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Function Design of Firefighting Personal Protective Equipment: A Systematic Review

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Received Date: September 14, 2020**Published Date: September 25, 2020****Abstract**

Firefighting is a hazardous occupation. It has a variety of risks associated with fatal and non-fatal injuries. To protect against heat and unsafe environment, firefighters wear personal protective equipment (PPE), including self-contained breathing apparatus (SCBA), boots, helmet, and thermal protective clothing, including coat, pants, hood, and gloves. To obtain knowledge of injuries and issues related to the functional design of firefighting PPE, especially firefighting PPE for female firefighters, a systematic review of related literature in related disciplines was conducted. It was found heavy and bulky turnout ensemble and inappropriate sizing system are the two dominant barriers to effective and efficient firefighting performance. Also, research on female firefighters' PPE is limited but highly demanded. Therefore, this review provides insights for improving the design, fit, and functionality of future PPE. In particular, it summarizes the design and sizing issues of existing PPE products, thus providing a valuable guide to the industry in improving future functional design and production of PPE. It also identifies critical knowledge gaps of firefighting PPE and specified future research opportunities, such as improving the design of firefighter PPE based on gender, height, age, and the category of firefighters.

Keywords: Firefighting; Personal protective equipment; Female firefighters; Functional design; Injuries; Safety; Performance

Abbreviations: PPE: Personal Protective Equipment; SCBA: Self-Contained Breathing Apparatus; NFPA: National Fire Protection Association; FEMA: Federal Emergency Management Agency

Introduction

In recent years, multiple countries and regions worldwide, such as Australia and California, have experienced the deadliest and most destructive wildfire in their history. For instance, according to the California Department of Forestry and Fire Protection, there were 5,924 fires reported and 1,059,583 acres were burned in California from January 1, 2020 through August 20, 2020 [1]. Those devastating fires drew a significant amount of attention to the protection and safety issues of firefighters.

Firefighting is an occupation with societal and moral importance, but hazardous [2]. Firefighters save not only physical property and environment but also people's lives and well-being [3]. Their duties range from responding to fire ground emergencies, including

structures fires, vehicle fires, brush fires, to a non-fire emergency such as rescue calls, hazardous calls, and natural disaster as the first responders in a community [4-6]. However, to perform those duties, firefighters expose themselves to substantial physical risks and psychological stress. They deal with life-threatening situations such as dangerous fire suppression scenarios, motor vehicle accidents, chemical hazards, burned bodies, and suicides. Additionally, they experience extreme psychological stress, particularly in failed rescue efforts, including knowing the victim and witnessing the death of a coworker [6,7]. Furthermore, firefighters' strenuous work may continue to a period of unpredictable duration under conditions of high environmental heat strain [8-11].

To enhance safety and improve performance, firefighters are expected to constantly enhance their physical body strength and wear advanced firefighting gear on duty. For example, they train on a regular basis to perform tasks that demand high muscular performance and motor coordination, such as the clearing of debris with heavy manual tools and roof work.

According to the 2015 United States Fire Department Profile, there were 29,727 fire departments domestically in 2015, which had 1,160,450 firefighters in total. Seventy percent of them were volunteer firefighters, and the rest of them were career firefighters [10]. On the other hand, half of the firefighters are forty or more than forty years old, and there were about 2170 female firefighters [10]. However, an increasing number of female firefighters have been choosing this occupation [12].

Personal Protective Equipment (PPE)

To protect against heat and hazardous environments, firefighters wear personal protective equipment (PPE), which includes a helmet, boots, thermal protective clothing (coat, pants, hood, gloves), and a self-contained breathing apparatus (SCBA) [13]. The design and production of PPE is regulated by the National Fire Protection Association (NFPA) 1971 and 1981 standards. NFPA has standard methods for rigorous testing of firefighting equipment. The purpose of these tests is to protect firefighters from flame and high heat and exposure to hazardous liquid, physical, and electrical hazards [14].

The PPE is necessary for the health, safety, and performance of the firefighting tasks. However, firefighters, particularly female firefighters, frequently reported dissatisfaction with their turnout gears [12,15,16]. For example, previous studies show that the heavyweight and bulkiness of PPEs increase the risks of injuries of the firefighters and limit firefighters' performance because it results in barriers to mobility and comfort [13,17,18].

