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RESEARCH

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# Exploring the appropriate test methods to examine the effects of firefighter personal protective equipment on mobility

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## Abstract

This study aimed to ascertain the appropriate test methods for the investigation of the effect of personal protective equipment on mobility of firefighters. Nine male volunteers performed a physical performance test (crawl, obstacle course, side-to-side jumps, heavy-object drag, and step-ups), functional balance test (functional reach, timed up and go, and wooden plank time), range of motion test, and subjective evaluation under four clothing conditions with different weights and combinations of personal protective equipment. The results showed that physical performance, functional balance ability, and joint angles significantly declined with increased weight of personal protective equipment. On subjective evaluation, wearing heavy personal protective equipment increased perceived exertion and discomfort on movement. Our results proved that some of our test methods, including the obstacle course, side-to-side jumps, functional reach, timed up and go, range of motion test, and subjective evaluation, can be used to examine the mobility of personal protective equipment wearers. The findings of this study provide an effective guide for researchers and firefighters regarding the evaluation of mobility with personal protective equipment, as well as for manufacturers in the development of enhanced, comfortable personal protective equipment.

**Keywords:** Firefighter, Personal protective equipment, Mobility, Physical performance, Functional balance ability, Range of motion

## Introduction

Firefighters are continuously exposed to a multitude of hazards as a part of their job. A high level of physical performance and sufficient mobility is required for all firefighter duties such as protecting life and property and responding to fire alarms, medical emergencies, hazardous materials, and urban rescue. However, the heavy weight and bulkiness of personal protective equipment (PPE), which consists of personal protective clothing (PPC) and wearing gear such as masks, helmets, boots, gloves, and a self-contained breathing apparatus (SCBA), could adversely affect the firefighters' mobility during their work. According to survey on the working environment and satisfaction of firefighters while wearing PPE, firefighters have expressed that they prefer greater PPE comfort and ease of movement over improved protection (Lee et al., 2015; Tochihara et al., 2005). Approximately half of the respondents reported that wearing PPE restricted their mobility, defined as the degree of body movement at the scene of a fire.

Research on the mobility of PPE wearers and discussions on international standards have been ongoing until recently, although the number of studies is smaller than that on the thermal strain and heat resistance of PPE. EN 469 specifies performance requirements for firefighters' PPE, such as general design, material durability/resistance, and the test methods for determination of these performance levels. ISO/TS 11999-2 (2015) and ISO, 13688 2013 provide general performance guidelines on ergonomics, innocuousness, size designation, aging, marking of PPE information, and compatibility. While this standard specifies the ergonomic features of PPE performance, there are limited studies on achieving improvements in movements, such as standing, sitting, walking, climbing, and arm or trunk movements. All these standards mainly focus on the PPE's design, chemical performance of the material (EN469, 2020), and compatibility related to PPE ensembles or combinations (ISO/TS 11999-2, 2015; ISO, 13688 2013); however, the methods for evaluating firefighters' mobility while wearing the PPE are not indicated. BS 8469 (2007) specifies the requirements and test methods for the ergonomic features of the PPE's practical performance levels, participant numbers in the benchmark and comparative tests, and PPE items that should be worn. The simulated firefighting activities that have been suggested for evaluating mobility restrictions imposed by PPE include walking, climbing, overcoming windowsill obstacles, and hose rolling and crawling. The completion time or frequency of performance and subjective evaluations of the wearer's movement are used to rate the mobility levels while wearing PPEs. In BS 8469, mobility levels are determined based on the results of the performance test; however, BS 8469 does not specify the effect of several types of PPE, with different designs and weights, on the wearer's mobility. Moreover, the effects of static movements, such as joint motion and balance ability motion, are not considered.

