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Structural firefighter personal protective clothing user needs in the US: a mobility perspective

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Abstract

Firefighting involves performing intense physical activity under a wide range of movements; thus, it is essential that firefighting personal protective equipment (PPE) allows for dynamic ergonomic mobility. Little research has been performed on structural firefighting PPE user needs in the United States (US) recently, especially that which has a specific focus on mobility to reduce the high incident rate of firefighter injuries. The purpose of this research was to investigate current structural firefighting personal protective clothing user needs in the US as they relate to ergonomic mobility. An online survey was designed and distributed *via* fire service organizations across the US to career and volunteer structural firefighters. Four hundred and twenty responses were received regarding the fit, mobility, comfort, and design of current turnout gear. Main areas of fit and mobility improvement were identified in the lower body region, specifically in the crotch area of the pants. Functionality features were also identified with priority given to interface integration, specifically in the hood/collar region, improved closure functionality, and enhanced tool and radio access. Additional comfort enhancing needs were expressed to further reduce heat stress such as clothing ventilation and other passive means of heat loss. This research confirms the continued need for turnout gear fit improvement such that firefighters can perform their jobs while experiencing less mobility restrictions and fewer injuries.

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Introduction

Firefighting is one of the most hazardous and challenging professions[1]. Firefighters are routinely exposed to hazards on the fireground, and work demands that require assuming awkward physical postures under heavy loads[2,3]. Additionally, they perform this work in weather-related temperature extremes in the presence of heat, flame, sharp objects, chemicals, blood-borne pathogens, and slippery surfaces[2]. Firefighters rely on personal protective clothing (PPC) and equipment (PPE) to protect them as their last line of defense from these numerous hazards[4].

The act of firefighting involves performing intense physical activity under a wide range of movements[5]; thus, it is essential that firefighting PPE allows for dynamic ergonomic mobility. However, to protect from thermal hazards, improvements in thermal protection have led to increased weight and bulk of firefighting protective gear, which have significantly compromised firefighters' mobility and comfort[1,5–7]. While structural firefighting PPE continues to evolve, the largest focus recently has been toward providing greater chemical and carcinogenic protection due to the prevalent rate of cancer amongst firefighters[8–11]. In fact, firefighting is now classified as a Group 1 known human carcinogen by the International Agency for Research on Cancer[12]. Injury rates, however, remain high with 118,070 non-fatal injuries reported on the fireground between 2016–2020[2]. Nearly a third of these injuries (27%) resulted in lost work time and 17% required treatment by a physician[2]. During this period, the third leading cause of injuries was directly linked to slips or trips with sprains and strains being the number one type of injury (24%)[2] which can be caused by ill-fitting and poor ergonomically designed PPE.

Structural firefighting PPE and ergonomic mobility

Structural firefighting PPC, or turnout and bunker gear as it is often referred to, typically consists of a three-layer garment system that includes the outer shell, moisture barrier, and thermal liner layers. These fabric and garment layers are manufactured from aramid fibers for heat and mechanical protection from harsh environments. The middle moisture barrier layer is often constructed using an e-PTFE membrane that is semi-permeable. The thermal liner layer is worn closest to the skin, or base layers, and typically consists of a woven facecloth quilted to at least one, if not multiple, nonwoven batting layers. Together, the moisture barrier and thermal liner provide 75% of the suit's thermal protection.

With thermal protection being of upmost importance, turnout gear continued to increase in weight, bulk, and thickness to achieve higher thermal protective performance (TPP) values to provide greater time for escape from second degree burns[1,5]. As a result, the prevalence of heat strain and reduced ergonomic mobility continued to rise, with overexertion and stress being the leading cause of acute firefighter fatalities since the National Fire Protection Association (NFPA) began collecting such data in the 1970s[13].

Previous studies have assessed the ergonomic impact of commercially available turnout gear[14–19]. These studies have found numerous issues throughout the turnout coat and pants in relation to pinch points, lowered range of motion, fit and sizing issues, and differences between firefighter sex (male vs

female)[1]. Little has been done, however, to determine potential design solutions for improved mobility. Therefore, assessing the user needs of structural firefighters in the US is necessary to determine what specific areas of their PPE need prioritized improvement.

Structural firefighting PPC user needs

The user needs of structural firefighting PPC and PPE in the US have not been gathered in recent years, nor has specific attention been paid to the need for mobility improvements[5–7,20]. Barker et al. conducted focus groups (n = 67) of male firefighters to determine their greatest PPE needs[6]. Findings from this study indicated there were issues with the fit of the pants, dexterity of gloves, boot height, poor breathability, and hindered mobility[6]. Park et al. laid the foundation for additional user needs research including work that also involved focus groups (n = 54; female = 6)[7]. The findings of Park et al.[7] reiterated those of Barker et al.[6] and identified ergonomic design issues with a specific focus on PPE elements in interface areas including the boots, gloves, helmet, and self-contained breathing apparatus (SCBA).

