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Original Article

An empirical investigation of firefighting personal protective equipment and burn injuries in Korea

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Abstract: This study aimed to investigate the current situation of firefighting burn injuries and personal protective equipment (PPE) in Korea using a questionnaire. A questionnaire was constructed and then distributed to fire stations via the Fire & Disaster Headquarters of Korea. Responses from a total of 536 firefighters who were currently responsible for suppressing fire or doing rescue work were analysed (39.2 ± 8.58 y in age, 173.8 ± 5.0 cm in height, 73.4 ± 8.9 kg in body weight). The results showed that 22% of firefighters had experienced burns but of these 93% of were burns of less than 1% of total body surface area. The most common body site of burn injury was the hands (37%) and the head (face and neck) (34%). There were significant relationships between PPE non-compliance and career years, especially for the hood and boots. According to firefighters their gloves were the most vulnerable part of their PPE. We also elucidated relationships between the body sites most vulnerable to burn injuries and PPE wear compliance by item. The present results suggest that officially-undisclosed minor burn injuries but prevailing among firefighters can be reduced through improving firefighters' protective helmet, hoods and gloves.

Key words: Firefighters, Personal protective equipment, Firefighting gloves, Burn injuries, Burn location

Introduction

Firefighters, by the nature of their jobs, are exposed to various hazards that may put them at risk of both fatal and non-fatal injuries. Therefore, they experience work-related injuries at rates that far exceed those of most other professions[1, 2]. According to recent statistics released by the Korean National Fire Agency in 2019, the number of Korean firefighting work-related injuries has been increasing steadily in the last 10 years[3]. Such injury rates among Korean firefighters are considerably higher than in other countries such as the United States, Japan, etc[4]. The U.S. Fire Administration reported that the leading firefighter injuries were strains/sprains, and other injuries related to mechanical trauma, while burns accounted for approximately 11%[5]. Although firefighters' burn injuries are not as prevalent as other injuries, they do remain one of the most disfiguring

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and psychologically taxing categories of occupational injury[6]. Severe burn injury is clearly a serious threat to physical health, but also to the psychological and social well-being of the individual[7]. However, limited data exist in the literature regarding the epidemiology of firefighters' burn injuries[8] and high-quality clinical data and outcomes regarding burned firefighters is insufficient[9]. Better quality data is a fundamental aspect of improving PPE and managing firefighting operations in a more appropriate direction for burn prevention.

The aforementioned high occupational hazards require firefighters to wear personal protective equipment (PPE). PPE use is often necessary because it can provide quick and primary protection from risks that cannot be fully controlled although it is the last and least preferred means to protect workers in the hierarchy of controls[10]. However, it may simultaneously bring about significant physiological strain and impaired mobility decline[11–14]. According to several previous survey studies on firefighters' opinions concerning their PPE, firefighters experienced discomforts like heat stress, impaired mobility, heavy physical workload and impaired balance while wearing PPE[12, 15–18]. It is generally understood that there is an inverse relationship between protection and comfort, i.e., the more protection, the less comfort and vice versa. In addition, a wearer who finds his or her PPE uncomfortable may be tempted not to wear the PPE, making it useless[19]. Hence, it is important to determine an optimal balance between protection and comfort in order to maximize firefighter safety. Optimal PPE comfort can be determined through investigating firefighters' evaluations and opinions of their PPE. And such optimally comfortable PPE will result in safer firefighters as they will be more likely to wear their PPE effectively.

Performance of firefighting PPE has been steadily improving in Korea since the huge 2001 house fire in Hongje-dong, Seoul, where six firefighters died in the line of duty. These firefighters were wearing waterproof clothing instead of the recommended fire-protective turnout gear due to a PPE supply shortage[20]. Nevertheless, a shortage of adequate PPE continues[21] due to some practical reasons, such as the lack of cumulated manufacturing technology of local PPE manufacturers and the discontinuation of manufacturing due to the procurement prices of PPE formed too cheaply. The Korean news media has reported that Korean firefighters are discontent with both the quantity and quality of their PPE[22], and a government report suggested the need to improve the performance of firefighting PPE[23]. A few studies have investigated firefighters' PPE evaluations and the need for improvements in the design of PPE, mainly addressing ergonomic issues such as size, fit, comfort, and weight[24, 25]. However, there is still limited literature on and systematic investigation of the overall state of PPE in Korea, and especially a lack of research concerned with reasons for not wearing PPE in conjunction with burn injuries. Moreover, there are no comprehensive regulations governing firefighting PPE maintenance and replacement like NFPA 1851 of the United States[26]. Even the highest quality of firefighting PPE without proper maintenance become unusable before its full life expectancy is seen[27].

In this regard, this study aimed to investigate the current state of firefighters' burn injuries and personal protective equipment (PPE) in Korea using a questionnaire. The term PPE in this study includes the turnout jacket & pants, helmet, hood, structural firefighting gloves, boots, and station uniform.

Methods

Respondents and procedures

Data were collected by questionnaires sent in April 2016 to professional firefighters with backgrounds in supressing fire or rescuing in 15 administrative districts throughout Korea. The reason for recruiting respondents from various districts was to take into account the regional specificity of firefighting activities. A total of 1,050 printed copies of the questionnaire were distributed to fire stations in each district via the Fire & Disaster Headquarters, and 983 were finally collected. Prior to undertaking the main survey, we conducted semi-structured in-depth interviews with ten seasoned male firefighters with over 20 years' experience from five regions. During the in-depth interviews, the above-mentioned ten firefighters inspected the draft questionnaire and commented on the appropriateness of the sentences and choices for each question. They also advised us on whether there any questions should be deleted or added. In this process, they provided their diverse and overall experience and knowledge related to PPE use and burn injuries so that the questionnaire could reflect the actual situation well. Based on this collected information, we completed the final questionnaire. Of a total 983 respondents, 536 firefighters currently responsible for suppressing fire or rescuing work were analysed in this study, because our intention was to assess the current state of firefighting PPE in Korea. The ages of these firefighters ranged from 20 to 59 [mean ± SD: 38.6 ± 8.60 y] and 523 (97.6%) were male. They were on average 173.8 ± 5.0 cm tall (158–186 cm) and weighted 73.4 ± 8.9 kg (41–120 kg). About 54.1% worked in fire stations for less than 10 years, 22.6% for 10

