published, however, none focus specifically on the female firefighter population and most lack the number and type of anthropometric measurements needed for firefighting PPE design (Center for Health Statistics, 2015; Kuebler et al., 2019). For example, the Center for Disease Control's (CDC) 2021 report on health statistics for U.S. adults collected from 2015–2018 only includes female waist circumference, mid-upper arm circumference, upper arm length, and upper leg length (Center for Health Statistics, 2015).

Hsiao, et al. (2014) published the first available U.S. national firefighter database of 71 anthropometric measurements including 88 female firefighters (Hsiao et al., 2014; NIOSH, 2015). This work was conducted in collaboration with the National Institute for Occupational Safety and Health (NIOSH) and the results demonstrated that women in the fire service were, on average, 29 mm taller than their female counterparts in the general U.S. population (Hsiao et al., 2014; NIOSH, 2015). This finding demonstrates the need for specific female firefighter anthropometric measurements. Although firefighter specific, the NIOSH database was limited by the heavy focus on male firefighters (n = 863) and the specific fire apparatus design application that impacted measurement selection.

Other occupational anthropometric surveys have been conducted previously such as the 1988 and 2012 Anthropometric Surveys of U.S. Army Personnel (Gordon et al., 1998; 2014) and the Anthropometric Source Book which is a handbook of weightless anthropometric data produced by the National Aeronautics and Space Administration (NASA) for engineers engaged in the design of equipment and clothing for the NASA Space Shuttle program (National Aeronautics and Space Administration (NASA, 1978). Most recently, a female firefighter anthropometry survey was completed and published in the United Kingdom (United Kingdom) (Stirling, 2022). Approximately half of the national United Kingdom female firefighting population was represented in the dataset and a total of 61 measures were included from body mass to handgrip strength (Stirling, 2022). Few circumferential measures, however, were taken and many more could be included.

The United Kingdom female firefighter anthropometry database rightly points out the common belief amongst many PPE designers that women are scaled-down versions of men (Stirling, 2022). Stirling also points out that while this general rule of thumb may be true for a few measurements such as height and weight, many other dimensions should not be handled in the same manner such as the head, hands, and feet. This was illustrated using the 1998 Anthropometric Survey of U.S. Army Personnel (ANSUR) (Gordon et al., 1998; Stirling, 2022). This further demonstrates the need to collect specific U.S. female firefighter anthropometry to address the high self-reported rate of improper fit and dissatisfaction with gear comfort, mobility, and performance. Therefore, the purpose of this research was to determine the root cause of female firefighter personal protective clothing (PPC) design, fit, and sizing issues to improve their comfort, mobility, and ultimately, protection.

2 Methods

A mixed methods research approach was adopted and implemented for this study. This approach allowed for the collection and analysis of both quantitative and qualitative data that offers a deeper comprehension of the research problem. This study employed a user needs questionnaire, end-user focus groups,

TABLE 1 Female firefighter user needs questions related to PPE occupational exposure.

Survey section	Question	Answer type
Selection	Is the sizing of your turnout suit/wildland PPC female specific or sized in women's sizes?	Y/N
Fit	Have you ever encountered problems with ill-fitting turnout gear/wildland PPC?	Y/N
Fit	How well does your turnout suit/wildland PPC fit?	5-pt Likert
Fit	Do you believe your turnout suit/wildland PPC fits you properly?	Y/N
Mob	Do you believe the improper fit of your PPC limits your mobility?	Y/N
Mob	Does the limited mobility of your turnout suit/wildland PPC significantly affect your: comfort, safety, thermal protection, liquid protection, chemical protection, and smoke and particulate protection?	Y/N
Mod	How often do you leave off a part of your turnout/wildland gear because it does not fit?	5-pt Likert
Mod	Do you have to modify your turnout gear (coat and pants)/wildland gear (shirt and pants) in any way?	Y/N
Mod	Have you ever modified or customized any part of your turnout/wildland gear?	Y/N

and three-dimensional body scanning to collect female firefighter body measurements.

