

What do firefighters desire from the next generation of personal protective equipment? Outcomes from an international survey

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Abstract: The purpose of this study was to investigate smart features required for the next generation of personal protective equipment (PPE) for firefighters in Australia, Korea, Japan, and the USA. Questionnaire responses were obtained from 167 Australian, 351 Japanese, 413 Korean, and 763 U.S. firefighters (1,611 males and 61 females). Preferences concerning smart features varied among countries, with 27% of Korean and 30% of U.S. firefighters identifying ‘a location monitoring system’ as the most important element. On the other hand, 43% of Japanese firefighters preferred ‘an automatic body cooling system’ while 21% of the Australian firefighters selected equally ‘an automatic body cooling system’ and ‘a wireless communication system’. When asked to rank these elements in descending priority, responses across these countries were very similar with the following items ranked highest: ‘a location monitoring system’, ‘an automatic body cooling system’, ‘a wireless communication system’, and ‘a vision support system’. The least preferred elements were ‘an automatic body warming system’ and ‘a voice recording system’. No preferential relationship was apparent for age, work experience, gender or anthropometric characteristics. These results have implications for the development of the next generation of PPE along with the international standardisation of the smart PPE.

Key words: Auxiliary cooling, Firefighter, Location monitoring, Personal protective equipment (PPE), Wireless communication

Introduction

Structural firefighters work under stressful and dangerous conditions. Accordingly, they wear layered thermal protective clothing and a wide range of other personal

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protective equipment (PPE). The former minimises heat penetration, but significantly and simultaneously elevates the metabolic cost of locomotion and impairs heat dissipation¹⁻⁴). Personal protective equipment, on the other hand, is designed to protect specific body regions from various injuries. For instance, the feet are protected against puncture, hot steam, liquid splash and crush injuries, the head against impact injuries and the breathing apparatus guards against smoke and gas inhalation. However, these protective components also elevate the metabolic demands of work⁴⁻⁸). Indeed, this mass-specific impact is body-location dependent^{4, 9-12}).

Not surprisingly, the complete protective ensemble reduces comfort and range of motion¹³⁻¹⁵), it adversely modifies gait, metabolic efficiency and fatigue¹⁶⁻¹⁸), maximal work tolerance is impaired^{4, 19, 20}), and the ambulatory oxygen consumption reserve is decreased by as much as 30%⁴). Despite the efforts of occupational health specialists to improve firefighter safety, injuries are still very common, varying in nature from country to country (Sweden²¹), Poland²²), United States²³), Korea²⁴), United Kingdom²⁵), Australia²⁶).

Recent epidemiological evidence has shown that, within one of the largest fire and rescue organisations in the world, the two principal causes of firefighter injury were muscular stress and slips, trips and falls²⁶), with these outcomes also being reflected internationally within sprain and strain injuries^{22, 27-29}). It is possible that these injuries were, to some extent, associated with the burden of the PPE²⁶). Furthermore, as smart technologies are developed and miniaturised, they are readily integrated into existing protective ensembles. Therefore, a need exists to better understand both the requirements and the physiological impact of such equipment on operational firefighters.

The purpose of the current investigation was to seek advice from operational firefighters within four countries (Australia, Japan, Korea, United States [U.S.]) concerning the development of the next generation of PPE. It was anticipated this information would be critical to the designers of protective equipment and to the health and safety officers within fire and rescue organisations. Readers are also directed to a European initiative with similar objectives (<http://www.smartatfire.eu/what-is-smart@fire.aspx>). To gather this information, a survey was administered within each of the four participating countries, with responses provided by approximately 1,700 operational firefighters.

Methods

Survey development

Four universities and one national research institute collaborated for this study. Based on one-to-one interviews with Korean subject-matter experts in personal (thermal) protective clothing (PPC) and PPE, and firefighters, as well as extensive literature searches, a total of 13 features (smart elements) were identified for possible use within the next generation of protective equipment. These elements and attributes are identified in Fig. 1. In parallel, 12 survey questions were developed for administration within the four target countries. These questions are presented in Table 1, and were used with Fig. 1. However, each question was tailored to optimise response precision and data validity using the native language (English, Japanese, Korean), spelling and appropriate equipment nomenclature, although the content of each questionnaire remained consistent across countries. To assist participants in answering these questions, images that best depicted the characteristics of the PPC and PPE used within each country were included in the survey (Fig. 1). This developmental process required several iterations before the final local approval for survey administration was granted by each fire and rescue organisation. In retrospect, additional questions related to clothing contamination and the incidence of personal injuries may have proven beneficial.