More recently, an assessment of Portuguese firefighters' needs was conducted *via* a pilot study. This study involved an online survey and participant interviews which determined participants experienced reduced mobility[5]. While this study is timelier and more relevant, it focuses on European firefighting PPE which is significantly different from that of the US. Other PPE user need studies have focused on wearable technologies, smart textiles, and e-textiles[21,22]. These studies relied on end user surveys to investigate current PPE technologies for firefighters across the globe. Findings demonstrated that while imaginable solutions exist for most all unmet PPE needs, integration requires specific attention to the harsh use conditions of the fireground[21]. Further, PPC mobility was not a priority of these studies.

In reviewing previous scientific literature, little to no research has been carried out on structural firefighting PPE user needs in the US in recent years, especially that which has a specific focus on PPC mobility to reduce the high incident rate of firefighter injuries. Therefore, the purpose of this research was to investigate current structural firefighting PPC user needs in the US as they relate to ergonomic mobility. PPC designers, product developers, and manufacturers will benefit from this research as it may lead to design improvements for injury rate reduction.

Methods

To determine the mobility perceptions of structural firefighter turnout suits, a Qualtrics survey was designed and distributed *via* email across the US. The survey was developed as part of a larger, multi-stage project. As such, only the data relevant to the mobility stage of this research project will be discussed in this article. To reach our intended population, organizations such as the Florida State Fire College, local fire departments, and the Fire Industry Education and Resource Organization (FIERO) assisted with the dissemination of the survey. The Institutional Review Board (IRB) from the researchers' institution approved the questionnaire and participant recruitment activities. Data was collected from career and volunteer firefighters throughout the US.

The questionnaire was developed in blocks (Appendix A), with six different blocks addressing different types of questions (quantitative and qualitative) as well as looking at different areas of interest as it relates to the PPE suit. Quantitative questions addressed demographic information, as well as perceptions of fit, mobility, and PPE design features. Demographic data included age, gender, ethnic group, service type (career or volunteer), service commitment (full or part-time), years of experience, rank in fire service, and current city and state of service. Perceptions of PPE fit, mobility, and design were measured with yes/no, and 5-point Likert scale questions rating the user's satisfaction of their turnout suits with additional space available for further explanation. The perception questions were directed toward specific identified areas of the turnout suit (i.e., chest, shoulder, elbow, etc.) as well as interface areas (i.e., boot/pant, sleeve/glove, etc.).

The final block of questions contained qualitative questions in a semi-structured format; first defining the topic in question, then encouraging the participants to provide additional, meaningful, descriptive responses. These questions gathered specific information about the fit of their current PPE suits, the perceived mobility and range of motion of specific areas of their turnout suit and requesting descriptors of what they perceived the current issue(s) was if they considered their gear to fit improperly or restrict mobility. The final questions in this block inquired about possible improvements they would like to see that might be included in future iterations of the gear (i.e., venting, lighter weight, alternative closure options, etc.).

Descriptive statistics of participants' demographic information and perceptions of mobility were collected. Data were analyzed following the statistical analysis methods of similar previous studies[23–25]. Written comments provided by the firefighters were coded by three independent researchers using an interpretive thematic analysis approach, then grouped into overarching themes[26].

Results

A total of 420 questionnaires were completed online *via* Qualtrics. Not all questionnaires were complete; however, to gain as many perceptions as possible, all responses were included in the collected data. As a result, the reported sample size for each question and figure varies. The data collected represents active career and volunteer firefighters that perform firefighting duties across multiple regions of the US.

Participant demographics

Most participants were male (95.62%; 349/365) between 30–59 years of age (83.2%; 302/363) and Caucasian (87.9%; 333/379). The majority were full-time firefighters (91.5%; 332/363) with most participants having more than 10 years of experience (82.9%; 301/363). The median years of experience was 20 years; the minimum number of years was 1 and the maximum number of years was 49. The rank of participants was varied, but the highest percentage of respondents (29.9%; 109/364) indicated they were fire chiefs. A similarly high percentage of the respondents (24.2%; 88/364) were firefighters. The higher number of fire chiefs completing the questionnaire is likely due to the organizations that assisted us in our survey distribution. Our participants represented all regions of the country; however, the Southeast had the largest percentage of responses (63.3%; 231/365) and the Southwest had the smallest percentage of surveys completed (5.2%; 19/365).