On reviewing previous studies, which have evaluated the mobility of PPE wearers other than the above standards, simple and effective test methods for measuring mobility in a PPE-wearing state can be obtained. Several research groups have measured mobility while wearing PPE and have shown that functional balance is impaired due to wearing of PPE, resulting in slow movements, decreased reach performance, and increased errors. These measurements were performed using the functional reach test (FRT), timed up and go (TUG) test, and wooden plank time (WPT) test. These studies have reported declining mobility on wearing PPE (Hur et al., 2013; Kong et al., 2012; Orr et al., 2019; Punakallio et al., 2004; Son et al., 2014). A few other studies have compared mobility variation due to wearing different PPE combinations and designs using range of motion (ROM) test parameters (Ciesielska-Wróbel et al., 2017; Coca et al., 2008, 2010; Son et al., 2010).

Thus, it is necessary to comprehensively evaluate the effect of various PPE combinations on mobility by applying the existing test methods and thereby proposing appropriate test methods to measure mobility when wearing PPE. Therefore, this study aimed to ascertain appropriate test methods for the objective measurement and comparison of wearer mobility with various PPEs. Further, we investigated how PPE differences in weight and combination affect a wearer's mobility by using simple and valid measurements, such as physical performance, balance ability, ROM, and subjective evaluations.

## Methods

### Participants

The study participants were nine healthy Asian male volunteers (mean ± standard deviation: age, 24.6 ± 3.1 years; height, 171.2 ± 5.2 cm; body weight, 63.8 ± 8.5 kg; body mass index, 22.1 ± 0.6 kg/$m^2$; and body fat (%), 14.3 ± 5.1%). All participants were informed about the experimental procedures and risks before obtaining written consent. All experimental procedures were approved by the ethics committee of Kyushu University (IRB number: #H24-129).

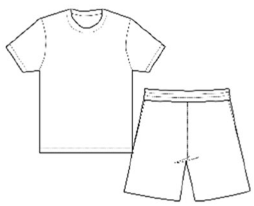
### Experimental design and procedures

The present study was designed to include three tests: physical performance, functional balance, and ROM tests. The tests were conducted on two different days. On day 1, a physical performance test was conducted, and on the other day of testing, functional balance and ROM tests were conducted. Functional balance and ROM tests were performed with sufficient recovery time between each test. The sequences of the three tests were randomized. At the endpoint of the physical performance test, rate of perceived exertion (RPE) and perceived muscle fatigue, discomfort, movement, and sweat sensation were self-evaluated by the participants. Body regional mobility and comfort were subjectively evaluated at the end of the functional balance and ROM tests. All experiments were conducted at the Experimental House for Living Space Design, during the summer season (mean outside temperature, 32.4 ± 2.4 °C and mean relative humidity, 73.2 ± 6.3%). The temperature and relative humidity of the experimental house were maintained under 26 °C and 50% using an air conditioning system.

### Experimental clothing conditions

We tested four experimental clothing conditions with one regular exercise clothing ensemble and three different ensembles of PPE with and without SCBA. The baseline condition corresponded to wearing regular exercise clothing consisting of T-shirts, short pants, socks, and running shoes, with a total weight of 1.1 kg. The PPC clothing condition corresponded to wearing firefighter turnout jackets and pants made of aramid material, station uniforms, gloves, a helmet, a gear belt with a rope, and rubber boots. The total weight of PPC conditions was 8.7 kg. The light SCBA condition (L-SCBA) corresponded to wearing a SCBA consisting of a 6.9 kg carbon fiber-reinforced aluminum alloy cylinder with a standard strap combined with the PPC clothing condition; the face mask was carried, but not worn on the face. The total weight of the L-SCBA condition was 15.6 kg. The heavy SCBA condition (H-SCBA) corresponded to wearing a 13.1 kg chromium-molybdenum steel cylinder with a standard strap combined with the PPC clothing condition; the face mask was carried, but not worn on the face. The total weight of the H-SCBA condition was 21.8 kg. The clothing conditions tested in this study are compared in Table 1.