Survey administration

Printed surveys were distributed in Japan and Korea, while online surveys were used in Australia and the U.S. In Korea, the written questionnaires were distributed at two fire stations in Seoul (November, 2013), and collected one month later (December, 2013). The total firefighter count at these stations was 563 and the total number of firefighters was 6,676 at 23 fire stations in Seoul. In Japan, written questionnaires were distributed at fire stations in Fukuoka City (December, 2013), and these were also collected after one month (January, 2014). At those fire stations, there were 799 firefighters. For the online surveys in Australia, an electronic invitation letter, calling for voluntary participation in the survey, was distributed centrally through the electronic mail facility to every full-time (3,457) and on-call firefighter (3,368) of Fire & Rescue New South Wales. This sample included 338 fire stations. Within the U.S., the online survey was advertised through the International Association of Fire Fighters (IAFF), and the total firefighter population covered by that organisation was approximately 78,000. The online data collection peri-

Elements of personal protection



- ① Alarm and monitoring system of noxious gases at the scene of a fire
- ② Alarm and monitoring system of air/object temperatures at the scene of a fire
- ③ Alarm and monitoring system of heart rate at the scene of a fire
- ④ Alarm and monitoring system of blood pressure at the scene of a fire
- ⑤ Monitoring and feedback system of body temperature
- ⑥ Location (position) monitoring system
- ⑦ Automatic body cooling system to alleviate heat strain
- ⑧ Automatic body warming system to prevent cold injuries
- ⑨ Vision support system: Infrared discrimination system or moisture-proof visor
- ⑩ Flexible and hands-free lighting system
- ⑪ Voice recording system
- ⑫ Wireless communication system
- ⑬ Quick wearing and release system

Fig. 1. Thirteen possible elements and attributes considered for the next generation of smart, personal protective equipment. This Figure was used in combination with the firefighter questionnaire (Table 1).

Table 1. Survey questions for firefighters, used in conjunction with Fig. 1.

Item	Question
1	Consider the 13 elements shown in the Figure, which single item do you consider the most important element required for firefighter safety and comfort?
2	From those 13 elements, choose five items that you consider to be very important elements for firefighter safety and comfort, including your answer to question 1.
3	List these same five elements. Next to each item, tell us how you would like to see that element of your PPE designed to give you the greatest comfort and safety.
4	Please describe other elements that you consider important in developing smart-firefighting PPE, in addition to these 13 elements.
5	Please provide any feedback or further suggestions for improving your current PPE.
6	Year of Birth: _____
7	Gender: Male [] Female []
8	Your height and body weight are: _____feet (or cm), _____pounds (or kg)
9	Work experience as a firefighter: Permanent (Professional) _____yr Retained (Volunteer)_____yr
10	Your protective boots are made from: (1) rubber, (2) leather, (3) other.
11	The SCBA that you use currently lasts _____min. (1) 30 min, (2) 45 min, (3) 60 min, (4) more than 60 min, (5) I do not use a SCBA.
12	How many times were you called to the scene of a fire in the PAST YEAR? (1) Never, (2) on average 1–2 times/month, (3) 3–4 times/month, (4) 5–6 times/month, (5) more than 7 times/month

PPE: personal protective equipment; SCBA: self-contained breathing apparatus. These questions were provided using the native language and the appropriate jargon for each of the four fire and rescue organisations.

Table 2. Characteristics of the firefighters from four countries who responded to this survey

	Australia	Japan	Korea	United States
Sample size ¹ (male:female)	167 (157:6)	351 (351:0)	413 (384:23)	763 (719:32)
Age (yr)	45.0 ± 10.4	42.9 ± 11.7	41.7 ± 9.1	42.7 ± 9.5
20–30 yr (%) ²	7.5	18.6	8.9	8.0
30–40 yr (%)	21.7	23.5	32.8	31.1
40–50 yr (%)	34.2	20.1	34.2	35.7
50–60 yr (%)	30.4	32.3	23.3	21.5
>60 yr (%)	6.2	5.5	0.7	3.7
Height (cm)	178.6 ± 7.3	172.0 ± 9.8	173.2 ± 5.3	180.5 ± 8.9
Body mass (kg)	86.8 ± 11.6	71.5 ± 8.1	71.6 ± 8.6	92.6 ± 16.5
Experience (yr)	16.9 ± 9.4	20.6 ± 12.1	14.5 ± 9.2	16.0 ± 9.2