Table 1. General characteristics of the respondents

	n	%
Total sample size	536	100
Sex		
Male	523	97.6
Female	13	2.4
Age (years)		
20–29	69	12.9
30–39	241	45.0
40–49	150	28.0
50–59	71	13.2
No response	5	0.9
Career (years)		
10>	290	54.1
10≤&<20	121	22.6
20≤	122	22.8
No response	3	0.6
	n	value
Height (cm)	535	173.8 ± 5.0
Body mass (kg)	534	73.4 ± 8.9
BMI (kg/m^2)	534	24.3 ± 2.4

Fig. 1. Formal station uniform (left) and informal station uniform (right).

to 20 years, and 22.8% for more than 20 years (Table 1). The entire procedure of this study was approved by the Institutional Review Board of Seoul National University (IRB #E1602/001–005), and prior to participation of the survey, written consent was obtained from all respondents.

Questionnaire and data analysis

The questionnaire in the current study consisted of the following four parts (Table 2). First, respondents answered a series of questions related to burn experience during fireground operations provided in the form of a table. For respondents who experienced multiple burns, a total of 16 rows were provided for them to respond to up to 16 cases, one row for each case. The rows in the table consisted of cells for the answers to the following five questions: three multiple-choice questions on burn depth, percent of total body surface area (%TBSA) burned and etiology of burns, and two multiple-answer questions on the anatomic distribution of burn injuries, and which PPE they had on the injured body part at the time of the accident.

Second, firefighters responded to PPE wear compliance and reasons for non-compliance. These PPE wear compliance questions consisted of a series of ten self-evaluated multiple-choice concerning wear compliance for each of the eight PPE items: the helmet, hood, turnout jacket, turnout pants, structural firefighting gloves, boots, formal station uniform and informal station uniform. In Korea, there are two types of station uniforms. One is the formal station uniform consisting of a shirt-collar top and straight-fit pants, made of non-stretchable and flame-retardant material; aramid (60% or more) and flame-retardant rayon. The other is the informal station uniform consisting of zipped stand collar top and easy-fit pants, made of stretchable and non-flame-retardant material; polyester, nylon, polyurethane, etc. (Fig. 1). There were five multiple choices provided for this series of questions expressing the percentage of wear compliance (0, 20, 50, 80%, 100% wear compliance). In addition, respondents were also asked a series of ten multiple response questions about the reasons for not wearing each of the aforementioned eight PPE items.

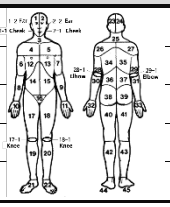
Third, in order to gather firefighters' opinions on their current PPE, it was asked what were the important performance factors in each of the three PPE items: the gloves, helmet and boots, what were the overall evaluations of the current PPE, and what types of PPE damages there were. To begin with, they were asked to choose the most important performance factors, ranked in order from the first to the third among the 13 choices given from each of the

Table 2. Four parts of the questionnaire in the present study

Part 1. Burn experience during fireground operations

Q 1-1 Have you ever experienced burns since you became a firefighter (Including 1st degree burns)?
Yes→ Q 1-2 / No → Q 2-1

Q 1-2 Please fill in the table below for all burn injuries (Including 1st degree burns) you have experienced since becoming a firefighter. (You can write down up to 16 cases.)

#	Year of Occurrence	Burn depth	Percent of total body surface area (%TBSA) burned	Etiology of burns	The anatomic distribution of burn injuries (Select the number in the picture below)	Which PPE did you have on the injured body part at the time of the accident?
Type	(Short-answer)	(Multiple-choice)			(Multiple-answer)	
1						
2						
3						
~						
16						

Part 2. PPE wear compliance

Q 2-1 Please select your wear compliance rate for each of the eight PPE items: the helmet, hood, turnout jacket, turnout pants, structural firefighting gloves, boots, formal station uniform and informal station uniform.
(Multiple choices were given as follows: 0, 20, 50, 80%, 100% wear compliance)

Q 2-2 Please select all the reasons for not wearing each of the eight PPE items: the helmet, hood, turnout jacket, turnout pants, structural firefighting gloves, boots, formal station uniform and informal station uniform.
(Multiple choices were given as follows: Poor flameproof performance; Poor waterproof performance; Low sweat absorbency; Obstruction of sight; Movement obstruction; Inconvenience of first wearing; Difficult to don & doff when wet; Too hot due to the PPE; Too stuffy; Too heavy; Poor design; Humble-looking; Bad tactility of the material; Poor fit; Always wearing; Other)

Part 3. Opinions on current firefighting PPE

Q 3-1 What are the three most important performance factors for each of gloves, helmet and boots?
(Multiple choices were given as follows: Protection against heat and flame; Waterproof performance; Compatibility with helmet; Sweat absorption performance; The feel of fabric; Material management convenience; Easy to don and doff; Without disturbing visibility; Protection against impact; Protection against cuts; Ease of operation; Weight reduction; Slip protection)

Q 3-2 Please select the single problematic item among the current PPE that best matches each of the following six sentences. *(Multiple choices were given as follows: Helmet; Hood; Turnout Jacket; Turnout pants; Gloves; Boots; Formal station uniform; Informal station uniform)*

- Which PPE was most easily damaged or destroyed?
- Which PPE should be improved to reduce firefighting injuries?
- Which PPE should be supplied more for firefighter safety?
- Which PPE firefighters would purchase at their own expense?
- Which PPE was most unsatisfactory in design (color or form)?
- Which PPE was most uncomfortable?