Structural firefighting PPC fit

The ultimate focus of this study was on mobility; however, much of the mobility is dependent upon properly fitting turnout gear. As such, the questionnaire first inquired about fit. This section of the survey first asked directed questions, such as 'Do you believe your turnout suit fits properly'. If their answer was no, they were asked to elaborate further. The individual responses were coded first into general areas of concern (i.e., coat, pants, weight distribution, mobility, bulkiness, etc.) that were then further coded by more specific areas. For example, if the respondent indicated they had bulkiness issues (F.) then further went on to describe bagginess of the coat (1.) and even further classified as extra fullness in the arms (a.) the comment would receive a code of (F.1.a).

Most of the survey respondents perceived that their turnout suit fit properly (78.1%; 266/342). Of the nearly 22% of those who responded no, many discussed issues of general fit problems, rather than of specific areas of concern. Comments about how fit was determined, ('our agency does not work with a trained individual from that distributor or brand that is certified to fit bunker gear') and dimensional changes, both increases and decreases, of the respondents over the lifetime of the gear were common issues, ('I have gained some weight since I was issued this gear', or 'was issued to me prior to weight loss'). Beyond general fit issues, the bagginess of the turnout suit was the second most frequent comment, ('loose fitting and very bulky'). However, in contrast, the gear being too tight was the next most common set of responses, ('my current gear was not designed for a male with larger shoulders, so range of motion is hindered').

To further determine how the firefighter participants associated fit with range of motion, respondents were asked to rank from, 'not at all important' to 'extremely important', the correlation between fit and motion. Over 70% (71.1%; 243/342) considered fit as extremely important and nearly 30% (28.1%; 96/342) considered it very important. A similar question asking the participants' level of satisfaction between the turnout suit and interface areas (including the neck/collar; sleeve/glove; coat/pant; and boot/pant) was investigated. The firefighters were most satisfied, with rankings of 'somewhat satisfied' to 'extremely satisfied' for the interface between the boots and pants at 85.1% (291/342), 83.9% (287/342) for the coat and pant interface, 81.0% (177/342) for the sleeve and glove interface, and 77.5% (165/342) for the neck and collar interface. Although most interface areas were generally considered satisfactory, the neck and collar interface had the lowest satisfaction ranking, with 11.4% (39/342) being extremely or somewhat dissatisfied with this area.

To drill down even further, the respondents were asked to rank on a scale of 'extremely dissatisfied' to 'extremely satisfied', 19 different areas of the turnout suit. Of the identified areas, 12 (coat length, chest, upper back, shoulder, sleeve length, armhole, upper arm, elbow, forearm, pant length, calf, and ankle) had at least 80% of the respondents ranking these areas as somewhat or extremely satisfied. An additional six areas (neckline/collar, wrist, waist, hip, thigh, and knee) were ranked as somewhat or extremely satisfied by at least 75.5% of the respondents. The lowest ranking area was the crotch, with only 69.3% considering the area somewhat or extremely satisfied, and 14.9% (51/342) considering this area extremely to somewhat unsatisfactory. Expanding further on the fit of the crotch, the survey asked respondents to identify the pant rise that they preferred. A mid-rise pant, designed to fit between the hips and belly button was preferred by 68.4% (234/342) of the respondents, with an additional 22.8% (78/342) preferring a high rise (sitting at or above the belly button) fit and 8.8% (30/342) preferring a low rise fit (sitting on the hips).

Ergonomic mobility and range of motion perceptions

The next survey block focused on overall mobility and the range of motion available when wearing the turnout suit. Respondents were asked whether they perceived their current turnout suit to limit mobility and range of motion. Of the 264 respondents who answered this question, 36% (95/264) did not feel like their range of motion was inhibited, whereas 64% (169/264) considered their range of motion to be restricted. Of those who felt impeded by their turnout suit, 68% (124/184) considered that it affected the overall comfort of the gear, as well as their overall safety (39.3%; 72/183). Although the respondents were only asked to complete this specific question if they responded yes to the range of motion question, there were 15 additional people who responded to this question, so percentages could be slightly skewed.

To determine the area of the turnout suit that firefighters considered the most problematic in terms of mobility and range of motion, respondents were asked to choose one of seven specific areas (shoulder, upper back, elbow, seat of the pants, knee, crotch/groin, and other). Two areas, the crotch (25.8%; 68/264) and the shoulder (25%; 66/264), were considered the most limiting areas in terms of mobility. Of the 26 respondents who chose other in the above-mentioned question, the wrist was identified by four firefighters and the thigh by an additional two firefighters. There was no duplication in answers from the remaining 20 respondents. In contrast, the respondents were asked to identify the area that provided the greatest freedom of movement, from the same list of seven areas. The knee was rated as providing the greatest mobility (21.6%; 57/264). Contradictory to the previous question, the shoulder provided a good range of motion by 20.1% (53/264) of those responding. The upper back (17.8%; 47/264) and elbow (17.1%; 45/264) were also considered areas with high ease of movement. The shoulder being considered as both restricting and freeing in terms of motion may speak to the need for proper fitting gear, noting that nearly 22% of the firefighters did not believe that their current suit fits them properly.