¹Sample sizes are totals with separate male:female counts shown in parenthesis. Data are means with standard deviations (± SD). ²Numbers within each of the age divisions represent percentages of the total sample.

ods were open from January to March (2014) in Australia, and from October to December (2013) in the U.S. Overall ethical approval was obtained via the Institutional Review Board of Seoul National University (Korea; SNU IRB No.E1312/001-018) and Cornell University (USA). In addition, each local fire and rescue organisation approved administration of the survey.

Data analysis

Data were obtained in three formats: categorical data (questions 1, 2, 7, 10, 11 and 12), quantitative data (questions 6, 8 and 9) and descriptive data (questions 3, 4 and 5). Categorical data were analysed using χ^2 and Kruskal-Wallis tests, while quantitative data were analysed using one-way ANOVA and Tukey's *post hoc* test. Data are presented as means and standard deviations (SD) to illustrate distribution differences across these population samples. In all analyses, statistical significance was accepted when a probability value was less than 0.05. Descriptive data were grouped into related themes.

Results

Survey respondents

A total of 1,694 survey responses were collected from the four countries (Table 2). Questionnaire responses were obtained from 167 Australian, 351 Japanese, 413 Korean, and 763 U.S. firefighters (1,611 males and 61 females). The Australian firefighters were significantly older ($p=0.005$), U.S. firefighters were taller ($p<0.001$) and heavier ($p<0.001$), and the Japanese firefighters had more fire-service experience than each of the other three groups ($p<0.001$). An interesting difference among these coun-

tries was the frequency of call-outs to fires, with Korean firefighters reporting the highest fire-attendance incidence. The percentage of firefighters from each country attending five or more fires per month was 51% (Korea), 29% (Australia), 20% (USA) and 9% (Japan). These differences were statistically significant ($p<0.05$).

The most important smart elements

When asked to identify the single most important element or characteristic of the next generation of PPC or PPE, the responses were clustered around three elements (Fig. 2): 'wireless communication', 'automated body cooling' and 'personal location (position) monitoring'. The Australian responses were equally split between the perceived need for wireless communication and body cooling, whilst the Japanese firefighters overwhelmingly rated personal cooling as their highest priority. Personal location monitoring dominated both the Korean and U.S. responses, and in an approximately equivalent priority.

To increase the power of these survey responses, data from the four countries were combined (Fig. 2: far right bar). Whilst it is important to retain the integrity of the national responses, the aim of this analysis was to evaluate whether or not these pooled data would reflect both national and international priorities. The top five elements identified from these overall data were: 'personal location monitoring' (highest priority), 'automated body cooling', 'wireless communication', 'vision support' and 'hot-object alarm monitoring'. These elements included 83% of the Japanese, 78% of the U.S., 77% of the Korean and 65% of the Australian firefighter responses.

Question 2 gave firefighters an opportunity to rank the smart elements, and thereby created tiered responses.

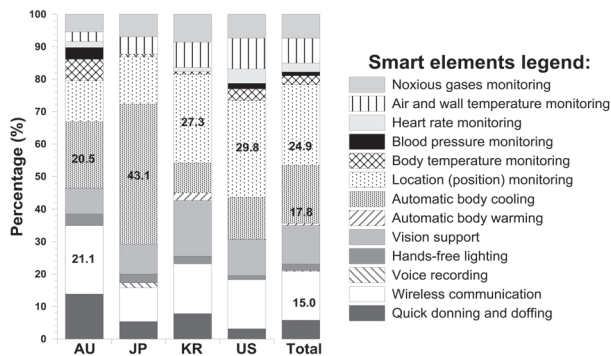


Fig. 2. Voting distributions for the single most important elements of the next generation of smart, personal protective equipment (see Fig. 1), as reported by Australian (AU), Japanese (JP), Korean (KR) and United States (US) firefighters.

Data are national response percentages. The far right bar displays the distributions for the entire firefighter sample (Total).