Research objectives

The purpose of this study is to systematically review published literature related to 1) firefighters' duty associated injuries, risks, and issues in hazardous environment of firefighting, and 2) the current advancement in the functional design aspect of firefighters' PPE, particularly concerns related to female firefighters' PPE. Another goal of this review paper is to identify research gaps and provide recommendations for positioning new research activities.

Method

To achieve the objectives mentioned above, a systematic review, which is "a means of identifying, evaluating and interpreting all available research relevant to a particular research question, or topic area, or phenomenon of interest" was conducted [19]. The review process started with three keywords: firefighter, female firefighter, and personal protective equipment. These keywords were arranged in multiple combinations by using Boolean AND's to get sophisticated search strings.

Using the search strings mentioned above, related literature was extracted from Web of Science database, which has comprehensive peer-reviewed academic literature coverage. Primarily, 1164 literature published were found without a filter of time in the Web of Science database. The articles that did not address firefighting PPE and repetitive items extracted from more than one search strings were removed from the review list. Based on the title's relevance with the topic, then 111 literature were identified for abstract screening. Meanwhile, the researchers completed a batch of hand searches using Google Scholar to collect additional literature based on multiple publications' reference lists to ensure comprehensive coverage of related topics. Finally, forty-nine articles and eight other types of literature such as reports were identified for a thorough review.

Results

Analysis of publications distributed in various journals

In total, thirty-three journals published research on firefighters' protective equipment and the injuries related to firefighters' protective gear. Ergonomics published the highest number of papers (four). National Fire Protection Association, one of the leading sources of information and knowledge regarding fire, electrical, and related hazards, also published four papers on related topics [20]. However, twenty-three journals only published one article. Meanwhile, according to the articles' publication year extracted from both the electronic database and hand search, most of the articles were published after the year 2010. No relevant article was found before 1990 in the Web of Science database, although the search was not filtered by time.

Articles focusing on female firefighters

Very few articles focused primarily on female firefighters. Only nine out of the fifty-seven reviewed publications were centering on female firefighters (Table 1). Various issues of female firefighters' PPE were reported. It was particularly reported that it was more challenging for female firefighters than for male firefighters to find satisfying PPE and female firefighters tended to customize and/or alter their PPE [12,15].

Discussion

Injuries

According to a report on firefighter injuries issued by the NFPA (2016), approximately 62,085 firefighters were injured on duty in 2016. Among them, 39.2% of the injuries occurred during the fire ground operations [21]. The top three causes of fire ground injuries were identified as (a) overexertion or strain (27.1%), (b) falls, jumps, or slips (21.0%), and (c) exposure to fire products (13.6%) [21,22]. On the other hand, for several years, the NFPA has reported the sudden cardiac death as the number one cause of in-line duty deaths of the firefighter [23]. According to NFPA, in 2017, of the total deaths while on duty, sudden cardiac death (29 deaths) accounted for most deaths [24].

Injuries related to firefighting PPE: Firefighting PPE is critical to firefighters as it protects against heat stress, hazardous chemicals, gas, and physical collision [25]. Firefighters consider PPE's safety/protection, mobility, and comfort as the three most important factors when evaluating their gear [15]. To provide adequate and appropriate protections, as well as to satisfy firefighters' physical and psychological needs, the size and fit, fabrication, and design of a turnout ensemble should be well developed in a holistic manner.

According to an estimation between November 2005 and December 2009, there were four main reasons for firefighters' work-related burn injuries: improper removal or dislodging of equipment, failure of equipment to protect the firefighter (either because of equipment misuse or design flaws), training errors, and burns from sweat evaporation. A study found that faulty equipment design and misuse often (70%) resulted in steam or hot fluids entering the firefighters' turnout gear in vulnerable areas of firefighters [26]. Various studies also identified that weak areas usually are interfaces where two pieces of equipment overlapped or failed to overlap [26,27]. The integrity of protection in these interfaces is a significant issue for improving mobility, comfort, and safety. For instance, poorly-fitted pants frequently ride up above the boots, particularly when in a crawl position, exposing the calf to heat hazards [27]. Besides, the reasons why firefighters sometimes chose to work without PPE were also reported: (1) firefighters felt PPE interfering with physical performance, (2) firefighters felt donning gear might slow down a rescue, (3) firefighters were lack of knowledge relevant to PPE, and (4) some cultural factors unique to the profession [28,29].