Next, the survey respondents were asked to identify the top three most important areas of their turnout suit for improving range of motion. This question included a list of 13 different areas listed in order of importance: the shoulder (22.5%), knees (18.0%), crotch (15.1%), upper back (10.1%), seat of pants (7.7%), waist (6.9%), underarm (6.2%) elbow (6.1%), hips (3.7%), wrist (2.5%), ankles (.4%) and calves (.1%). The shoulder, knees, and crotch were considered the top areas that could be improved in range of motion. A reverse question asking for the respondents to identify the three least important areas for improving range of motion confirmed the findings from the previous question, with the ankles (23%), calves (19.2%), and forearm (13.3%) considered the least important areas for improvement.

Understanding that range of motion can be task dependent, the questionnaire asked respondents to rank their level of

satisfaction ('extremely dissatisfied' to 'extremely satisfied') in terms of range of motion for 15 specific garment areas while thinking about the common actions of walking, bending over, kneeling/crawling, and reaching out/pulling down. Not surprisingly, for walking, the respondents who were either extremely dissatisfied or somewhat dissatisfied identified the crotch (17.8%; 47/264), knee (10.2%; 27/264) and waist areas (9.9%; 26/264) as most restrictive. All areas were ranked as 'extremely' to 'somewhat dissatisfied' by at least one respondent.

When respondents were asked to consider their turnout suit mobility when bending over, the level of dissatisfaction increased with eight areas providing significant levels of dissatisfaction; crotch (19.6%; 52/264), waist (17.4%; 47/264), seat of pants (16.2%; 43/264), shoulder (13.2%; 35/264), upper back (12.8%; 34/264); hip (12.5%; 33//264); knee (12.1%; 32/264) and back (10.9%; 29/264). As the action of the firefighter increases in difficulty, so does the dissatisfaction with their turnout suit. When considering kneeling and crawling, only the chest, wrist and ankle areas received dissatisfaction scores lower than 10%. All other areas had dissatisfaction levels above 10%, with the crotch (26.5%; 70/264), knee (25.8%; 68/264) and shoulder (17.8%; 47/264) having the highest levels of dissatisfaction.

Dissatisfaction areas shifted slightly as respondents were asked to consider reaching out and pulling down. When considering this movement, similar to performing overhead motions during overhaul, the levels of dissatisfaction focused primarily on areas of the coat, with the shoulder (26.9%; 71/264), upper back (20.5%; 54/264) and sleeve (18.9%; 50/264) providing the highest levels of dissatisfaction. However, even when considering reaching out and pulling down, the crotch still led to dissatisfaction (10.6%; 28/264). Figure 1 reflects the combined data for the 15 different turnout suit areas and the four firefighting tasks in one table.

PPC comfort and functionality

In the next questionnaire block, a section on design related questions asked participants about the current comfort of wearing their PPC as it related to mobility restrictions. Participants were first asked to indicate their level of satisfaction with the comfort of their turnout suit in multiple areas. Figure 2 reflects the percentage of participants that were either dissatisfied or neutral in their satisfaction towards the wearing comfort of their turnout suit. These results indicate firefighters experience the most dissatisfaction with comfort in the lower body, specifically in the crotch, knees, hips, and seat of pants. This was closely followed by the pant waist as well as the shoulders in the turnout coat. These findings related to discomfort are similar to the areas identified for restricted mobility.

Participants were also asked what features might offer more comfort through changes in their turnout suit; 18.3% wanted lighter weight gear and 7.0% desired more freedom of movement and mobility. Similarly, 13.4% desired softer and more flexible materials to be able to move more easily. A few participants (3.7%) mentioned vents for air and heat flow, along with overall heat management (7.0%). An additional 5.9% desired thicker padding for increased protection in the knees and shoulders while others expressed the need to reduce bulk (less thickness and padding). Most would redesign their gear (34.2%), specifically in the crotch region (31.3%).

Respondents were then asked where they experience the most pain or discomfort and pinch points in their turnout suit. Figure 3 provides the percentage of participants that experienced issues of pain and pinch points which could lead to movement restriction and reduced mobility. Of the respondents, 22.3% (123/552) cited the shoulder area as being the most painful or uncomfortable, followed by the crotch (18.7%; 103/552), knee (16.3%; 90/552), and upper back (10.5%; 58/551). Pinch points occurred most frequently and equally in the crotch and knees (20.9%; 102/487) followed by the shoulder (15.4%; 75/487) and elbow (13.1%; 64/487).