This type of question is very important for assembling the protective components into a complete protective system according to the perceived utility of each element. Such an outcome should serve the needs of most firefighters, and the results are summarised in Fig. 3, with the top five elements indicated for each country. A combined response bar has again been added to Fig. 3 (far right), with the top eight elements accounting for 81% (lowest: U.S.) to 92% (highest: Japan) of the voting preferences of each country. Five of those elements were identified in Fig. 3 (location monitoring, wireless communication, vision support, body cooling and hands-free lighting), with three additional attributes being revealed: hot-object alarm monitoring, noxious gas monitoring, and rapid equipment donning and doffing capabilities.

Whilst it is important to understand the perceived needs of firefighters, it is equally important, given the added mass that might be carried, to identify protective elements that may be considered superfluous. Close inspection of Figs. 2 and 3 reveals that five elements did not appear within either the top five (Fig. 2) or top eight (Fig. 3) ranks. These items related to personal monitoring (heart rate, blood pressure and body temperature), automated body warming and voice recording systems. Whilst an emphasis upon personal monitoring appears to be a focus of some manufacturers and health and safety officers, this seems to be a low-priority element from the perspective of the firefighters responding to this survey.

Current personal protective equipment

Some protective elements must always be used, for example, self-contained breathing apparatus (SCBA),

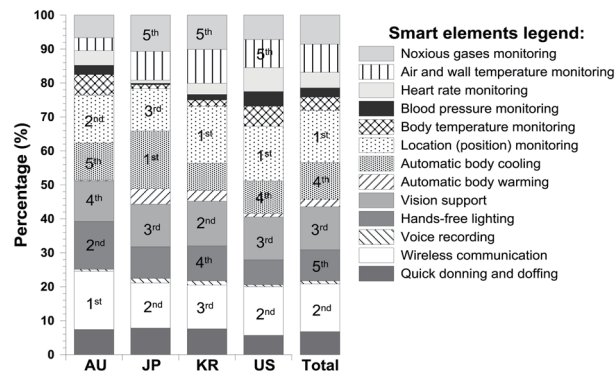


Fig. 3. National voting patterns for the top five elements of smart, personal protective equipment shown in Fig. 1, as reported by Australian (AU), Japanese (JP), Korean (KR) and United States (US) firefighters.

The far right bar is the distribution for the entire sample (Total). Data are response percentages. Missing ranks signify two or more elements obtained equal votes.

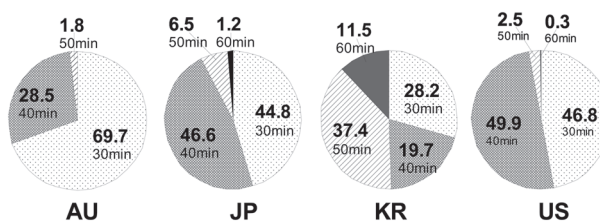


Fig. 4. Operational capacities of self-contained breathing apparatus reported by Australian (AU), Japanese (JP), Korean (KR) and United States (US) firefighters.

Data are presented as national response percentages within capacity bands.

protective boots and helmets. However, it was of interest to evaluate international variations and attitudes regarding this equipment. In these instances, attention was directed towards air-supply durations and footwear construction.

The capacity of self-contained breathing apparatus varied considerably from country to country ($p < 0.05$). Approximately 70% of the Australian respondents perceived the capacity of their apparatus to be about 30 min (Fig. 4). For Japan and the U.S., votes were approximately equally split between 30- and 40-min capacities. On the other hand, the Korean responses were primarily within the 50-min capacity band. This outcome may well have introduced bias into the perceptions of thermal strain among these nations, since shorter-duration breathing apparatus limits the maximal heat-exposure duration, and thereby reduces the risk of developing hyperthermia.

The materials of fire-protective boots significantly differed among countries ($p < 0.05$). Most Australian and U.S.

firefighters wore leather boots (85% of Australian and 79% of U.S. firefighters), while 99% of the Japanese firefighters wore rubber boots. Korean firefighters were equally split between leather boots and rubber boots.

Protective clothing and equipment requiring improvement

Comments and suggestions concerning improvements to the PPC and PPE currently worn (Question 5) are summarised in Tables 3 and 4, with whole-ensemble needs grouped in Table 3. These relate to problems identified concerning the thermal characteristics, over-protection, load and dimensions, and the cleaning and management of this equipment. Table 4 contains a summary of the specific components within each protective system, such as the helmet, visor, facemask, hoods, gloves, boots, turnout coat and pants. Comments in common among the countries are summarised, with country-specific comments also identified.