Injuries related to the bulkiness and inflexibility of PPE: The bulkiness and inflexibility of PPE are the dominant factors of a significant number of injuries. They can limit firefighters' mobility while performing firefighting tasks such as climbing ladders, dragging hoses, and entering/exiting emergency vehicles [25,30]. First, the massive weight of firefighting PPE (approximately 55lb or 22.1kg in total) intensifies firefighters' fatigue with increased energy expenditure [17,31-33], causing stressful situation by long working hours and persistent sleep disorders due to prank calls (14.2% of the occurrences) [34]. Second, PPE's bulkiness increases blood pressure, heart rate, and the risk of cardiovascular diseases [35,36]. It also results in a physiological strain on firefighter [36]. For example, the massive weight causes fall-related injuries as it changes firefighters' center of gravity, flexibility, and mobility [37]. Third, various studies reported that the weight and design of PPE impair firefighters' functional balance and limit their range of motion (ROM) [30]. ROM refers to the range of angular displacement between the longitudinal axes of two adjacent body segments through which these two adjacent segments may move [38].

Injuries related to PPE turnout ensemble: Firefighters face various problems due to the flawed functional design aspect of their turnout ensemble (coat, pants, hood, gloves) in the fire ground. For

instance, firefighters sometimes have difficulty accessing cargo pockets while they are on duty, as the placement and design of such pockets are not appropriate [39]. The effect of personal protective turnout coats and pants becomes worse in wildfire activities [40]. In wild firefighting activities, in addition to the weight of different tools and extreme adverse environments, the additional use of the turnout ensemble counterintuitively increases the thermal strain of wildland firefighter [41]. Consequently, it limits firefighters' performance [42].

Properly fitted clothing enhances firefighters' ability to perform work tasks [43,44]. Too tight clothing can restrict movement, while too loose clothing can inhibit firefighter's movement and make them more likely to sustain injuries [43]. However, it can be difficult to achieve a proper fit, if garments are not available in size needed. The size and weight of the firefighter garments affect ROM to a great extent [5]. For example, undersized turnout coat and pants affect the hip flexion by reducing the average ROM for about 24%.

Poorly fitting turnout ensembles can restrict firefighters' body movement and comfort. The protective clothing should be moderately loose-fitting, so it contains an appropriate amount of space between the body and the garment. This type of space is the microclimate region [43], which provides a thermal layer to insulate firefighters from thermal hazards [43,44].

In terms of the turnout ensemble design, ergonomic design features such as the tail jacket, which gives participants an impression of lower garment weight burdens, the contoured jacket, which has a higher range of motion than the traditional cut type has, and the contoured knees which help with bending knees [31,32].

Regarding fabrication, the coat and pants have thermal protective features, including a flame- or fire-retardant outer shell, a moisture barrier, and a thermal liner. This encapsulated condition can lead firefighter to heatstroke and cardiovascular malfunction, leading to firefighter deaths on duty [33].

Injuries related to the PPE turnout boots: Structural firefighting boots might directly or indirectly increase firefighters' fatigue and risk of injury through overuse or altering gait cycle and increasing metabolic requirements [43]. For example, researchers found a higher heart rate associated with wearing firefighting boots than wearing sneakers [45]. Besides, multiple studies reported that the poor fit of turnout boot such as looseness and the high outsole is a primary reason for changes in gait and impair safety on the fire ground [27,46,47].

Firefighting turnout boots have a negative impact on firefighters' ROM. For example, boots height may limit firefighters in bending legs [48]. Stiff materials such as ridged outsoles, metal toecaps, and metal shanks are needed for protecting firefighters from the collision. However, these extra attachments can constrain the ankle movement and increase the risk of injury during landing [39]. Additionally, stiff materials, together with poor construction,

may result in faulty foot function, altered gait, and high flexing resistance [39,45].