Part 4. Basic information

Q 4 Sex; Age; Height; Body weight; Work periods; Specific tasks; Service areas

gloves, helmet and boots, which were selected as items requiring performance upgrades through the in-depth interviews. For the evaluations of the current PPE, six sentences were presented concerning PPE problems and respondents were asked to choose the PPE that was most relevant to each sentence. And then they responded to series of eight multiple choice questions about the type of PPE damage for each of the eight aforementioned PPE items.

Fourth, respondents' basic information included their physical characteristics such as age, sex, height and weight, and detailed information about their work history including work periods, specific tasks, and their service areas.

All analyses were performed using SPSS version 23 (SPSS, Inc., Chicago, IL), the results from multiple choices, multiple responses and short answer questions were expressed as the frequencies and percentage or mean value and standard deviation (mean ± SD). Logistic regression was used to calculate Odds ratio (ORs) and 95% confidence intervals were used to analyze the association between PPE non-compliance and career years. The same sets of analyses were repeated after adjusting for age, sex and service area. Statistical significance was set at $p<0.05$.

Results

Burn experiences during fireground operations

When asked if they had experienced burn injuries after becoming firefighters, 117 respondents (21.8%) replied that they had experienced burns during fireground operations. Among them, 102 firefighters (19.0%) answered that they had experienced first-degree burns, 38 respondents (7.1%) responded that they had experienced second- or third-degree burns (Fig. 2-Left). Among them, only 92 firefighters responded with details of their burn experiences. This total of 167 burn cases is described below (Fig. 2).

The majority of burn size was less than 1% TBSA. Some 6.4 percent of the respondents answered about 1% TBSA (Fig. 2-Middle). The etiology of burn injuries was divided into flame, contact, scald, and steam burns. Flame burns represented the largest cause of injury with 95 of the 167 cases (55.9%). Contact burns were the second largest cause of injury with 45 cases (26.5%) followed by scald (10.6%)

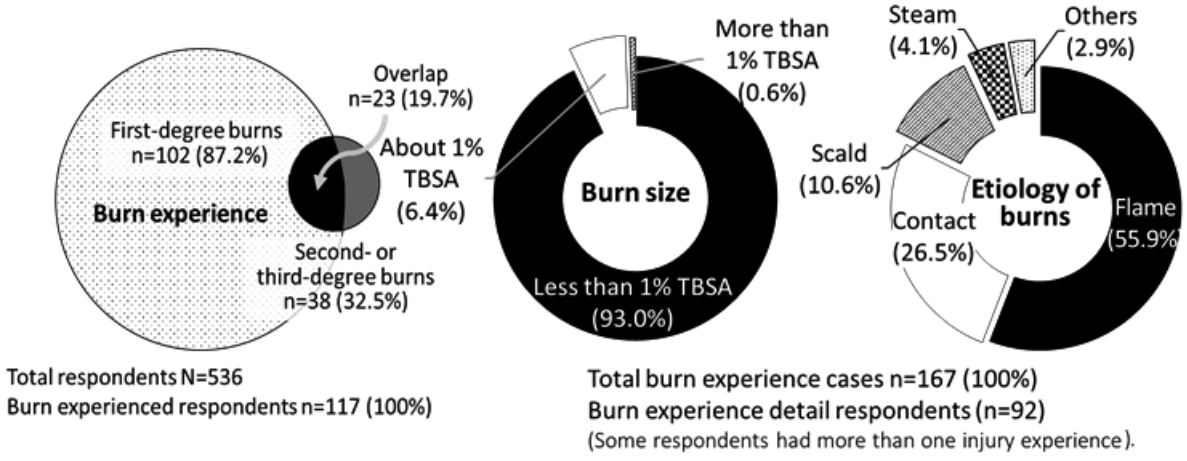


Fig. 2. Burn injuries experience.

Table 3. The anatomic distribution of burn injuries

Burn location	Frequency[a] (valid %)	Frequency[b] of not wearing PPE when injured (%[c])
Face/neck	36 (33.9)	5 (13.9)
Upper body	8 (7.5)	2 (25.0)
Arm	11 (10.4)	1 (9.1)
Hand	39 (36.8)	1 (2.6)
Hip	1 (0.9)	1 (100.0)
Leg	6 (5.7)	0 (0.0)
Foot	5 (4.7)	1 (20.0)
Valid total	106 (100)	11 (10.4)

Total burn cases N: 167 (no response n: 61); Some respondents had more than one injury experience.
a = Frequency of burns for each location; b = Frequency of not wearing PPE when injured for each location.
$c = b/a \times 100$, where the value of 'c' is only available as a mere reference because the sample size of 'a' is too small.

and steam (4.1%) burns (Fig. 2-Right). Firefighters sustained burn injuries to several distinct anatomical sites. The most common body site of burn injuries was the hands (36.9%), followed by the face and neck (33.9%) (Table 3). The majority of the 39 respondents experienced with burns on their hands answered they were wearing the appropriate structural firefighting gloves at the time of injury. And only one answered that he had not been wearing them. Of the 36 respondents who said that they had burns on their faces and necks, only five said that they had not been wearing both the helmet and the hood (Table 3).

Firefighting PPE wear compliance

More than 90 percent of the firefighters in this study answered that they always wear (100% wear compliance) each PPE except the hood and station uniform while firefighting (Table 4). For the formal station uniform, only 328 respondents (63.7%), relatively small number compared to other cases, answered they always wear the formal station uniform (100% wear compliance). In addition, 55 respondents (10.7%) never wore the formal station uniform (0% wear compliance). A relatively less obvious but similar trend appeared in the responses concerning the informal station uniform. To investigate the relationship between PPE non-compliance and career years, we analysed the association between continuous years of working value and PPE non-compliance (Table 5). The results showed that an increase of one year of work significantly increased the adjusted ORs of PPE non-compliance for the hood (OR, 1.11, 95% CI, 1.05–1.18), and the boots (OR, 1.11, 95% CI, 1.01–1.22). The above significant two items had the lowest compliance among the types of PPE other than the formal and informal station uniform that firefighters reported as disliking the most in the open questions.