The most frequently noted adverse comments were that the thermal protective ensembles were too hot and too heavy, especially after becoming wet. A comment in common with Korean, Australian and U.S. firefighters was that their new protective equipment was much hotter and heavier than the older ensemble. This may be related to over-protection³⁰. In this regard, firefighters felt strongly that equipment and clothing manufacturers should not unnecessarily increase the thermal protective properties of their clothing. It is curious to note that, in the case of the Australian sample, a moisture barrier was incorporated into the clothing, yet thermal injuries accounted for only 1.4% of all injuries within that organisation²⁶.

With regard to specific protective items, there was an extensive range of recommended improvements (Table 4), and the following general summary statements are highlighted. There was a consensus that headwear should be improved to reduce its load and hearing impediment, while simultaneously increasing the field of vision and goodness of fit. Similarly, the mass of the breathing apparatus and its impact on flexibility and mobility were crucial issues. For the gloves, firefighters reported that poor manual dexterity, due to glove stiffness and poor fit were important problems, while they preferred leather boots to rubber in terms of mass, flexibility and fit. For instance, one U.S. firefighter commented: *“I have leather at my full-time department and rubber at my volunteer department. I prefer the leather much more than the rubber”*.

Discussion

The present survey from four countries has revealed five priorities that need to be considered for inclusion within the next generation PPE for firefighters: personal location monitoring, automated body cooling, wireless communication, vision support and hot-object alarm monitoring. When these smart elements are being designed, the following issues that may hinder firefighter comfort and safety should also be considered: body-heat production and heat retention (trapping), equipment mass and bulkiness. Whilst it is recognised that firefighter input into these processes is very important, and must not be neglected during equipment development, it must not be considered in isolation. Furthermore, opinion variations among these countries are related to differences in fire-fighting situations (structural versus wildland), gender representation, physique (taller and heavier U.S. and Australian firefighters than Korean and Japanese firefighters), climate (hotter and more humid during the Japanese summer), fire-fighting tactics and policies (response frequencies, aggressive versus defence fire fighting, breathing apparatus capacities, thermal resistance of the PPC), or to variations in the design of existing PPC and PPE currently provided. Nevertheless, we shall now elaborate, in order of priority, upon these key elements for advancing firefighter protection.

Location monitoring system

Personal location monitoring (positioning) was the most important element preferred by both the Korean and U.S. firefighters (Fig. 2), since firefighters in trouble often cannot accurately describe their precise location to rescuers, especially in large commercial fires, and this may increase their injury or mortality risk. The ability to quickly locate trapped, lost or injured firefighters will reduce injury impact and severity, as well as increasing survival. Rescue teams may have less than 10 min to save lost firefighters if the air supply has been exhausted, due to the presence of noxious gases and the associated risk of brain damage³¹. Also, a fire-ground commander needs to know exactly where firefighters are located at all times, so that more efficient fire fighting can occur with minimal risk to firefighters. However, signals from some of the current positioning equipment appear to be impeded by thick steel, concrete materials or the dense walls of large commercial buildings. Therefore, more effective equipment needs to be either identified or developed for these circumstances, and manufacturers should consider integrating this equipment into the PPE, in addition to the Personal Alert Safety System.

Table 3. Firefighters' recommendations for general improvements to the entire personal protective system