2.1 User needs questionnaire

To meet the objectives of this research, a 77-question nationwide end-user questionnaire was disseminated electronically via Qualtrics to structural and wildland female firefighters across the United States. The questionnaire was developed in collaboration with multiple industry, research, and fire service experts through the project's technical panel and in collaboration with Women in Fire (WIF). Over 2,000 responses were received with 954 fully completed surveys included in the dataset. After gathering informed consent, per our institutions' Internal Review Board (IRB) requirements, the survey began with a 9-question demographic section that immediately eliminated any male participants. The remaining four sections were split to analyze structural and wildland firefighter groups separately. A general section on firefighting PPC selection was asked (11 questions for structural, 6 for wildland), followed by a section on fit (8 questions), mobility (9 questions), and design modifications (8 questions). Only those questions related to fit, protection, or other topics relevant to the potential increased risk of exposure for female firefighters are included in the scope of this article. These questions are detailed in Table 1.

2.2 End user focus groups

To facilitate end-user focus groups, approximately 37 female firefighters were recruited to participate in research regarding their impressions and experiences with their current personal protective clothing. Focus group participants were also attendees at the 2021 Women in Fire (WIF) national conference in Spokane, Washington.

Participants of all fire service types were invited to join; this included structural, wildland, and wildland-urban interface (WUI) firefighting. Recruited female firefighters ranged in fire service type, as well as the length of service. Additionally, there were overall more career female firefighters than volunteers based on responses regarding department resources and interactions with PPE manufacturers.

The IRB-approved end-user focus groups with 37 female firefighters were conducted to gather information regarding their current PPC. Focus groups were organized based on the availability and schedule of participants at the WIF conference–this study had a total of six focus groups with each group accommodating between two to nine female firefighters. Each of the sessions lasted approximately 90 min and firefighters were asked open-ended questions regarding fit, mobility, design, and safety concerns about their PPC. These six sessions were recorded for analysis purposes and transcribed.

2.3 Three-dimensional body scanning

A three-dimensional remote body scanning application was utilized to collect female firefighter body measurements. The MeThreeSixty (Size Stream, LLC) application, available on iOS and Google devices, provides a simple, accurate method for collecting anthropometrics (Size Stream, 2022) via remote scanning technology when a physical three-dimensional body scanner cannot be relocated. A standardized protocol for all body scans was developed to ensure consistent measurements were taken across all scanning locations. The protocol included providing participants with form-fitting clothes, if necessary, collecting height and weight measurements, and taking a pre-scan reference photo. Scans were taken using a portable tablet device placed on a stationary tripod at designated heights to ensure proper placement of the participant within the scanning application. Each scan took less than 20 s to complete and gathered more than 240 body measurements per participant. Within the scope of this paper, 14 measurements corresponding to the National Fire Protection Association (NFPA) standard sizing requirements for structural and wildland firefighting PPC were analyzed, including chest circumference, sleeve length (r), waist circumference, inseam (r), neck circumference, front jacket length, wrist circumference, hip circumference, seat circumference, thigh circumference, knee circumference, ankle circumference, front rise, and back rise.

TABLE 2 Example coding of content analysis used for synthesis.

Question 5: How satisfied are you with your current size and fit of your turnout coat, pants, and/or wildland shirt and pants?	
Coding Category	*Participant Response*
B. Dissatisfied	I do not like my gear. It just depends on which pants I'm wearing. So again, it goes back to having the same size pants but they're not the same size pants so most of problems I have are with our pants and it's the crotch issue
C.2. Problem Area regarding Crotch	

These measurements were analyzed to determine differences between female firefighter body measurements and women's PPC sizing requirements for structural and wildland firefighting.

Similar body scanning technology and equipment have been utilized in previous studies to assess the fit of firefighting PPE (McQuerry, 2020; Jo et al., 2022; Sokolowski et al., 2022). Firefighter body scanning occurred in three locations: Spokane, WA, Orlando, FL, and Raleigh, NC. All body scan data was immediately uploaded in real-time to a shared, password-protected drive that only the research team had access to, per IRB approval. In total, 189 U.S. female firefighters were scanned, creating the largest anthropometric database to date. The female firefighter anthropometric data was then compared to current NFPA standard sizing requirements for structural and wildland firefighting PPC.

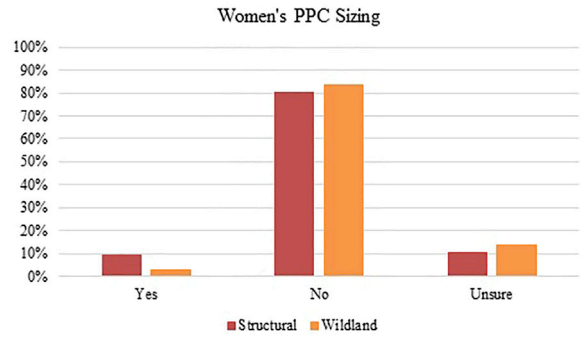


FIGURE 1
Percentage of female structural and wildland firefighters with women's sized gear.