The most common reason for not wearing PPE when adding up all responses from the surveyed PPE items was ‘Movement obstruction’ (a total of 624 cases). Other common responses were ‘Too stuffy’ (380 cases) and ‘Low sweat absorbency’ (294 cases). The hood was most frequency ‘Too stuffy’, followed by ‘Low sweat absorbency’. For the rest of the items, the most frequent response was ‘Movement obstruction’. It is noteworthy that the response of ‘Movement obstruction’ was given as a very frequent reason for not wearing gloves or turnout jacket, 110 (32% of respondents) and 104 cases (34% of respondents), respectively. Among the reasons for not wearing gloves, 64 responded that it was ‘Difficult to don and doff when wet’ accounting for 20% of all reasons for not wearing gloves, making it the second most common reason (Fig. 3).

Opinions on current firefighting PPE

A summary of firefighters’ three most important performance factors for each of the three types of PPE (the hood, gloves, and boots in order of importance) is presented in Fig. 4. The most important performance factor was ‘Protection against heat and flame’ for all three types of PPE. The

Table 4. Self-evaluated PPE wear compliance by item

PPE item	n	Wear compliance				
		100%	80%	50%	20%	0%
Helmet	535	513 (95.9)	20 (3.7)	2 (0.4)	0 (0.0)	0 (0.0)
Hood	534	365 (68.4)	110 (20.6)	43 (8.1)	15 (2.8)	1 (0.2)
Turnout jacket	534	520 (97.4)	13 (2.4)	0 (0.0)	0 (0.0)	1(0.2)
Turnout pants	535	511 (95.5)	17 (3.2)	6 (1.1)	0 (0.0)	0 (0.0)
Gloves	535	504 (94.2)	24 (4.5)	5 (0.9)	1 (0.2)	1 (0.2)
Boots	532	486 (91.4)	17 (3.2)	7 (1.3)	14 (2.6)	8 (1.5)
Informal station uniform	529	434 (82.0)	45 (8.5)	31 (5.9)	11 (2.1)	8 (1.5)
Formal station uniform	515	328 (63.7)	46 (8.6)	37 (7.2)	49 (9.5)	55 (10.7)

Values are presented as n (%); Total number of respondents: 536

Table 5. The association between PPE non-compliance and years of working

PPE item	Years of working	
	OR (95% CI)	Adjusted OR (95% CI)
Helmet	1.01 (0.96–1.06)	1.12 (0.97–1.29)
Hood	1.05 (1.02–1.07) ***	1.11 (1.05–1.18) ***
Turnout jacket	1.03 (0.97–1.09)	1.43 (1.19–1.72)
Turnout pants	1.01 (0.97–1.06)	1.18 (1.03–1.34)
Gloves	1.02 (0.98–1.06)	1.09 (0.98–1.22)
Boots	1.01 (0.98–1.05)	1.11 (1.01–1.22) *
Informal station uniform	0.99 (0.97–1.02)	1.05 (0.98–1.13)
Formal station uniform	0.99 (0.97–1.01)	1.00 (0.95–1.06)

*p<0.05; ***p<0.001;
OR and 95% CI represent Odd Ratio and 95% Confidence Interval, respectively;
Adjusted OR: controlled for age, sex and service area.

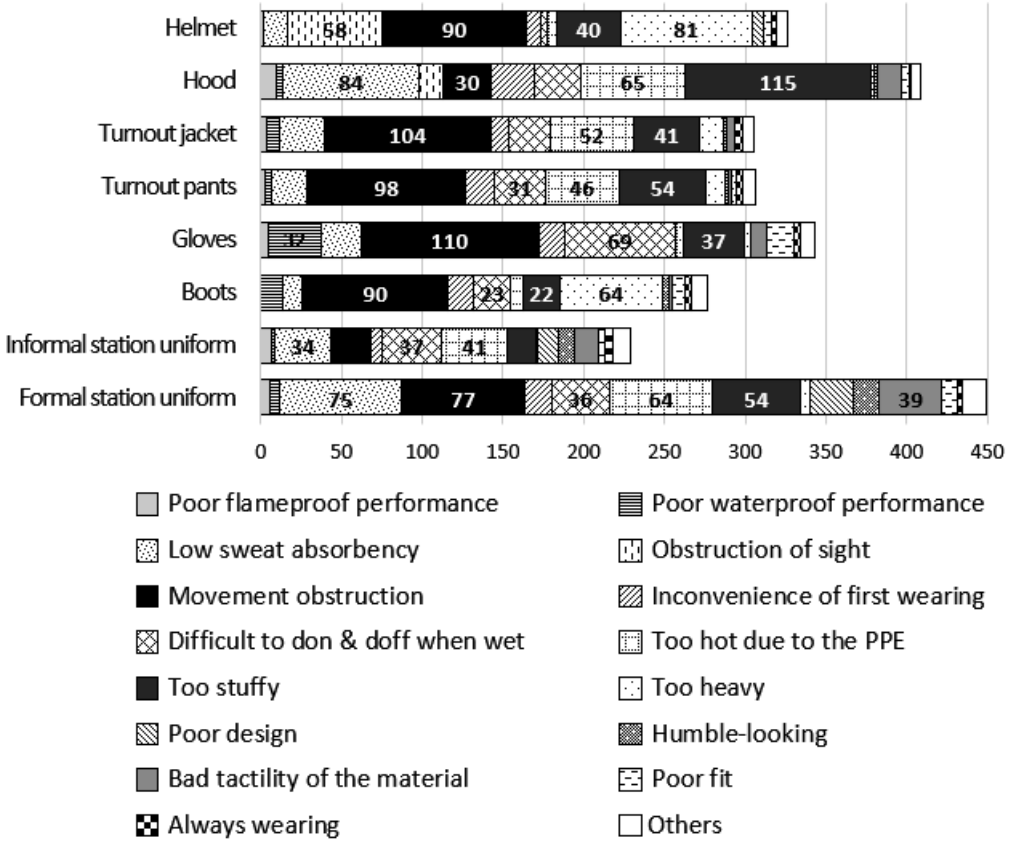


Fig. 3. Reasons for not wearing PPE.
Total respondent N: 536
The values on bars are frequencies.
Multiple response analysis, i.e., some respondents choose more than one reason per item.