Leather boot and rubber boot are the most commonly used two types of boots. Rubber boots can weigh up to 4.4 kg, which adds extra weight to a firefighter's already heavy garment and equipment load [17] and leads to more significant muscular fatigue [49]. In addition, the heavyweight rubber boots cause high metabolic rates and put a considerable burden on the firefighters due to further distance from the wearer's center of gravity [40]. Because of increased metabolic rates, the firefighter wearing heavier rubber boots needs greater oxygen uptake, more significant blood lactic acid, greater mechanical work production, and lower running speed than wearing lightweight leather boots [39].

Researchers' recommendations for improving firefighting boots design include reducing the weight and bulkiness, as well as increasing the flexibility of firefighting boots [39]. Moreover, since firefighters have difficulty taking off boots during quick recovery, two vertical zippers on both sides or a detachable design were proposed for quick doffing and donning [48]. However, few studies of firefighting boot focused on lowering body biomechanics and ergonomic concerns surrounding boot design. As a result, more works is demanded in these areas [45].

Injuries related to the PPE turnout gloves: Turnout gloves protect firefighters from sharp objects, fluids, flame, and heat; thus, firefighters' gloves need to meet specific performance requirements on fit, construction, and materials such as outer shell, moisture barrier, and thermal barrier [50]. In terms of fit, firefighters' gloves need to fit firefighters' multifaceted hand dimensions and shapes [50], as the fit of firefighters' gloves affects essential firefighting operation and the protection of firefighters [50,51]. For example, a tight-fitting glove can restrict finger circulation and increase the risk of burn and frostbite injuries. In contrast, loose-fitting gloves can hinder the accomplishment of finger dexterity and grip tasks [50].

In general, there is a lack of complex and consistent sizing system among manufacturers [27]. The sizing method of firefighter gloves contains several problems. According to NFPA (2012), glove sizing is critical in ensuring firefighter gloves' protection and performance. However, the NFPA standard determines the gloves' size mainly by hand lengths and girths, while the lengths and girths of individual fingers only work as supplemental measurements. More measurements are included in a sizing system, the greater likelihood of achieving a good fit [52]. NFPA's standards on gloves cannot ensure the firefighter hand variations and the excellent fit. Another challenge is the large accommodation range of glove sizes [50]. To minimize this problem, researchers proposed a cluster-based seven-size system of firefighter gloves to include both the overall size of hand and fingers as well as the breadth-to-length contrast instead of a single dimension at a time [50].

Furthermore, gender differences were not considered in glove

sizes. Thus, a comprehensive study of the anthropometric data of both male and female firefighters' hands is necessary to improve the sizing and fit of turnout gloves.

Injuries related to the SCBA: SCBA is essential for a firefighter to work in hot and dry environments filled with debris, fine airborne particles, and limited oxygen supply [34]. It is a pressurized bottled supplier of either air, oxygen (O₂) enriched air or pure O₂. It may also induce positive pressure inside the facemask to protect against the inhalation of atmospheric air in the event of a facemask leak [35].

SCBA has a significant impact on firefighter's discomfort and gait due to its heavyweight. The massive weight of an SCBA has a considerable effect on oxygen consumption and metabolic rate [35,54]. Besides, SCBA causes gait imbalance by changing the center of mass, which increases the risk of slipping trauma and causes fall-related injuries [14].

Moreover, firefighters experience restricted head and arm movement, soreness of shoulder, and back pain due to SCBA. The impact is more significant for a firefighter with a relatively shorter frame than a firefighter with a more extended frame. This is because shorter frame firefighters cannot place a SCBA further down on the back to avoid the helmet's back brim from hitting the top portion of the SCBA for ensuring neck mobility [54]. Accordingly, researchers proposed flat-pack SCBA for improving ROM, comfort, and fatigue reduction [27].

Besides, researchers reported issues with the shoulder harness for carrying a SCBA. It interferes with chest motion, affects breathing, and impairs ventilation and gas exchange [28]. Previous researchers and designers propose a design solution to add a soft and wide cushion on the shoulder and hip straps, so there is a better load distribution on the trapezius muscle [35]. Moreover, SCBA straps hinder access to the pocket, which impedes firefighters from reaching tools in the pockets when they need to use [27]. A functional design project covering both the turnout ensemble and SCBA needs to be carried to address this challenge.