2.4 Data analysis

Descriptive statistics of questionnaire participants' selection, fit, mobility, and modifications to their PPC were used to determine the prevalence of women's sized gear, the prevalence and type of fit and mobility issues for women in the fire service, and the occurrence of gear modification. This analysis is similar to previous questionnaire-based studies (Huang et al., 2012; Park et al., 2014; McQuerry et al., 2018).

The interpretative thematic analysis method was used for the synthesis of the focus group data. All focus group sessions were recorded, transcribed, and coded by three independent researchers for content analysis (Spiggle, 1994). Coding categories were determined by the frequency and prevalence of keywords or phrases that appeared amongst participants in each focus group–these were also developed based on questions asked by the research moderators. Once a category was established within the context of the question and conversation theme, alpha and/or an alphanumeric code was assigned. This method was adopted given its common use in previous firefighter user needs studies (Boorady, Barker, Lee, et al., 2013; Boorady, Barker, Lin, et al., 2013; Park and Hahn, 2014). An example of a question from a single focus group session, a participant's response, and its corresponding code can be seen in Table 2. Once each focus group session was coded individually, a full synthesis of all focus group sessions occurred, identifying holistic themes and categories from the qualitative data.

Descriptive statistics were also utilized to provide the average, median, mode, minimum, and maximum body measurements of the 187 female firefighters that were body scanned in this study in 14 specific locations. These locations were selected based on their correlation with women's sizing requirements included in the NFPA 1971 *Standard on Protective Ensembles for Structural Fire Fighting and Proximity Fire Fighting* and NFPA 1977 *Standard on Protective Clothing and Equipment for Wildland Fire Fighting and Urban Interface Fire Fighting*. The number and resulting percentage of participants whose body measurements fell outside of the women's size range for each specific sizing requirement in the NFPA standard was calculated.

3 Results

3.1 User needs questionnaire

All questionnaire participants were female with 62.9% between 20 and 39 years of age. The majority of participants (86%) identified as white/Caucasian and worked in the southeastern region of the United States. 70.5% were career firefighters with the most common rank being a firefighter (59%). Most (61%) identified as structural firefighters while the rest (39%) indicated they perform both structural and wildland firefighting. A broad range of experience was represented with 30.7% having less than 5 years of experience followed by another almost 30% with 11–20 years of experience.

In the section of the questionnaire related to PPC selection, participants were asked if the sizing of their turnout or wildland gear was female-specific or sized in women's sizes. Figure 1 illustrates these results. For structural firefighters, just under 10% indicated their gear was specifically sized for women. For wildland female firefighters, this percentage was drastically lower at just 2.8%.

In the second section on PPC fit, participants were asked if they had ever encountered problems with ill-fitting structural turnout suits or wildland shirts and pants. Results of how well structural and wildland female firefighters' PPC fits are shown in Figure 2. Similar

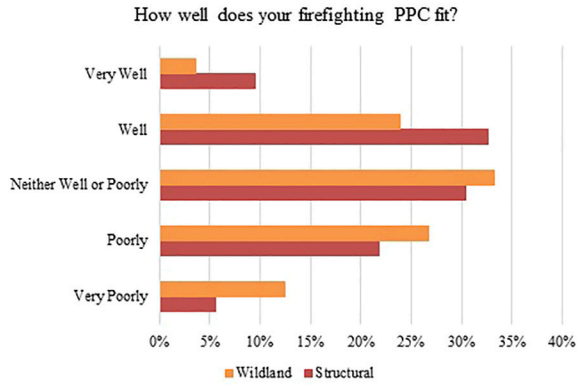


FIGURE 2
Overall fit ratings of wildland and structural turnout PPC for female firefighters.