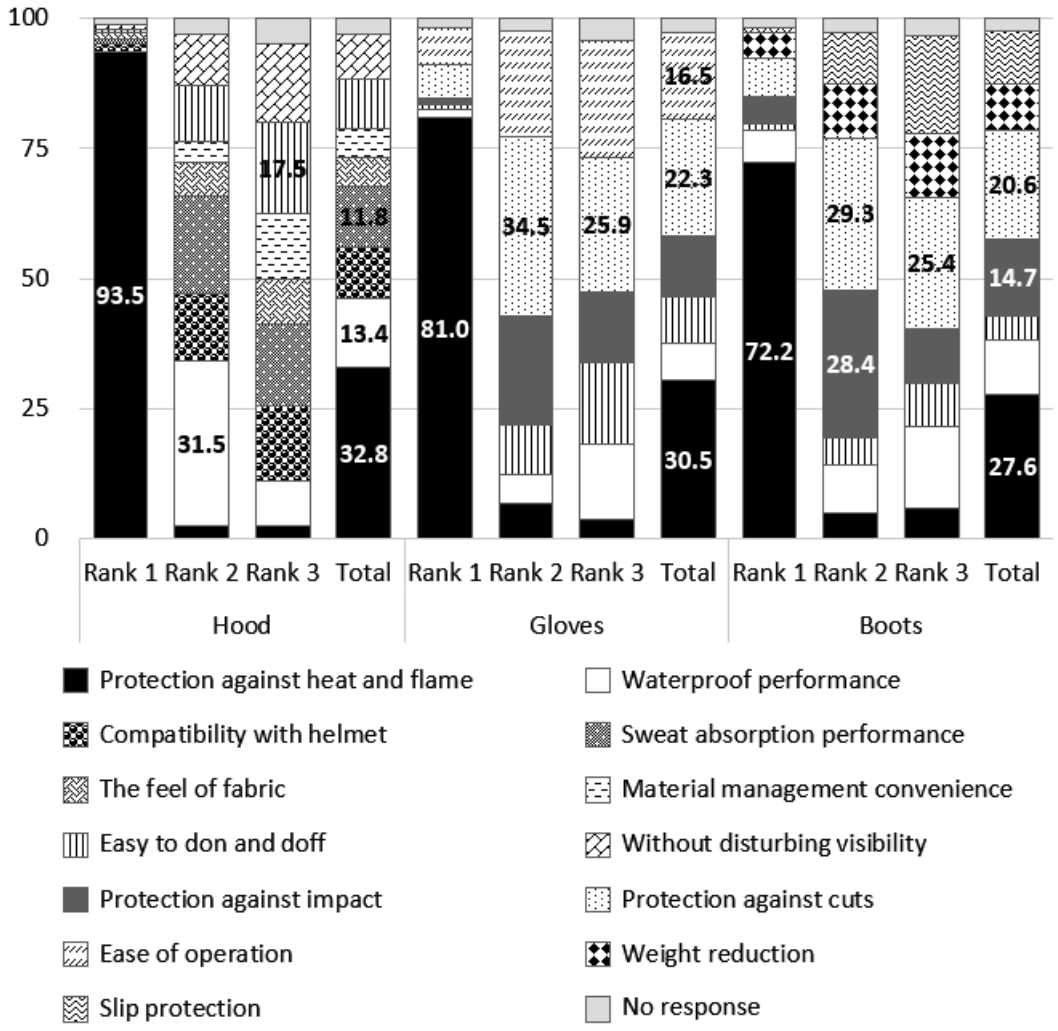


Fig. 4. Percentages of response frequencies of important performance factors.
Total respondent N: 536
The values on bars are percentages.

second most important factor was 'Waterproof performance' for hood, and 'Protection against cuts' for both gloves and boots. The third most important factor was 'Easy to don and doff' for hood and 'Protection against cuts' again for both gloves and boots. Similar trends were observed even in the cumulative total, and they were selected in order of 'Protection against heat and flame' for all three types of PPE, 'Waterproof performance' for hood and 'Protection against cuts' for both gloves and boots. In addition, 'Sweat absorption performance' was also ranked high for hood, 'Ease of operation' for gloves, and 'Protection against impact' for boots.

When asked to choose the single problematic item of their current PPE that best matches each of the six sentences described for problems concerning PPE, most firefighters chose gloves in four of the six sentences in total (Fig. 5). When asked which PPE was most easily damaged or destroyed, the 291 of 536 firefighters (54.3%) answered gloves. Besides gloves, no other PPE item stood out. When asked which PPE should be improved to reduce firefighting injuries, 188 firefighters (31.5%) also answered gloves. In addition, when asked which PPE should be supplied more to enhance firefighter safety and which PPE firefighters would purchase at their own expense gloves was answered 243 (45.3%) and 251 (46.8%) times, respectively. The most frequently selected PPE for the other two questions was the same. 192 firefighters (35.8%) selected the formal station uniform when asked which PPE was most unsatisfactory in design (colour or form) and 120 (22.4%) also selected it when asked which PPE was most uncomfortable.