**Table 1** Comparison of clothing conditions

| Baseline | PPC | L-SCBA | H-SCBA |
|---|---|---|---|
| Regular exercise clothing (T-shirts and short pants), socks, and running shoes | Firefighter turnout jackets and pants (90% meta-aramid and 10% para-aramid), station uniforms (shirts: 55% acrylic and 45% cotton, pants: 20% polyester, 75% meta-aramid, and 5% para-aramid), gloves, helmet, gear belt with rope, and rubber boots | PPC and light SCBA (6.9 kg of carbon-fiber reinforced aluminum alloy cylinder with face mask carried on the body) | PPC and heavy SCBA (13.1 kg of chromium molybdenum steel cylinder with face mask carried on the body) |
|  |  |  |  |
| 1.1 kg | 8.7 kg | 15.6 kg | 21.8 kg |

*PPC* personal protective clothing; *SCBA* self-contained breathing apparatus

## Test methods for mobility evaluation

### *Physical performance test*

The physical performance test was set by referring to the firefighting activities that cause physical strain in firefighters with PPE (Son et al., 2014). In the physical performance test, participants randomly performed tasks that were similar to the actual work performed by firefighters: (1) crawl: crawling on the ground for 20 m; (2) obstacle course: completing three sets of 24 m sprints combined with crossing a 70 cm obstacle and passing under a 100 cm obstacle; (3) side-to-side jumps: jumping side to side as many times as possible for 20 s; (4) heavy-object drag: dragging a 20 kg object for 20 m; and (5) step-ups: stepping up and down on a 45 cm bench 20 times in 1 min. The performance time was measured for the crawl, obstacle course, and heavy-object drag, whereas performance frequency was measured for the side-to-side jumps. Participants' heart rates were recorded using a heart rate monitor (RS400; Polar Electro, Kempele, Finland) during the test to ensure safety and to measure performance.

### *Functional balance test*

The participants were randomly assigned to performing three types of functional balance test, as shown in Fig. 1.

In the FRT test, the right hand and right shoulders were set as the measuring points. The participants were asked to stand up and stretch their right hand forward in a straight line to measure the start position. After the start signal, the participants extended their right arms forward as far as possible while maintaining controlled balance (Kage et al., 2009). We recorded the length of the participants' outstretched right arms in the maximal forward reach. The length of FRT was measured using a three-dimensional (3D) motion analysis system (EVaRT 5.0.4, Motion Analysis Corp,

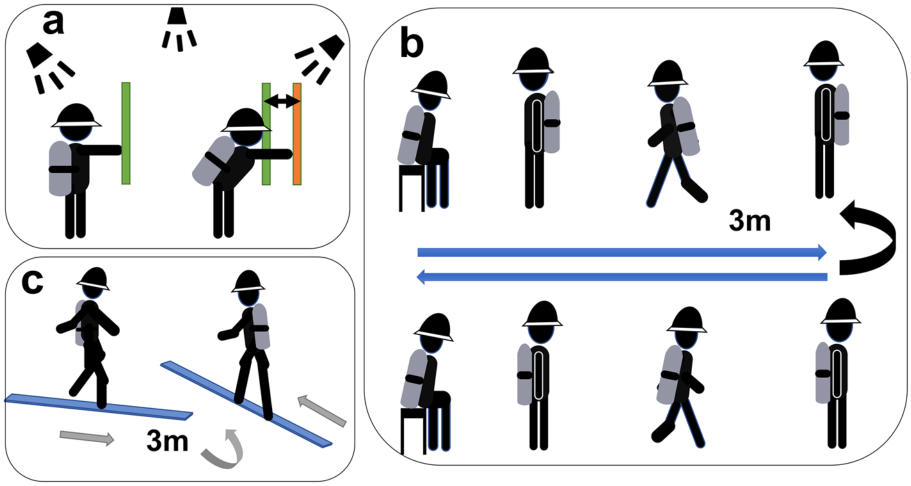



**Fig. 1** Functional balance test. **a** Functional reach test: participants extended their right arms forward as far as possible with controlled balance; **b** timed up and go: participants stood up, walked in a straight line at their normal walking speed for 3 m, returned to the starting point, and sat down on the stool again without using their hands; **c** wooden plank time: participants crossed a 3 m wooden plank (height, 9 cm and width, 5 cm) from one end to the other while maintaining their balance and returned to the start position

Santa Rosa, CA, USA; KineAnalyzer, Kissei Comtec Corp, Matsumoto, Japan). All measurements were amplified and sampled at 60 Hz.