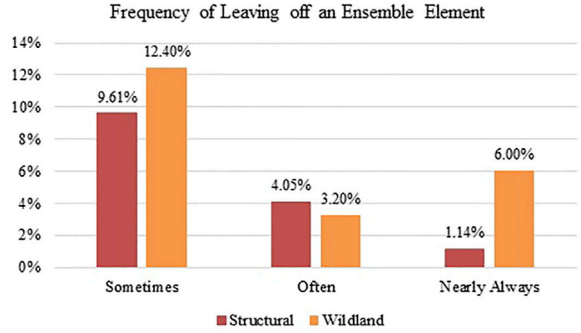
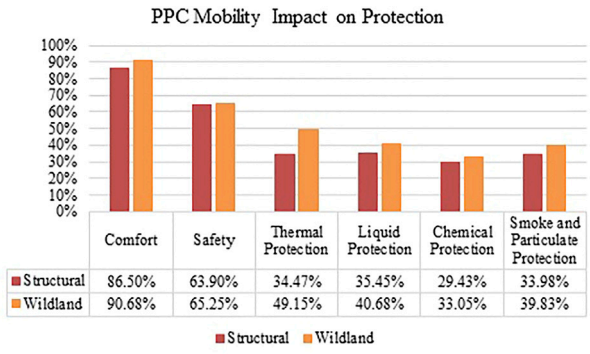


FIGURE 4
Percentage of structural and wildland female firefighters who "sometimes", "often", or "nearly always" leave off a part of their turnout or wildland gear due to improper fit.



	Comfort	Safety	Thermal Protection	Liquid Protection	Chemical Protection	Smoke and Particulate Protection
Structural	86.50%	63.90%	34.47%	35.45%	29.43%	33.98%
Wildland	90.68%	65.25%	49.15%	40.68%	33.05%	39.83%

FIGURE 3
Percentage of female firefighters perceiving an impact on their protection from improperly fitted PPC.

to Hulett, et al.'s findings, 82.9% of structural and 52.1% of wildland female firefighters indicated they have encountered problems with ill-fitting PPC. When asked how well their PPC fits, less than 10% of structural female firefighters and less than 4% of wildland female firefighters reported their PPC fits them "very well". Overall, more than half of female firefighters (54.88%, structural; 59.29%, wildland) reported they do not believe their PPC fits them properly.

Close to 80% of participants reported the improper fit of their clothing limits their mobility, further reducing their ability to perform their job safely. Figure 3 illustrates how female firefighters felt this limited mobility impacted their comfort and safety, specifically their thermal, liquid, chemical, and smoke/particulate protection. Between 86%–90% indicated the improper fit of their PPC leads to reduced mobility that negatively impacts their comfort. On average, 64.5% of female firefighters feel this reduced mobility impacts their safety. For structural female firefighters, the biggest protection concern was liquid, followed closely by thermal and smoke/particulate protection (34%–35.4%). For wildland firefighters, concerns were even higher between 40%–49% regarding thermal, liquid, and smoke/particulate protection.

When asked how often a part of their firefighting ensemble is not donned because of ill-fit, 15% of structural and 21% of wildland female firefighters reported they "sometimes", "often", or "nearly always" leave off a part of their gear because it does not fit properly, as illustrated in Figure 4. Shockingly, the number one PPE item that was intentionally not worn was the turnout coat or wildland jacket (58/140; 41.4%) due to improper fit in the bust, arms, sleeves, hips, and/or neck. This was closely followed by the turnout or wildland pants (28/140; 20%). 19% of female structural firefighters and 20% of female wildland firefighters reported they have to modify their coat/shirt or pants in some way to simply wear them on their body. Almost a quarter (23.6%) of female structural firefighters in this study indicated they have modified or customized a part of their turnout gear. For wildland PPC, 12% of female firefighters in this study indicated they have also modified or customized their gear in some way.

3.2 End user focus groups

Through the six focus group sessions, themes of improper fit, lack of mobility, discomfort, and PPC design issues were most prevalent. Most coding categories were based on the dissatisfaction with the female firefighter's current PPC as well as desired areas for improvement. These included but were not restricted to, bulkiness and excess material in structural turnout coats and pants, and oversized and long wildland shirts and pants. Specific issues cited also included oversized collars and restrictions in mobility due to tightness in areas such as the hips and across the chest. Many participants emphasized that the pant crotch length was very prohibitive when performing many on-job duties such as climbing on and off the fire truck or up a ladder. Due to the excess length and drop of the pant crotch, female firefighters are having to adjust their approach before executing movements such as crawling or entering smaller spaces; this includes "hiking up" the waist of their pants or else "the pants get stuck so it is hard for me to be able to move my knee up".