Body size and physique variations

Occupational groups, such as firefighters, have body size or body segment measurements different from general populations [54,55]. The U.S. firefighter population's body size and physique are different from those of the general U.S. population [54,55]. For example, firefighters' upper-bodies were larger than those of the general U.S. population, suggesting firefighters require specialized sizing systems [54]. Moreover, researchers found that volunteer firefighters have less cardiorespiratory fitness than career firefighters. They have a higher obesity rate and more prehypertension than career firefighters. In addition, wearing full PPE, including SCBA, leads to an exaggerated systolic Blood Pressure and Heart Rate levels to volunteer firefighters than to career firefighters [36].

Besides occupations, studies showed that firefighters' hand dimensions are different among gender, race/ethnicity, and age groups [50]. For instance, black firefighters have more elongated hands than other race/ethnicity groups have [50]. Moreover, older firefighters have larger hands than younger firefighters [18]. However, very few studies were conducted on the effect of age on other body dimensions of firefighters.

Age of firefighters: According to a breakdown of the 2015 U.S. fire department profile, half of the firefighters are more than 40 years old [10]. However, more than two-thirds of the firefighters cannot meet the NFPA standard in their fifth decade of life. In addition, 43% of the female firefighters do not have the same fitness level to meet the aerobic benchmark from age 45 to 54. On the other hand, firefighters' job demands on physical work capacity remain the same across the age spectrum [55]. According to the 2017 report of firefighter fatalities in the United States, more than half of the firefighters who died of a heart attack were older than forty [24]. Thus, it was suggested that firefighters should increase their physical fitness throughout their careers and do less physically demanding tasks when they are getting old [56].

Female firefighter: Although male and female firefighters work side by side in highly strenuous and risky conditions, there is

limited information published involving female firefighters [5,57]. This lack of diversity in the published literature is due to, in part, difficulties accessing the relatively small population of female firefighters [57].

Neither male firefighters nor female firefighters are satisfied with their PPE, however, female firefighters are even less satisfied than their male counterparts [12,15,16,18,25]. Female firefighters tend to alter their turnout gear, but typically have difficulty receiving help when dealing with poorly-fitted gear [25]. Also, female firefighters also expressed psychological discomfort concerning the negative impact of wearing ill-fitted uniforms during public presentations [25].

Female specific PPE issues: The gender gap in the firefighting occupation has resulted in institutional barriers for female firefighters [58]. Most firefighting PPE are developed based on male body measurements or via a unisex sizing system, leaving female firefighters to adapt to the ill-fitting sized-down versions of men's gear [18,25,59]. Although women are a minority group in the firefighting occupation, they still deserve the same protective equipment as their male counterparts [18]. The research found that only 25% of North American female firefighters have access to female-specific PPE, and only 11.5% were satisfied with it [16].

Table 1: Articles related to Female Firefighters.

Author	Year	Journal/Other Sources	Title of the literature
Watkins ER, Walker A, Mol E, Jahnke S, Richardson AJ	2019	Women's Health Issues	Women Firefighters' Health and Well-Being: An International Survey
Jahnke SA, Poston, WSC, Jitnarin N, Haddock CK	2018	Maternal and Child Health Journal	Maternal and child health among female firefighters in the U.S.
Kirlin LK, Nichols JF, Rusk K, Parker RA, Rauh MJ	2017	Occupational Medicine	The effect of age on fitness among female firefighters
Park J, Langseth-Schmidt K	2016	International Journal of Industrial Ergonomics	Anthropometric fit evaluation of firefighters' uniform pants: A sex comparison.
Hsiao H, Whitestone J, Kau T, Hildreth B	2015	Human factors	Firefighter hand anthropometry and structural glove sizing: A new perspective
Park H, Hahn KHY	2014	Fashion Design, Technology, and Education	Perception of firefighters' turnout ensemble and level of satisfaction by body movement
Sinden K, MacDermid J, Buckman S, Davis B, Matthews T, Viola C	2013	Work	A qualitative study on the experiences of female firefighters
Boorady LM, Barker J, Lin SH, Lee YA, Cho E, Ash-down SP	2013	Journal of Textile and Apparel, Technology and Management	Exploration of firefighter bunker gear Part 2: assessing the needs of the female firefighter
Hulett DM, Bendick M, Thomas SY, Moccio F	2008	International Association of Women in Fire & Emergency Services	A national report card on women in firefighting