To avoid the above pain and pinch points, some firefighters employ countermeasures to improve their comfort and mobility. The most frequently reported countermeasure used was suspenders (36.6%; 171/467) followed by wearing a proper fitting turnout suit (30.4%; 142/467). This statistic demonstrates there is no substitute for proper fitting gear. Other reported countermeasures included using a belt (13.1%; 61/467) and wearing an oversized turnout suit (10.7%; 50/467) to provide more room for movement. Participants were given the opportunity to add 'other' responses to this question, some of which included, 'removing items from my pant pockets prior to donning the gear helps to reduce the tightness in the thighs', 'limit thickness of clothes under turnout', and 'keep neck flap very loose or off'. Removing critical tools from pant pockets and not wearing the collar appropriately reduces wearer safety. Specifically in terms of weight distribution, participants were asked which mechanisms they currently use including suspenders, belts, or a combination of both; 55.7% (131/235) indicated they only wear suspenders, while 37.5% (88/235) wear a combination of belt and suspenders. Only 5% of participants (12/235) indicated they wear a belt alone to distribute weight around the waist and maintain proper fit of the pants.

The design section of the survey concluded by asking questions pertaining to PPC functionality. Participants were asked to identify the top three features, when provided a list of nine, that would increase the functionality of their turnout suit the most. As shown in Fig. 4, replaceable padding inserts, such as in the shoulder and knee, were selected most frequently at 18.2% (112/614) followed by an integrated collar/hood interface (15%), internal radio pocket integration (12.9%), a weight distribution belt (12.5%), and a high-low coat hem design (12.2%). Other features such as alternative closures, side-entry pockets, tapered pant legs, and high back pants were also included. Additionally, 51% (120/235) indicated they might consider a diagonal front access entry zipper, with 23.8% indicating a definite 'yes' and 25.1% indicating 'no'. A human-factors design feature such as this could improve the ergonomic function and quicken don/doff time, which can be essential to firefighter and victim safety.

Lastly, participants were asked to provide their thoughts on specific design details they would like to have incorporated into their turnout suits to make them more functional. Responses pertaining to pockets, including the need for internal radio pockets, tool slots, along with deeper, reinforced pockets with easier access were identified by 41.1% of the respondents. The need for an integrated hood was mentioned by 27% of respondents (49/180) along with the need to replace the traditional hook and loop (Velcro®) closures (17.22%). Other features mentioned by respondents included built in harnesses, boot and pant attachment, microphone attachment, heat vents, tapered design, interchangeable outer shell, articulated joints, replaceable padding, and an internal cooling system.