While a small handful of female firefighters had no issues with their current PPC, most participants agreed that design

TABLE 3 Descriptive statistical analysis compared to NFPA standards/.

Body measurement (cm)	Average	Median	Mode	Min	Max	NFPA 1971 range	NFPA 1977 range
Chest Circumference	106.1	104.1	110.5	85.3[+]	141.5[a]	71–127	99–150
Sleeve Length	77.7	77.8	78.6	70[ǂ]	92.3[ǂ]	71–86	77.5–90
Waist Circumference	89.3	87.9	88.9	71	123.5[+]	71–127	58–94
Inseam	77.3	77.5	78	67.6[+]	91[a]	61–86	71–91.5
Collar Circumference	36.7[+]	36.3[+]	37.2[+]	31.8[+]	43	n/a	37.5–50
Front Length	74	74	74.2	65.8	82.8[+]	n/a	63–75.5
Wrist Circumference	16.8[+]	16.7[+]	17.1[+]	15[+]	19.5[+]	n/a	30.5–37
Hip Circumference	114	112	114.5	97	114.6	n/a	96.5–147
Seat Circumference	112	109.8	112.7	94.6	145[+]	n/a	94–130
Thigh Circumference	64.6	63.4[+]	63.4[+]	53.4[+]	83[+]	n/a	63.5–81
Knee Circumference	40[+]	39.5[+]	38.9[+]	34.6[+]	48.9	n/a	45–58
Ankle Circumference	25.5[+]	25.5[+]	25.5[+]	22.5[+]	29[+]	n/a	38–47
Front Rise	25	25.2	25.2	15.4[+]	33.4[+]	n/a	22.5–28
Back Rise	26.2[+]	26.6[+]	28.4[+]	18.4[+]	33.7[+]	n/a	37.8–43.3

[a]Outside NFPA 1971 size range; + outside NFPA 1977 size range; ǂ outside both NFPA size ranges.

improvements are needed to address issues with mobility, comfort, and safety. Those few participants that were satisfied with their gear mentioned that it was comfortable due to the specific “female fit” and noted that they were able to don their suit for “a few hours doing training. without feeling like I need to take it off.”

Most female firefighters noted that their PPC has a direct impact on their on-duty performance and that along with their improperly fitting PPC, they felt their auxiliary PPE did not perform as intended due to ill-fitting interfaces between the helmet and collar, sleeve and gloves, and self-contained breathing apparatus (SCBA) and jacket. In one case, a participant stated that their PPC was causing hindrance to their vision due to their coat collar covering “my whole face since I have a smaller head. you just can’t fold it down because it is so stiff and it is about 5 inches.” Several others pointed to sleeve lengths on shirts and jackets as being “too long” and having to modify the sleeves to get their gloves on which in turn “limits the mobility of arm movement”.

In addition to fit, comfort, and mobility issues of their PPC, user wear confidence was also a predominant theme in the focus group sessions. This relates to concerns about injuries that could be sustained while wearing their PPC and the aesthetics and perception of others on how a female firefighter looks in what they perceive as ill-fitting gear. Notably, one female firefighter mentioned that her self-confidence is impacted as she sees her male counterparts “doing the skills and being efficient” while she “can’t move in the same way they can because of my gear”.

Lastly, focus group participants highlighted the need for appropriate female sizing and design for future turnout suits for structural and wildland firefighting. This included thoughtful placement of pockets for accessories such as radios and small hand tools as well as flared shaping for coats, so they zip over the hips easier. As one participant commented “There is actually a female fire gear that could actually fit our bodies better, so that would just be nice to have that option."

3.3 Female firefighter anthropometrics

Of the 189 body scans collected, 187 met the criteria for inclusion in the U.S. female firefighter anthropometric database. Descriptive statistics (Table 3) were calculated for 14 identified measurements related to the sizing requirements in the NFPA 1971 and NFPA 1977 standards for structural and wildland firefighting PPC, respectively.

4 Discussion

4.1 Availability and suitability of Women’s firefighting PPC

Questionnaire findings indicate less than 10% of structural female firefighters in the U.S. are wearing PPC designed specifically for the female human form. These results were much lower than Jahnke’s findings which reported 20% of female firefighters have access to and wear women’s gear. Jahnke’s study, however, surveyed female firefighters throughout North America, including Canada. End-user focus group data also uncovered that a small portion of female firefighters are unaware that firefighting gear made specifically for the female body exists on the market. A handful of participants noted during discussions regarding their current PPC that they did not know that “female-sized gear” was even an option for them.