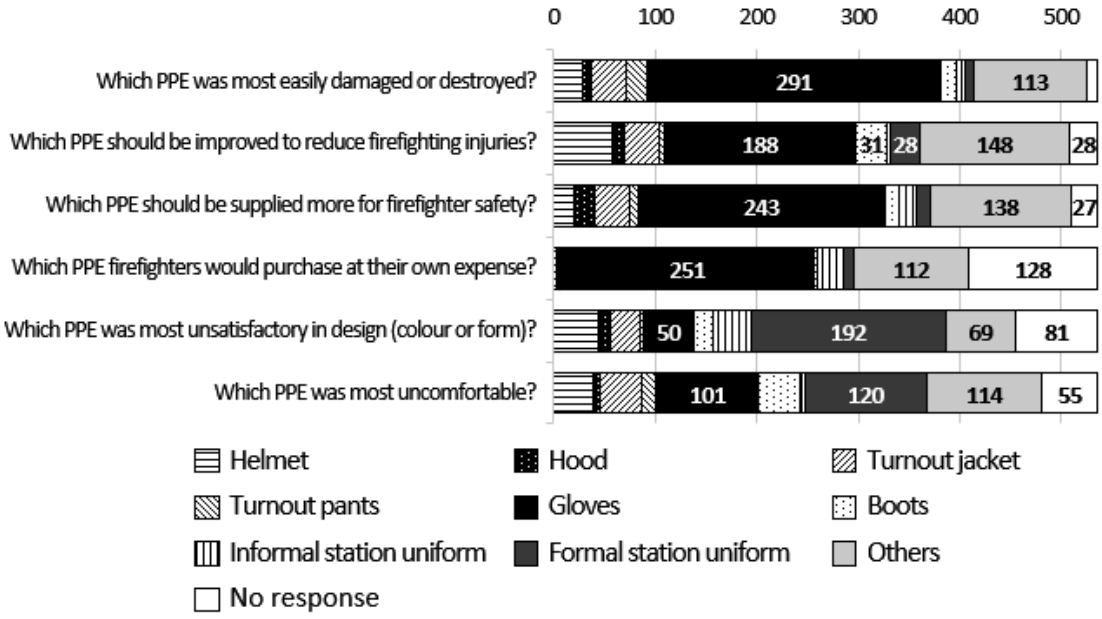


Fig. 5. Evaluations on current PPE.
Total respondent N: 536
The values on bars are frequencies.

When asked to choose the type of damage to the helmet, 'Damage by fire (burn or melt)' was the most chosen response with 79 firefighters (22.5%). Next, 'Closure system damage' and 'Face shield damage' were the second and third most common with 55 respondents (15.7%) and 52 respondents (14.8%), respectively. When asked about the hood, 116 firefighters (29.5%) chose 'Lint formation'. When asked about the turnout jacket, 185 respondents (40.8 %) chose 'Closure system damage', followed by 112 (24.7 %) who chose 'Looking dirty after washing'. As for the turnout pants, 154 respondents (34.1%) answered 'Reduced elasticity (material or hardware)', while 110 respondents (24.5%) chose 'Looking dirty after washing'. In more detail, among the responses of 'Reduced elasticity (material or hardware)', the responses of 'Reduced elasticity of suspenders' accounted for the majority, with 146 respondents (32.5%). Among the types of the glove damage, 96 firefighters (23.4%) chose 'Tears due to sharp objects', followed by 'Worn-out material' and 'Waterproof performance degradation' at 86 firefighters (20.9%) and 80 firefighters (19.5%), respectively. For the boots, the most common responses were 'Tears due to sharp objects' and 'Punctures due to sharp objects'. Both responses were selected by 71 respondents (21.2%). For the informal station uniform and the formal station uniform, the most frequently selected response was 'Looking dirty after washing' with 110 respondents (29.5%) and 162 respondents (43.4%), respectively (Table 6).

Discussion

Burn experience during fireground operations

About 22% of respondents in this study answered they experienced burn injuries during fireground operations. This was much higher than the percentage of firefighters who experienced burns surveyed in a 2020 Korean National Fire Agency (NFA) report[28] and a 2018 U.S. firefighter injury report[5], which was about 5% and 0.5%, respectively. Such a relatively high rate of burns is assumed to be due, in part to the fact that the respondents in this study were asked to respond to self-assessment questions about whether or not they had experienced any first-degree burns, including minor burns not requiring hospital treatment. In fact, the majority of the burn experiences investigated in this study were the first-degree burns and the burn sizes were less than 1% TBSA. In addition, the aforementioned Korean NFA report[28] was mainly concerned second or third-degree burns treated with public compensation, resulting in a seemingly low rate. Given that the application procedure to receive public compensation for firefighting injuries is very complicated and applications are often rejected in Korea[29], the low rate of burns in the above Korean NFA survey is

Table 6. Types of PPE damages

	Helmet	Hood	Turnout jacket	Turnout pants	Gloves	Boots	Informal station uniform	Formal station uniform
Closure system damage	55 (15.7)	4 (1.0)	185 (40.8)	60 (13.3)	5 (1.2)	3 (0.9)	14 (3.8)	10 (2.7)
Reduced elasticity (material or hardware)	2 (0.6)	18 (4.6)	30 (6.6)	154 (34.1)	9 (2.2)	1 (0.3)	14 (3.8)	3 (0.8)
Tears due to sharp objects	8 (2.3)	9 (2.3)	10 (2.2)	14 (3.1)	96 (23.4)	71 (21.2)	26 (7.0)	22 (5.9)
Punctures due to sharp objects	9 (2.6)	3 (0.8)	6 (1.3)	4 (0.9)	42 (10.2)	71 (21.2)	10 (2.7)	6 (1.6)
Seams burst	7 (2.0)	48 (12.2)	12 (2.6)	11 (2.4)	26 (6.3)	1 (0.3)	25 (6.7)	15 (4.0)
Worn-out material	27 (7.7)	76 (19.3)	23 (5.1)	30 (6.6)	86 (20.9)	58 (17.3)	79 (21.2)	62 (16.6)
Waterproof performance degradation	5 (1.4)	13 (3.3)	34 (7.5)	32 (7.1)	80 (19.5)	53 (15.8)	8 (2.1)	5 (1.3)
Flameproof performance degradation	4 (1.1)	45 (11.5)	21 (4.6)	17 (3.8)	5 (1.2)	2 (0.6)	2 (0.5)	8 (2.1)
Damage by fire (burn or melt)	79 (22.5)	9 (2.3)	6 (1.3)	5 (1.1)	9 (2.2)	15 (4.5)	9 (2.4)	6 (1.6)
Discoloration	31 (8.8)	7 (1.8)	4 (0.9)	4 (0.9)	5 (1.2)	5 (1.5)	24 (6.4)	28 (7.5)
Lint formation	1 (0.3)	116 (29.5)	-	1 (0.2)	2 (0.4)	-	42 (11.3)	16 (4.3)
Looking dirty after washing	23 (6.6)	28 (7.1)	112 (24.7)	110 (24.5)	17 (4.1)	36 (10.7)	110 (29.5)	162 (43.4)
Face shield damage	52 (14.8)	-	-	-	-	-	-	-
Separated lining	-	-	-	-	4 (1.0)	-	-	-
Others	48 (13.7)	17 (4.3)	9 (2.0)	9 (2.0)	24 (5.8)	18 (5.4)	9 (2.4)	28 (7.5)
None	-	-	1 (0.2)	1 (0.2)	-	1 (0.2)	1 (0.3)	2 (0.5)
Valid Total	351 (100)	393 (100)	453 (100)	452 (100)	410 (100)	335 (100)	373 (100)	373 (100)
No response	185	143	83	84	126	201	163	163
Total	536							