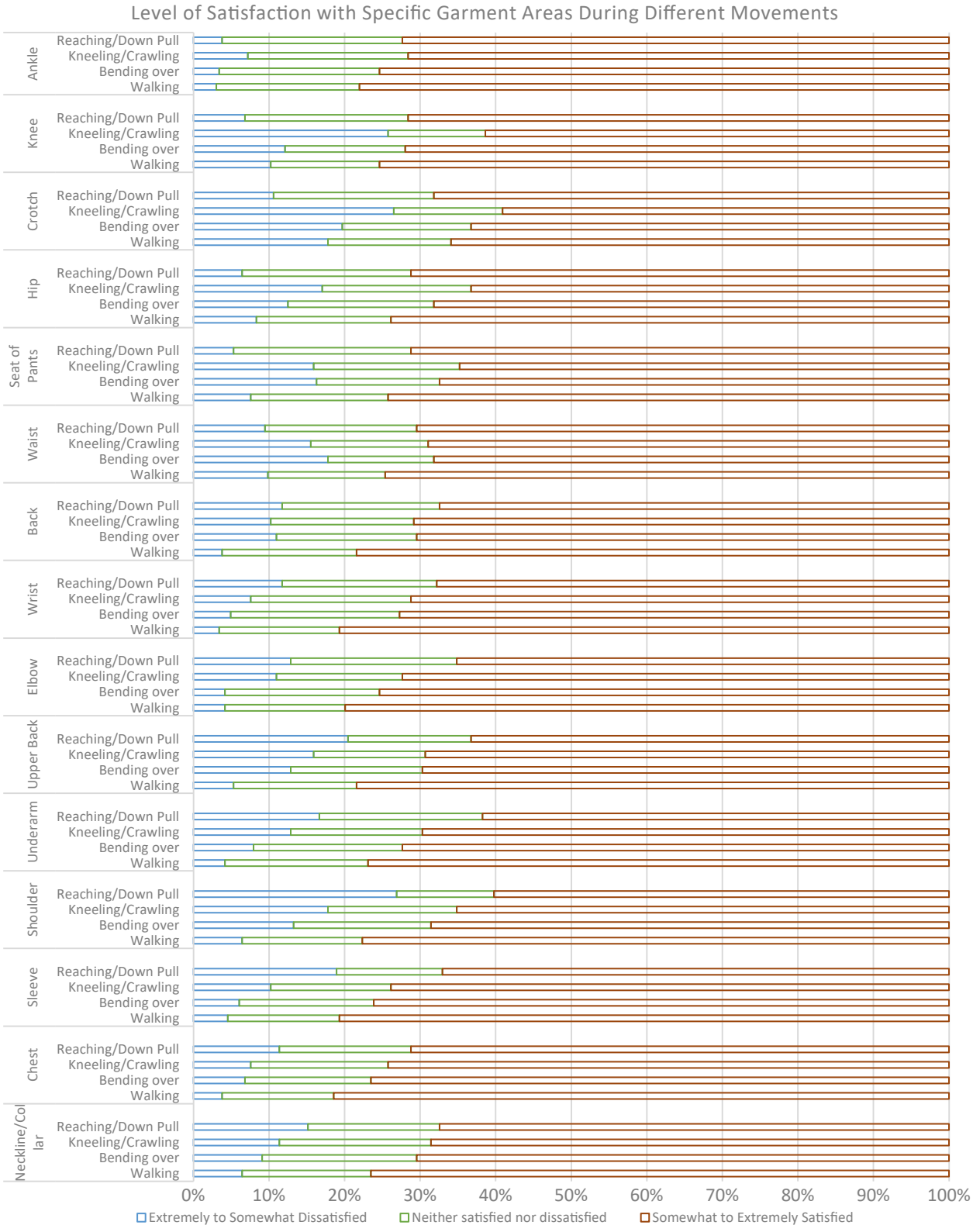

Fig. 1 Percentage of participants who were dissatisfied, neither, or satisfied with specific areas of their PPE while conducting common job-specific movements.

Discussion

Results of the firefighter user needs survey illustrate significant opportunities for structural firefighter turnout suit improvement, especially in terms of fit and mobility. In addition, the need for interface integration, streamlined pocket and radio access, and easier closure systems were mentioned

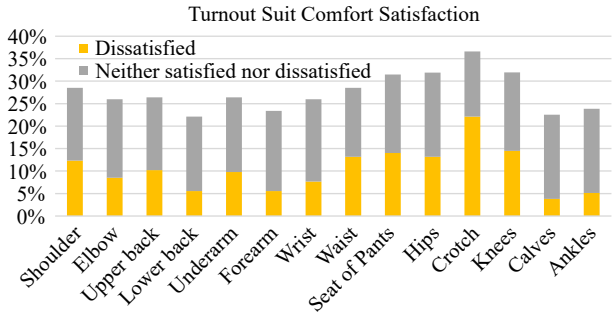

Fig. 2 Percentage of participants that were dissatisfied or neither satisfied or dissatisfied with the comfort of their turnout suit.

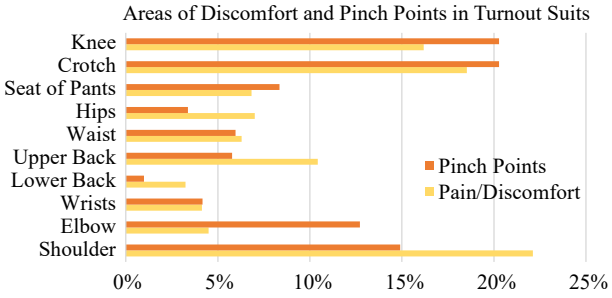

Fig. 3 Areas of the turnout suit that exhibit the most pain/discomfort and pinch points.

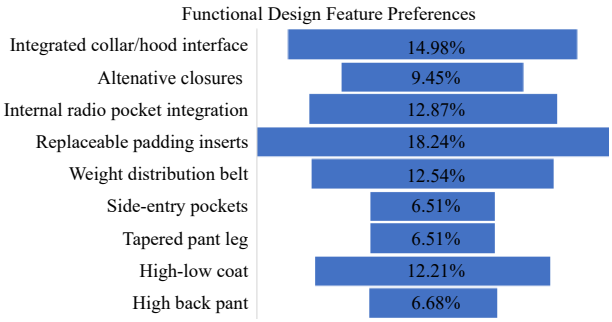

Fig. 4 User need preferences for each functional design feature.

frequently by multiple respondents, indicating a need to address specific functionality enhancing features. These and other important findings are discussed in more depth below.