Regarding fit satisfaction, results from this study are similar to findings by Jahnke, et al. in that the majority of participants in both

studies also indicated their turnout gear fit them well (32.2% *versus* 40.8%, respectively). The second largest and most frequent response in Jahnke's study, however, was that their gear fit them "very well" whereas, in this study, which was specific only to U.S. female firefighters, the second most frequent response was that women's turnout suits fit "neither well or poorly" at 30.6%. For wildland female firefighters, the majority of responses (33.5%) reported neutral satisfaction followed by 26% who felt their shirt and pants fit "poorly". These results indicate wildland female firefighters are even more dissatisfied with the fit of their gear than structural female firefighters at over 36% compared to 27% of structural firefighters.

Possibly the most concerning finding from the end user questionnaire was that 15% of structural and 21% of wildland female firefighters reported they "sometimes", "often", or "nearly always" leave off a part of their gear because it does not fit properly. These results indicate women in the fire service feel their protective clothing is unsuitable and so ill-fitting that it hinders their performance to the point they choose not to wear their two primary PPE elements for personal protection, which covers the largest portions of their bodies. This finding most certainly indicates that female firefighters are at greater risk for occupational exposure due to improper fitting PPC.

Participants who stated they had a female-sized suit, mainly structural and wildland-urban interface firefighters, usually commented that they had a preference for their "female set" compared to their "male set". This preference was because female firefighters were more comfortable and had increased mobility in gear that was patterned and tailored to the female form. This finding also highlights the fact that most female firefighters are still forced to wear a turnout suit designed for males, as only one provided set is often female-specific.

While many participants who had access to female-sized gear preferred it to male-centered designs, findings indicate there is still much room for improvement. Complaints related to female-sized gear were often due to having the incorrect or "wrong" size because of inconsistencies in PPE manufacturers' sizing systems and measuring protocols. This points to the need to streamline manufacturer and departmental sizing practices and fit-function assessments. Female firefighters who had been sized for female gear reported they often had the opportunity to have ill-fitting gear amended or fixed, however, some mentioned that regardless of the amendments made, their PPC ended up "being awful" and one participant reported ultimately going back to men's gear.

4.2 Anthropometric comparison to NFPA sizing standards

For structural turnout gear, there are only four sizing requirements included in NFPA 1971; two for the coat and two for the pants. These include chest circumference, sleeve length, waist circumference, and inseam. All four measurements have specific sizing requirements for female *versus* male firefighters. Sizing requirements in NFPA 1977 for wildland firefighting PPC include nine upper-body and eight lower-body measurements. However, female sizing is only required for the eight lower body measurements.

In general, it was found that minimum size range measurements for wildland PPC are much larger overall than for structural turnouts, by as much as 28 cm in the chest. In addition, the largest size required for the wildland pant waist circumference was 33 cm greater than the largest waist circumference required for turnout pants. These discrepancies are important as a large portion (39%) of female respondents to the end user questionnaire indicated they perform both types of firefighting. The comparison of the two PPC sizing systems alone illustrates the need for more consistent sizing in the fire service industry as required by the NFPA standards.

Descriptive statistics of the participant average, median, mode, minimum, and maximum measurements were compared to the size ranges for each measurement as required by each NFPA standard (Table 3). The chest circumference, sleeve length, waist circumference (pants), and inseam measurements are required by both NFPA standards. For wildland PPC, however, female sizing is only provided for the waist circumference and inseam, therefore the chest circumference and sleeve length size ranges apply to both male and female wildland firefighters.

Large percentages of female firefighter anthropometrics were found to lie outside of the required size ranges for both structural and wildland PPC. For chest circumference, 31% of female firefighters in this study were found to be smaller than the minimum NFPA 1977 sizing requirement of an XS wildland jacket and 5.8% had a chest circumference larger than the biggest turnout suit size required by NFPA 1971.

The greatest area for fit improvement was found to be in the sleeve with 47% of female participants having sleeve length measurements less than the smallest size of the wildland shirt. In the waist, almost a quarter (23.5%) of female firefighters measured in this study were larger than the largest NFPA 1977 sizing requirement in the pants, which is sized specifically for women. In fact, the smallest waist circumference measured in our study was 71 cm indicating the required size range from 58 to 70 cm is irrelevant. These large discrepancies between the required size range and the actual anthropometry of women in the fire service point to a major issue with the body proportions and overall design of the wildland PPC in relation to the female human form.