Category	Specific recommendations
Thermal characteristics	<ul style="list-style-type: none"> · Very hot as soon as I put it on, and before getting to the fire scene, due to the low breathability, accumulated sweat and heat, especially in summer. The turnout gear may withstand the heat, but the body will not endure the gear. Long duration work is impossible because of the heat, and mental performance is harmed as well. · Very hot due to the moisture barrier among three layers of the PPC. The liner should be removable in summer for easier rehabilitation. Further, the moisture barrier leads to increased heat injuries including skin burns due to steam, when we are wet (US). New PPC gives greater heat stress (KR, AU, US). · Officers have to wear an ID vest over the turnout gear, which makes the heat problem worse (AU). · It would be beneficial to develop undershirts with tubing running over the trunk that could have a quick connection to circulate cold water during rehabilitation (US). · PPC gets frozen in winter when wet by water or sweat.
Over-protection	<ul style="list-style-type: none"> · Because current PPC is so effective at reducing the sensation of heat, we are getting caught deep in fires that are extremely hot. We don't know the temperatures we are getting into. Once the heat penetrates the gear it is almost too late to avoid flashover. Having gear that is too good gives a false sense of security. This causes more deaths and injuries to firefighters. A sensor could be incorporated into the PPC that warns us that we are in high temperature area (US).
Load and dimensions	<ul style="list-style-type: none"> · Equipment is very heavy and bulky when the gear is soaked by water (outer) and sweat (inner layer); when many tools/devices are added. Hard to move, hard to doff, and hard to raise the arms or feet when wet. · The waist area is especially bulky, often with layering of the coat over the pants, a belt for tools and the SCBA waist strap, making bending over at the waist almost impossible. Newer PPE is becoming bulkier, but any adjustments that add weight to the gear should be avoided. · Sizing of PPC does not take into account each individual's unique body shape. A female size system is especially needed. SCBA harnesses are really not user friendly for females. Female shoulders are not as wide as males, and the chest strap is sometimes not placed in the best place. For gloves, females have smaller hands with a smaller palm.
Cleaning and management	<ul style="list-style-type: none"> · PPC develops nasty smells from sweat, blood or contaminants. More deodorisation is required. · Current PPC absorbs too much water which increases the total weight. · Anti-pathogen layer choices are needed. · Flame-resistance is reduced as cleaning is repeated. · Lint on the fabric surface and shrinkage increase after repeating cleaning. It is hard to clean soot from the PPC and takes many hours to clean up the gear. · Light colours are avoided in terms of the cleaning and management. · It takes a long time to dry the wet PPC. Extra liners are needed because firefighters often wear their gear half-dried.

Comments have been pooled within categories. Unless otherwise indicated using country identifiers (AU [Australia], JP [Japan], KR [Korea], US [United States]), these comments were common to all four countries. PPC: personal protective clothing (turn-out gear); PPE: personal protective equipment; SCBA: self-contained breathing apparatus

Automatic body-cooling system

Japanese firefighters reported an automatic auxiliary cooling system as the most important of the 13 smart elements evaluated. This does not necessarily mean those firefighters experienced a greater incidence of heat illness. Instead, it could simply reflect an elevated thermal perception due to greater heat trapping within the PPC. It could also be related to the hot and humid Japanese summers, or perhaps to the length of heat exposure during fire suppression. Overheating is perceived by many to be the most common cause of firefighter injury. Whilst this is absolutely not the case for Australia's largest fire service (Fire & Rescue New South Wales)²⁶⁾, this statistic varies among nations. Moreover, it is perhaps one of the least controllable variables, and it represents a significant health problem for less-fit or older firefighters. Firefighters usu-

ally do not realise they are overheated until the symptoms reach dangerous levels. Therefore, slowing the rise in deep-body temperature helps prevent heat-related illness and the resultant cardiovascular and thermal regulatory complications³⁰⁾. In the present survey, the reasons that firefighters chose the automatic body-cooling system were to improve mental performance and increase work time. Body cooling (pre-cooling) prior to entering a fire scene will reduce cardiac strain and elevate work tolerance³²⁾, but it does not reduce the time taken to reach dangerously high deep-body temperatures^{32, 33)}. However, an automated body-cooling system that removes heat can achieve both outcomes³⁴⁾, but it might also increase the risk of entering dangerously hot sites due to a reduced thermal perception. Moreover, such a system will add significantly to the overall mass of the protective ensemble, and this will elevate

Table 4. Recommendations for item-specific improvements within the personal protective system