Need for improved fit and mobility

As one participant responded in this study, 'each and every suit should be measured, not out of the box fitting'. In many cases, the fitting process of structural firefighters is inadequate. Some departments issue ill-fitting 'hand-me-down' gear either out of budget necessity or department protocols, resulting in poor fit from the start. Other departments may follow a formal 'sizing' process in which sales representatives from PPE manufacturers may visit the station with sizing sets and/or tape measures to take a small sample of measurements. Often, the sales representatives, or in some cases, even fire department representatives, are not adequately trained in taking hand body measurements. Further, the current NFPA 1971 *Standard on Protective Ensembles for Structural Firefighting* only requires two measurements in the upper body (chest circumference and sleeve length) and two measurements in the lower body (waist circumference and pant inseam) to properly 'fit' firefighters[27]. This combination of inadequate and inconsistent sizing protocols, along with minimal sizing requirements per the standards, leads to the bulky, oversized, ill-fitting gear issues demonstrated in the results of this study, and others[6,7,28–30]. Barker et al.[6], Park et al.[7], Boorady et al.[28], and most recently, McQuerry et al.[30], found significant fit issues for both male and female structural firefighting PPE. All these previous studies found the most significant improper fit issues occurred in the lower body regions, specifically in the crotch, hip, and waist. This larger and more recent sample of firefighters confirms that, despite knowing these issues for a decade now, these problems are still persistent.

Improper fit, especially in the lower body, leads to reduced mobility. The crotch is consistently the worst fitting area causing the highest levels of dissatisfaction for firefighters. As a result, the crotch area requires firefighters to make the most movement modifications out of the entire turnout suit system. What is known from a design standpoint is that the crotch provides the most movement when the crotch seam sits close to the body, right at the top of the thigh. Therefore, it makes sense that if the pants are improperly fitted, or do not remain at the correct location, or height, then movement is restricted. Further design changes may increase mobility issues, but what remains to be determined is how much of this issue lies in poor design vs improper fit of the pant in the waist area. The survey asked for the wearer's preferences for low-, mid-, and high-rise pants. Depending on the PPE manufacturer, custom crotch rise variations are available; however, firefighters may be wearing their pants at the level they prefer rather than where the pants were designed to fit. For example, a pant designed to be worn at the true waist that is currently worn mid-rise, will never provide the mobility for which it was designed.

Changes in body dimensions during the life of the assigned turnout suit (typically 10 years per NFPA 1851 standard requirements[31]) can also dramatically impact where firefighters' turnout pants sit on the body. Participants in this study noted that they were no longer the size they were when their gear was assigned. Reduced physical fitness across the span of their careers has resulted in larger mid-sections leading to improper fit of the pants at the waist, or more often, the need to wear the pant at a lower waist height, resulting in an improperly fitting crotch height. This issue is supported by the fact that 73%–88% of male firefighters are obese[32,33]. On the opposite side of this issue, firefighters newer to the discipline noted that they lost weight after a few months on the job but having already been assigned their gear, they too experienced problems with poor fit in the crotch. Albeit the opposite cause (weight loss instead of gain), the result is the same in that the pants are still not worn at their designed height. Regardless of the cause, wearing the pants at an unintended waist height leads to improper placement of the crotch, limited mobility, and discomfort in the groin region. Design innovations, such as alternative gusset shaping, have the potential to improve garment movement, particularly in the crotch area, but no design improvement will make up for improperly fitting gear.

The knee was identified as another area of concern and improvement needed by the firefighters in this study. However, like the effect that improperly worn pants have on the crotch, the same can be seen in the knees. If knee height and padding placement are incorrect, then movement will likely be restricted or impeded, creating pinch points. The addition of

further articulation and padding could greatly benefit firefighters, particularly when they are crawling and squatting. Increased differences between front and back pant leg length could also assist in reducing pinch points behind the knee, although this design change would alter the hang of the pant when standing upright. Improved functionality of the pant is still possible, but only if the pants are fitted to hang at the correct knee height on the body.

Another area found to have improper fit, mobility restrictions, and pain and pinch points in this study was the shoulder. Unlike the pants, the coat sits directly on the shoulders, thus how the coat rides on the body is not as much of a variable. However, the coat still needs to hang properly, have the correct amount of ease, and the sleeve seam should be correctly placed to increase arm mobility. Nevertheless, fit is not as critical in the shoulder area as it is in the crotch and the knee regions. Findings from the questionnaire support these design and anthropometric differences between the upper and lower body. However, what is important is how the coat fits when worn with the SCBA. Like previous studies, the interaction between the coat and the SCBA is critical to the movement and comfort of the wearer[34]. Design features that enhance the wearability and movability of the coat while allowing for the SCBA is crucial, while still considering the potential for added bulk and weight. A bi-swing coat, with expansion pleats, is one technique that allows for additional range of motion while not being as affected by the SCBA and its straps. This is not a new technique but needs additional design considerations moving forward.