The current standard inseam lengths most closely fit the anthropometric measurements of the female firefighters in this study. Less than 5% of participants had inseams smaller than the NFPA 1977 requirements and less than 2% had inseams longer than NFPA 1971s maximum size requirement.

4.3 Wildland PPC interface exposure

Additional measurements were analyzed for wildland PPC according to NFPA 1977 including collar, wrist, hip, seat, thigh, knee, and ankle circumferences, as well as, front jacket length, front pant rise, and back pant rise. Of these areas, the most critical for ensuring firefighter protection from outside exposure is the interface areas: collar/hood, wrist/glove, ankle/boot, and coat hem/pant waist. At the neck, 68% of female firefighters in this study had a collar circumference up to 5.7 cm smaller than the minimum collar circumference requirement for wildland shirts. Even when factoring in the 2.5 cm ease requirement, 30% of female

firefighters would still have excess ease in the collar when wearing the smallest, size extra small (XS) shirt, which is not applicable for most female firefighters. This statistic alone indicates female firefighters are at a greater risk of exposure due to oversized interface openings in the neck/collar area.

Similar findings of improper PPC fit were found in the wrist/glove and ankle/boot interface areas. 100% of the 187 female firefighters scanned in this study had wrist circumferences and ankle circumferences less than the smallest size wrist and leg cuff openings required in the standard. Female firefighter wrist measurements were between 11 and 15.5 cm less than the smallest size XS sleeve cuff circumference requirement. Ankle measurements were at least 9 cm less than the smallest size leg cuff opening requirement. Factoring in ease values of 15+ cm for the wrist cuff and 28 cm for the ankle may alleviate some of these drastic fit discrepancies, however, that is assuming all participants in this study wear the smallest size shirt and pants, which they do not. This assessment also highlights confusion within the standard regarding where and how the specified sizing measurements should be taken on the body and how the ease measurements were determined and are to be appropriately used by designers and manufacturers. The current version of the NFPA 1977 standard does not include measurement drawings, diagrams, or written instructions for the specified sizing measurements. This limits garment design, patternmaking, certification, end-user satisfaction, and the ability to directly analyze anthropometric data.

In terms of the coat/pant interface, front coat length, front pant rise, and back pant rise were analyzed. 34% of participants had a front coat length larger than the maximum size requirement of 74 cm. Even with the required ease of 2.5 cm + extending below the top of the hip line, a large portion of the wildland female firefighters in this study would be wearing shirts that were not long enough for them. Couple that with ill-fitting pants that may not possess a high enough front rise and the risk for exposure, especially when arms are lifted overhead, can occur. For front pant rise, 33% of participants would not fit into a wildland pant according to the NFPA 1977 sizing requirements. For back rise, 100% of all female firefighters scanned had back rise lengths less than the minimum sizing requirement for the smallest size pants. When considering the ease measurement of 28 cm for back pant rise, even the smallest back pant rise measured (18.4 cm) would far exceed the maximum pant size of 43.3cm, indicating ease measurements need to be further considered for their inclusion in the standard. These data points are in line with a majority of qualitative feedback received during the focus groups that the crotch area is the most ill-fitting area due to excess length which prohibits their mobility.

4.4 PPC ill-fit and increased risk of exposure

Ultimately, findings from the questionnaire, focus groups, and anthropometric sizing system comparisons highlight the great need and opportunity for female firefighter wildland PPC development and improvement. It is evident by the results of the questionnaire, with only 10% of female firefighter respondents wearing women's cut PPC, that few offerings are available. In the structural space, "women's gear" has been manufactured for over 2 decades, albeit with many issues that remain to this day, however, even fewer options are offered in the wildland firefighting space for women. With almost half of the questionnaire participants indicated they perform both types of firefighting activities, and therefore must wear both types of PPC, it is imperative that the fit and sizing of structural and wildland clothing be designed in such a way that the same female firefighter can fit into both. From our anthropometric comparison analysis, however, that is not the case.