Element	Specific recommendations
Headgear: helmet, visor, facemask, and hood	<ul style="list-style-type: none"> · Helmet is heavy for long duration, which causes neck pain. The traditional US firefighter helmet styling lends to significant loading of the cervical spine with an impact to the front shield portion of the helmet, the back rim of the helmet or the lip that runs all around the outside of these helmets. Helmets fit poorly, especially the inner fit. The position of the helmet strap is poor. Leather pads inside helmets instead of material are preferred. Hearing and vision loss occur when wearing the helmet. The brim of the helmet is too big. The European style helmets are preferred for better protection and design (US). An incorporated microphone clip on the chin strap of the fire helmet is needed. Also adding radios, lights, cameras or GPS to helmets should be considered. · Interfaces between the hoods and face masks are poor (especially, around the ears and neck). Built in hoods in the collars of jackets are preferred. · The visor (mask) often fogs up and is hard to see through.
Breathing apparatus	<ul style="list-style-type: none"> · It's difficult to look up and when pulling down ceilings if the air pack is strapped in too high because the back brim of the helmet knocks the SCBA bottle. So shortening the bottle or having a stop on the straps to prevent over tightening helps avoid having to arch the back to look up. SCBA chest straps are usually too small. · Lighter and smaller SCBAs with a slimmer profile (lower or flat air packs) are preferred, especially for persons who are not tall. Metal components of the bailout harness should be lighter. A lower profile cylinder enables firefighters to fit inside tighter spaces and to get less entangled. · SCBA alters the centre of gravity of users and restricts mobility around the shoulder/arms. Also, when firefighters fall or slip on their back, they are likely to have significant injuries. · Integrated SCBA in jackets (a harness and rappelling bailout system) are preferred. · Hard to use radios or pockets because the SCBA straps block access to the pockets of the jacket. · The slow radiation of heat through heating of the SCBA affects the body.
Gloves	<ul style="list-style-type: none"> · Poor dexterity due to bulkiness and thickness, which make it difficult to grasp tools (e.g., radios), make a knot, hold a hose or pull ropes, especially in a zero-visibility environment. More flexibility and manoeuvrability are needed with thinner gloves for fingers. · Very difficult to put on/take off when hands are wet. Because the whole lining of the gloves comes off when taking off when they are wet and it is difficult to rearrange the gloves. Firefighters often hesitate to take off the wet gloves even though they feel uncomfortable. Liners that don't separate from the shells of gloves, and liners to keep hands dry or extra gloves are needed. · Current bunker jacket has both knitted cuff and thumb loop, but gloves also have a cuff. Replace current gloves with gauntlet style.
Boots	<ul style="list-style-type: none"> · Rubber boots are heavier, stiffer and have a poorer fit than leather boots. Rubber boots tend to cause blisters on the feet and chaffing injuries to the calves. Leather boots with a penetration proof sole plate are more supportive than the rubber boots, both on the ground and ladders. Better soles for rubber boots to prevent slip, trips and falls are needed. However, rubber boots are better for water areas on ground and less slippery in the winter time than leather ones. · The bottom edges at the ankles need to be stronger to keep from wearing off and creating a trip hazard. · Boots need to provide better thermal layering during cold temperatures. Turnout boots should be knee length to minimise hazardous material contact with lower legs via pants. Also the length of boots is not long enough in water areas. · Interfaces between turnout pant legs and boots are poor. At times the pant leg can ride up and get hooked on the top of the boot and cause an exposure problem around the calf. When wet, the boots become much heavier.

heat production and reduce mobility.

Wireless communication system

Wireless communication systems were ranked equally with 'vision support' and 'location monitoring' systems in all countries. This result may relate to the perception that a loss, or impairment, of communications may precipitate firefighter injury. In addition, current hand-held radio systems are often cumbersome, and can become entangled with external obstructions. As firefighters already have their hands full, then the traditional communication sys-

tems need to be simplified, perhaps through moving to integrated wireless communications. It is often reported that the radio messages are unclear³⁵⁾ and radio signals are weak³⁶⁾. Presumably, these radio communications also suffer from the same structural interferences that impede personal positioning devices. Therefore, both systems require enhancement.

Vision-support system and hands-free lighting system

Internal fire conditions are almost always blacked out with thick smoke also impairing search and rescue opera-

Table 4 continued.