Design features for enhanced comfort and functionality

Ultimately, there are various solutions to potential causes of improper fit and mobility. Improving the design of the crotch gusset can improve mobility if worn correctly; reducing bulk in the upper body can minimize pinch points; and tailoring the pattern so that it is more form-fitting can lead to less movement restrictions. Other factors, however, need improvement as well including enhanced standardized sizing systems and increased education and training of PPE sales representatives and department PPE coordinators in relation to measuring, sizing, and fit evaluations[30]. With the wide range of body shapes and sizes, an expanded sizing system may work better for the fire service industry. For example, rather than simply checking chest and waist sizes, a system based on body shape (round, rectangle, inverted triangle) could be included, in addition to measurements, to provide a more accurate fit, and therefore more mobility for the wearer.

Further exploration of design features that have not typically been utilized in PPE might also benefit the wearer in terms of fit, comfort, and mobility. A more forward-thinking approach to turnout suit design might dramatically increase the functionality. This approach might include features such as an asymmetrical coat entry, a T-tab collar, an integrated hood and collar, alternative closures, etc. Venting of the turnout gear might also be considered to decrease heat stress if a system could be designed that still maintained thermal, moisture and chemical protection requirements[35,36].

Other factors, still, fall outside the ability of even PPE designers, producers, and manufacturers to solve such as department selection and budget restrictions, gear availability, firefighter physical fitness across useful wear life, and other uncontrollable changes in body composition, such as pregnancy for female firefighters[37]. Some suggestions beyond design improvements include revisions to the NFPA standard to include additional sizing requirements in the upper and lower body, a potential exchange or inventory program to accommodate physical changes (weight gain, weight loss, pregnancy, etc.) across career decades due to the NFPA 1851 10-year retirement age and encouraging firefighters to speak up if their gear is ill-fitting. This last point is especially true for new trainees and academy graduates who often receive hand-me-down gear or experience large changes in body composition throughout training that can lead to their custom issued gear no longer fitting once on the job at the station.

Limitations of this study include the high response rate from local Florida participants. Larger samples from other regions of the country may lead to different outcomes such as the need for more insulation in the colder, winter months. This study was also limited to structural firefighting PPC and did not consider additional firefighting ensemble elements, including the helmet, hood, SCBA, boots, or gloves, beyond their interfaces with the turnout coat and pant. In addition, this study did not consider other types of firefighting PPE including wildland gear, wildland urban interface (WUI), proximity gear, or station uniforms. All the above are important types of firefighting PPC with their own potential set of user needs and problems to solve. As such, they should be investigated moving forward.

Conclusions and recommendations

This study provides the first comprehensive overview of current structural firefighter PPC user needs in nearly a decade. Main areas of fit and mobility improvement were identified in the lower body region, specifically in the crotch area of the pants. This research confirms the continued need for turnout gear fit improvement such that firefighters can perform their jobs while experiencing less mobility restrictions and fewer injuries. Functionality features were also identified with priority given to interface integration, specifically in the hood/collar region, improved closure functionality, and enhanced tool and radio access. Additional comfort enhancing needs were identified to further reduce heat stress such as clothing ventilation and other passive means of heat loss. This survey provides a comprehensive overview of the current state of firefighting turnout gear and the real time needs of firefighters on the job.

Future research should consider further analysis of the questionnaire data to identify correlations between fit, mobility, and other issues with the specific manufacturer and suit model worn. The researchers believe that firefighting manufacturers would greatly benefit from and value this data, which would be provided privately to each manufacturer. Second, focus groups would provide a valuable opportunity to further probe and gain insight into some of the results of this survey. Many questions remain that discussions through focus groups could help answer, like other studies[6,7,28,30]. Another area of future research would be to quantify the main regions of improper fit identified in this study, specifically in the lower body, through ease and air gap measurements, which can in turn have an impact on thermal comfort[38].

Finally, the researchers intend to take the findings from this survey and design a prototype turnout suit with enhanced

mobility, comfort, and functionality features such that firefighter performance is improved. One such way to assess full systems PPE functionality would be to follow the ISO/TS 20141 guidelines for compatibility testing of PPE which would ensure all ensemble elements interface and function appropriately together[39].

Author contributions

The authors confirm their contribution to the paper as follows: study conception and design: McQuerry MM, Schofield SS; data collection: McQuerry MM, Schofield SS; analysis and interpretation of results: McQuerry MM, Schofield SS; draft manuscript preparation: McQuerry MM, Schofield SS. Both of authors reviewed the results and approved the final version of the manuscript.

Data availability

All data generated or analyzed during this study are included in the published article.

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Conflict of interest

The authors declare that they have no conflict of interest.

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