Far more participants fell within the structural firefighting sizing requirements in NFPA 1971 than those for wildland PPC in NFPA 1977. It should be considered that wildland PPC must meet almost four times as many sizing requirements as structural PPC, however, much larger discrepancies were found in the wildland sizing system than the structural sizing system when assessing the same four measurements. Further, a significant portion of female firefighters in this study fell outside all wildland sizing requirements except for hip circumference. In general, results demonstrate that the wildland sizing system is too narrow and/or too oversized in most all measurements, with exceptions. For example, in the waist measurement where the smallest waist measured in this study was 71cm, the NFPA size range begins at 58 cm and only goes to 94cm, with the maximum waist measurement in this study being 124 cm. A third of the wildland waist circumference size range was irrelevant on the lower end and it was far too narrow to capture larger waist measurements for the sample collected in this study.

These anthropometric results are supported by female firefighters' fit perceptions as evidenced by the outcomes of the questionnaire with more female firefighters being dissatisfied with their wildland PPC at 36% than their structural PPC at 27%. Further, respondents indicated they leave off their wildland PPC (21%) at a greater rate than their structural PPC (15%). This could, in part, be due to the inherent differences in the two types of firefighting with wildland posing less of a direct thermal exposure threat, in some cases. But in terms of smoke and carcinogenic exposure, when considering short term *versus* long term duration, the risk and concerns remain the same. Therefore, it is imperative that the issues highlighted in the results and discussion sections above pertaining to wildland PPC fit, especially in the interface areas, be addressed by the NFPA technical committees and end users.

5 Conclusion

This study includes the largest U.S. female firefighter anthropometric database for women's PPC. The results from this study indicate female firefighters are wearing PPC with significant fit issues that not only reduce their comfort and restrict their mobility but pose increased safety risks related to occupational exposure. Interface areas and wildland PPC have been identified as the areas of female firefighter protective clothing with the greatest opportunities for design and fit improvement according to the end user feedback and anthropometric data. With 40% of questionnaire participants indicating they wear both structural and wildland firefighting PPC, there is a large need to close the gap between how these two types of protective clothing are sized for women in the fire service. This study identified large discrepancies between minimum and maximum sizing requirements for female firefighters in the chest, sleeve

length, and waist areas. This identifies an opportunity to collaborate with the NFPA standard technical committees to close the gap between these two types of PPC in terms of sizing and their consequential fit for both women and men in the fire service.

The majority of questionnaire data highlighted the greatest need for fit and performance improvement lies within PPC for women in the wildland fire service. These findings were further supported by the anthropometric measurements when compared to the NFPA 1977 sizing standard. By far, there appears to be larger dissatisfaction with the fit and performance of wildland gear for women and greater discrepancies between female firefighter anthropometrics and the current sizing system for wildland PPC. This underlines a large opportunity to close the gap between sizing, fit, performance, and safety for women in the wildland fire service.

Additional research is needed on the fit and function of specific ensemble elements connected to the interface areas to ensure occupational exposure is reduced for women in the fire service. This study was the first to assess U.S. female firefighter anthropometrics and the user needs of both structural and wildland female firefighter PPC. Limitations of this research include the exclusion of all other PPE elements outside of the specific shirt, coat, jacket, and pants worn for structural and wildland firefighting operations. From end-user feedback in this study and previous research (Boorady, Barker, Lin, et al., 2013; Park et al., 2014), there is a great need to address improper fitting boots, gloves, helmets, hoods, self-contained breathing apparatus (SCBA), and face masks for women in the fire service.

This research was possible because of the recent development of remote body scanning technology, however, the lack of historical use of this type of technology presents a limitation. Additional work is needed to validate remote body scanning technologies in their correlation to pattern development, sizing development, and the ultimate resulting fit on the wearer. Future research should assess PPC sizing systems and prototypes created with the female firefighter anthropometrics gathered in this study to determine improvements in the fit and function of PPE for women in fire services.

Data availability statement

Data are not publicly available due to the privacy of the human participants involved.

Ethics statement

The studies involving human participants were reviewed and approved by Florida State University Institutional Review Board. The patients/participants provided their written informed consent to participate in this study.

Author contributions

MM (PI) and CK (Co-PI) led this research and the bulk of data collection. MP-B assisted with collecting 90% of the data and 100% of the anthropometric data. In terms of writing the paper, MM led the creation of the document and the writing of the introduction, methods, results, and discussion for the questionnaire and anthropometrics. CK wrote all material related to the focus groups and heavily edited the entire manuscript. MP-B pulled reports, assisted with writing the methodology and producing figures for the results. MP-B contributed to overall writing and editing of the entire manuscript.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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