Element	Specific recommendations
PPC (turnout jacket and overpants)	<ul style="list-style-type: none"> · Pockets: More easily accessible and water proof pockets are needed. The position and size of each pocket should be redesigned for each tool/devices (e.g., wire cutters, webbing, door wedges, radio, flashlight, electronic devices, etc.). The inside of pockets should be reinforced because tools tend to fray and create holes. More compartments instead of big bulky pockets are preferred. · Closures (clasps, zippers, velcro): Velcro/zippers are preferred to coat and pants clasps. Velcro is easier and more comfortable than zippers, because zipping up takes more time when moving out in emergency and zippers are often broken. Velcro makes the gear thinner so easier to move in, but may be poor after being exposed to heat. So velcro closures stitching needs to be triple stitched and such. Two-way zippers with nearly full length from the both sides of a turnout jacket are preferred, which allow for much easier reassembly of gear, doffing and donning possibly, and allow firefighters to open and vent on the lower half. If the zipper came a few inches short of the top in the jacket, and then a large “V” shaped closure could swing over, then it would be cooler because you don’t typically need the zipper to the top. · Suspenders and belt for overpants: Suspenders stretch too much, work loose after a short time and are uncomfortable when wet. Unstretchable suspenders are better than the stretchable suspenders. Metal (or plastic) suspender clips have a tendency to turn and dig into the shoulder when wearing SCBA (pain on the shoulders). The clips are often broken. · Protective pads: More padding is needed around the knee, elbows and the shoulder strap. Removable (detachable) pads to remove when worn out for the knee and elbows, but built in pads or double layering over the shoulder area are preferred. · Shell and liner: The moisture barrier layer hinders mobility and accumulates body heat. Quickly removable layered jackets are needed (e.g., one layer for car accidents, wild land fires or summer work, but two layers for structural fires). When crawling inside a structure fire, thermal protection around the upper and lower back are not the same because the liner and shell move independently of each other (One layered system is better). · Coverall style: One piece coverall style (pull up and zip up) would be better. As coveralls do not have the break between the pants and jacket, it is easy to don. We can save time while donning and also reduce the weight. · Interface: The wrists and neck are often exposed and get wet. Better waterproofing around these parts is needed to avoid getting steam-burns. The collar of the new coat hurts the neck. The cuffs become loose and do not dry fast. The thumb strap in the sleeves make wearing gloves more difficult. Emergency loop (for the drag rescue) built into the coat is needed. · Visibility and colours: It needs to have better visibility by sewing with reflective thread or attaching reflective trims that do not melt. High visibility colours are preferred. Specific marks to recognise the identity of firefighters are needed. · Size and fit: To get better range of motion in shoulder areas, larger arm holes give air space and ease of doffing. For people who have short but thick necks, it is hard to get the coat collar fastened without choking. As the front of jackets is too short, the stomach region may be exposed when arms are raised above the head. · Materials: Too stiff and too easily soaked. The exterior should have better waterproof fabrics, but quick-dry materials are needed for the liner. PPC is often torn with holes developing around the elbows and knees. Better durability and longevity of use is required for such regions. The aluminised coating on the bunker jacket is quickly worn out (JP).

Comments have been pooled within equipment elements. Unless otherwise indicated using country identifiers (AU [Australia], JP [Japan], KR [Korea], US [United States]), these comments were common to all four countries. GPS: global positioning system; PPC: personal protective clothing (turn-out gear); PPE: personal protective equipment; SCBA: self-contained breathing apparatus

tions, even when performed in good light. Since poor vision increases the risk of disorientation, and elevates firefighter anxiety and injury risk, then improved vision will be beneficial to faster rescues and quicker patient extraction. Visual support can be provided through fog-free visors, which prevent face-mask fogging on entry, and with helmet-mounted, smoke-penetrating lighting or infrared thermal imaging systems.

Alarm and monitoring system of air and object temperatures
Monitoring room air and hot-object temperatures can

help prevent flashover injuries and deaths, because those temperatures are a key to the recognition of an imminent flashover (air temperatures >400°C). Individual monitoring systems will also give firefighters advanced warning of changing conditions at the fire scene, when the local environment becomes dangerously overheated. The ability to read air and object temperatures prior to the initial fire attack may be more important in fires within light-weight truss construction, steel bow-string construction or fires involving flame impingement within closed vessels. Moreover, air temperature monitoring would assist with

decisions related to depth of entry for rescue or fire extinguishment (*e.g.*, air temperatures $>150^{\circ}\text{C}$ are untenable). Modern turnout gear allows firefighters to get deeper into buildings than ever before, but without feeling the heat. However, these life-threatening temperatures can now exceed the melting points of some components of the protective equipment.

Conclusions

In the present study, we have explored smart features that may be required, or at least seriously considered, for the next generation of firefighters' PPC and PPE. This information was acquired from a survey of almost 1,700 firefighters from Australia, Japan, Korea and the U.S. The most preferred smart features varied among these countries, but the top five elements identified were: personal location monitoring (highest priority), automated body cooling, wireless communication, vision support and hot-object alarm monitoring. The most appropriate technologies for achieving these outcomes remain to be further investigated. Notwithstanding these priorities, the addition of new support equipment must not adversely increase either the mass or bulkiness of the protective ensemble, which could significantly aggravate heat production, mobility and comfort. Therefore, developing simple and light devices that support firefighter performance and safety, without reducing comfort, are critical considerations when developing the next generation of firefighters' protective equipment.

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