Values are presented as n (valid percent).

understandable. Although the incidence of firefighter burn injuries was relatively low compared to other injuries such as strain/sprain, which had been investigated as the foremost cause of firefighter injuries in other previous studies[5, 29, 30], it should not be overlooked that burn have consistently represented a significant proportion of firefighter injuries.

In addition, while most of the burns investigated in this study were minor, it is worth noting that the most common sites of the burns were the hand, face and neck, which are functionally important body parts. These sites were also found to get frequently burned in a number of previous studies[6, 28, 31]. A very significant result of this study is that most burns on these sites occurred despite wearing appropriate PPE. In only 11 out of 106 burn cases, respondents answered that they were not wearing any PPE on the body part that was burned, indicating that in the other 95 cases, respondents were burned despite wearing appropriate PPE. This is in line with a study by Kahn *et al.*[32], which showed that among 20 U.S. firefighters who were treated at the hospital for occupational burns, 14 were there due to their equipment's failure to protect. Also, the most common burn locations in their study were the head and hands[32], as in the present study. These body parts seem to be particularly vulnerable despite wearing protective equipment, as flame, steam and hot liquids could enter through small gaps between the sleeve and glove, between the hood and the jacket, or via the interface between the hood and the face. This is a compatibility issue that occurs when different types of

PPE are worn at the same time. ISO 11999-2 stated that such compatibility problems could lead to reductions in protection provided by PPE, which could result in a limitation of tactical missions[33]. Injuries during firefighting are chiefly due to the hazards of heat, flame, and water penetration. And minimizing these hazards is one of the main reasons why all PPE worn must meet or exceed minimum performance requirements. One of the main ways to verify compatibility is by having test subjects perform a series of practical tests (practical performance tests) that demonstrate the compatibility of PPE items and ensembles measured against a set of performance criteria. However, as of yet, Korean firefighting garments must conform to material standards only. Other standards for Korean firefighting garments need to be implemented[34].

Meanwhile, to prevent direct skin exposure to flames or hot liquids through the small gap between the hand and wrist, manufacturers may make the inner layer of the firefighting glove long enough to cover the wrist and the lower part of arm with a rather flexible heat resistant material to completely overlap the sleeve of the turnout jacket. Since such gloves are difficult to don and doff while wearing the turnout jacket, designing gloves with fully separable outer and inner layers so that the outer layer can be donned and doffed easily may be appropriate. Seamless headgear, covering the entire head, can also better protect the face and neck. However, many advances in technology may be still needed to develop and commercialize such equipment at a level that does not result in a reduction of firefighters' mobility. Therefore, there are many things to consider when trying balance protection and comfort. For PPE such as the hood with relatively low wear compliance rates, enhancing wear compliance through appropriate safety training may be a more efficient approach than improving PPE design and will be discussed in the following.

Meanwhile, the questionnaire used in this study focused only on burns among various firefighter injuries. Therefore, there is the possible shortcoming that burn-related results may have been overestimated.

Firefighting PPE wear compliance

The PPE wear compliance rate in this study was quite high, with more than 90% answering that they always wear (100% wear compliance) each PPE except some items such as the hood. However, a previous study that analyzed some video recordings found that more than 40% of firefighters used their gear improperly or failed to wear it at all[35]. In a recent U.S. survey, more than 60% of respondents also replied that they had previously fought fires without a complete set of gear[36]. Both the above-mentioned studies and the present study showed low wear compliance rates for the hood, i.e., the hood was frequently omitted. The frequent omission of the hood is presumed to be closely related to the results of previous studies that identified the head as the most common site of firefighter injury[31, 32]. Similarly, this study showed that burns to head were frequent as were the proportion of respondents who said they did not wear the appropriate head PPE.

Interestingly, the analysis of the relationship between PPE non-compliance and career years in this study showed that especially for the hood, PPE non-compliance increased significantly by a factor of 1.1 per year (Table 5). This tendency was weaker but still significant for boots, but was not found in other items. According to several previous studies, because of wanting to appear tough and fearless many firefighters often neglect to wear their protective hood. In other words, a culture of 'toughness' in which using PPE is seen as being weak or unnecessary may also contribute to a lack of PPE wear compliance[32, 36]. A good approach to solving these issues might be to promote a safety-oriented work environment and to enhance wear compliance through appropriate education and training on the correct performance and use of PPE. In addition, considering that the most frequent responses to the question about the reasons for not wearing the hood were 'Too stuffy' and 'Low Sweat absorbency', different materials may be utilized for some inner, outer and parts of the hood. Also, efforts to develop ergonomic patterns are needed to improve the hood fit. Another analysis of the PPE non-compliance is that senior firefighters sometimes do not wear hoods intentionally to detect temperature through their bare skin[32]. The rational is that this non-compliance is acceptable because the high protective performance of the PPE blocks its wearer from sensing external hazards, resulting in delayed escape and greater risk. In response, we proposed integrating smart technologies that instantly measure and present on an intuitive display external hazards such as high temperatures. Similarly, Mrugala *et al.* have introduced a temperature sensor measurement system for structural firefighting gloves[37].