Female firefighters are more vulnerable to musculoskeletal injuries due to wearing ill-fitted gear, heavy and bulky equipment, typically designed for males [57]. One of the critical reasons is that, compared to male firefighters, female firefighters, on average, have lower body mass and weaker muscle strength. As a result, female firefighters, when carrying the same weight of fire equipment, experience a more significant physical burden. Besides physical imbalance, this heavier physical burden can directly cause cardiovascular malfunction and heat illness through a sharp

increase in body temperature in an encapsulated turnout ensemble [15].

These gender differences also have an impact on the fit of PPE worn by female firefighters. According to a previous study, about 79.7% of female firefighters experienced improper fitting equipment, which is four times greater than male firefighters' perception of ill-fit [12]. Specifically, more than half of female respondents of this study had fitting issues regarding the gloves (57.8%), because men's hand dimensions dominate glove design

even though the correlation between hand size and the hand/finger breadth-to-length ratio of females is different from that of males [47,60]. In addition, about half of female firefighters had a negative experience with boots (46.8%) and turnout coats/pants (38.9%).

Conclusion

The paper is a systematic review of published work on firefighters' duty-related injuries and issues related to the design and size of firefighters' PPE, focusing on female firefighters' specific problems. This review summarized various fire ground injuries associated with the functional design and sizing of firefighting PPE and highlighted literature related to a female firefighter. It also explored research gaps and identified future research opportunities.

Findings

This review summarized firefighters' injuries related to their PPE and the drawbacks of existing firefighting PPE. It identified dominant barriers to effective protection of firefighter and efficient firefighting performance. The first barrier is the heavy and bulky turnout ensemble, particularly heavy rubber boots and bulky SCBA. The second barrier is the inappropriate sizing system, particularly a lack of female-specific sizing system for female firefighters and improper sizing system of gloves [59]. Articles focusing on male firefighters dominate the research on personal protective equipment, even though the negative impact of PPE on females is more significant than that of males. One of the reasons for the lack of diversity is the lack of access to female firefighters in the firefighting occupation.

This systematic review of the articles provides insights for improving the design, fit, and functionality of future PPE. Improvements such as conducting human factor research, integrating ergonomic features, adopting functional design theory, framework and techniques, and valuing user input in the design and development process of firefighting PPE can all help improve firefighters' safety, performance, and satisfaction [18,30,60-62].

Implications for future research

Future research opportunities are listed as follows:

- Research and design practices in improving the functional design and sizing systems of firefighting PPE is needed. Particular attention should be placed on (1) reducing the weight and bulkiness of turnout ensemble, particularly boots, and SCBA, and (2) improve the sizing systems of turnout gear, particularly gloves.
- Female firefighters are more vulnerable to injuries than male firefighters are. However, most of the published work regarding the design of PPE and the health of firefighters was based only on male firefighters. More research focusing on improving the design, fit, and function of female firefighters' PPE is demanded.

- Design SCBA to accommodate the variations in firefighters' heights. Currently, the impact of SCBA on a relatively smaller frame firefighter is greater than taller frame firefighters.
- Enhance volunteer firefighters' performance and safety by ensuring cardiorespiratory fitness and designing PPE for this category of firefighters. It is reported that the major percentage of firefighters are volunteer firefighters [10]. However, volunteer firefighters are less cardiorespiratory fitted than career firefighters.
- The design of PPE may follow the firefighters' age spectrum.

Limitation

Web of science was selected as a database for this review. Although Web of science is an extensive database, including scientific, engineering, social science journals, the database does not include all related publications. Besides, only English publications within the Web of science were reviewed, which may exclude some relevant articles published in other languages. Thus, this study may not have included a few related papers.

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Conflict of Interest

Authors declare no conflict of interest.

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