Meanwhile, it is noteworthy that about 10% of respondents in the present study said that they never wore the formal station uniform (0% wear compliance), while only about 64% answered that they always wear the formal station uniform (100% wear compliance). At the time of this survey, according to Regulations on Attire of Fire Officers[38], Korean firefighters were required to wear the formal station uniform under the turnout gear when they respond to a scene. But recently this mandatory regulation has been

partially abolished due to continuous requests, and now firefighters are allowed to wear either the formal station uniform or the informal station uniform under turnout gear when they respond to a scene. As such, regulation making wearing the formal station uniform compulsory has disappeared, but complaints in this regard have been steadily increasing. We will discuss this in the following section.

Opinions on the current firefighting PPE

When asked to choose the three most important performance factors for the gloves, helmet, and boots, it seems natural for firefighters to first choose 'protection against heat and flame' for all three items due to their occupational characteristics. 'Waterproof performance', was especially frequent for the hood, which consists of a relatively thin material and simple design compared to other PPE items. The hood is also especially susceptible to getting wet while firefighting from water and head and neck sweat. A wet hood sticks to the face, causing discomfort. However, wet PPE sometimes provides greater thermal protection than dry PPE depending on combinations of conditions such as wetness level, material features and heat transfer paths. Due to its high heat capacity, the water within the PPE could store a big part of the supplied energy and initially reduce the energy transferred to the skin[39]. And temperatures measured in PPE combinations containing a wet layer were reported to be always lower than temperatures measured in the corresponding dry combinations because of evaporation occurred at constant temperature and at constant evaporation rate. However, when the PPE suddenly is exposed to a more intense external heat source, the temperature increase of the steam within the PPE may cause burns by stewing the skin in this hot steam. Furthermore, if steam is adsorbed by the skin and heat of sorption is released in the inner layers of the skin, this might also lead to second degree steam burns[40]. On the other hand, for conductive heat transfer mechanisms that occur when wet PPE comes into direct contact with the skin, water conducts heat about 23 times better than dry air, which could lead to high energy transfer to the skin. Therefore, moisture accumulation in the PPE has to be avoided. Taken together, if a hood is able to quickly absorb moisture and allow its immediate evaporation, a wet hood due to sweat and water could be advantageous in terms of heat dissipation. Thus, it seems more desirable for a hood to reduce discomfort through proper moisture management rather than strengthening the waterproof performance. This idea becomes more convincing, when considering that the most frequent responses to the reason for not wearing the hood were 'Too stuffy' followed by 'Low sweat absorbency'.

Meanwhile, it is noteworthy that the gloves were chosen as the PPE item that was most easily damaged or destroyed, as the PPE item that should be improved to reduce firefighting injuries, as the PPE item that should be supplied more, and as the PPE item that was purchased at their owners' cost. The most frequent response for not wearing gloves was 'Obstruction of movement'. Sizing and fit issues have been identified as major concerns for fire gloves, resulting in limited mobility and dexterity and, negative effects firefighting work efficiency and safety[12, 24, 41]. A key issue for protection and performance of structural firefighting glove is the sizing. Glove fit plays a critical role in the effectiveness of the glove; it affects material property engagement and ultimately impacts firefighter grip performance and dexterity and thus requires extra attention[41]. Currently, Korea's standard structural glove sizing system has five sizes based on hand length and girth, and needs to be re-assessed to accommodate hand shapes. To this end, it is necessary to collect and analyse firefighters' anthropometric hand dimensions.

When asked about types of PPE damage, the most frequent response for helmets was 'Damage by fire (burn or melt)', and 'Face shield damage' was also the third highest. Here, face shield damage mainly refers to heat damage, which decreases the transparency of the material due to heat, resulting in poor visibility and deformation. In Korea, within the past few years, materials with somewhat improved thermal properties have been utilized to this end, Ultem PEI (PolyEtherlmide) for caps, and PES (Polyethersulfone) for face shields of helmets. However, heat damage to the helmet is still reported frequently.

Except for the above-mentioned damage, most of the responses to each type of PPE damage converged on 'Closure system damage', 'Reduced elasticity' and 'Looking dirty after washing', which, interestingly, did not appear to be an immediate threat to life and safety. First of all, problems related to 'Closure System Damage', which largely depended on damage to zippers on the turnout jacket and pants, and 'Reduced elasticity', which largely due to stretched suspenders on the turnout pants, could be solved by improving hardware. The damage related to durability or elasticity of these items has been consistently occurring, so it is worth considering introducing a test of operability and strength for test zippers, and a test of elastic recovery test for the certification of firefighter PPE.

Conclusions

The findings from the present study were that burn injuries were prevalent for firefighters in Korea. Most burns were on the hands, face or neck but they tended to be first degree burns with burn areas less than 1% of the total body surface area. We elucidated the relationships between the body sites for vulnerable burn injuries and PPE wear compliance by item. The present study suggests that officially-undisclosed minor burn injuries are prevalent among firefighters and can be reduced through improving firefighters' protective helmet, hood and gloves. In particular, PPE interfaces may be modified so that flame, steam, and hot liquids cannot enter through small gaps between each clothing component such as that between the sleeve and glove, hood and the jacket, and hood and face. Other findings include the continued PPE non-compliance among Korean firefighters, and the importance of appropriate education concerning the potent health risks of such non-compliance and training for the correct usage of PPE.

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