To begin the TUG test, all participants were seated on a stool. When given the start signal, the participants stood up and walked in a straight line at their normal walking speed for 3 m. Thereafter, they were asked to return to the starting point and sit down on the stool again without using their hands. The time required to complete the stand-up-walk-sit task was recorded (Steffen et al., 2002; Thrane et al., 2007).

In the WPT test, the participants crossed a 3-m wooden plank (height, 9 cm and width, 5 cm) from one end to the other while maintaining their balance and were asked to return to the start position. They were asked to walk as rapidly as possible and their completion time was recorded. If they made a performance error (such as losing their balance and stepping on the floor instead of plank), 1 s was added to the performance time for each mistake (Punakallio et al., 2004).

#### *ROM test*

In the ROM test, the variation of the joint angle for six shoulder and three lumbar motions was measured by the 3D motion analysis system, similar to the FRT, using infrared markers, which are attached to the participants' joints. The experimental motions were as follows: shoulder adduction, abduction, flexion, extension, horizontal adduction, horizontal abduction, lumbar flexion, extension, and rotation. The moved shoulder and lumbar joint angles were calculated as the value of the starting position minus that of the end position (Fig. 2).

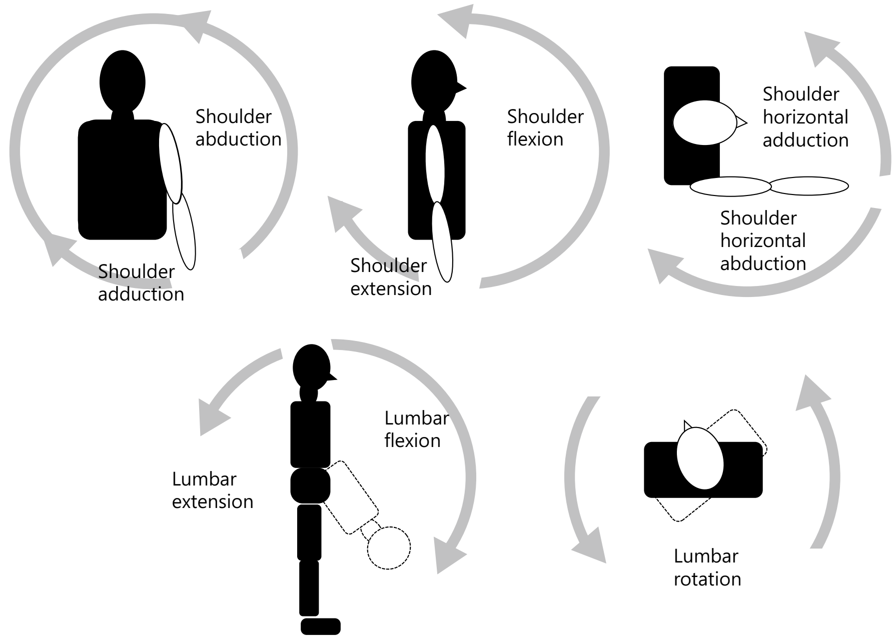



**Fig. 2** Experimental posture of range of motion. The postures presented above are starting postures of shoulder adduction, abduction, flexion, extension, horizontal adduction, horizontal abduction, and lumbar flexion, extension, and rotation. Participants moved their arms or upper body in the direction of the arrow, and the maximum moved angles of their shoulders or upper body were measured as the range of motion

### Subjective evaluations

After each task in the physical performance test, participants responded to a questionnaire on the RPE and subjective-evaluated perceived muscle fatigue, discomfort, movement, and sweat sensation on a 7-point scale from 1 (not at all) to 7 (maximum). Moreover, participants were asked to subjectively evaluate their body's regional mobility (head and neck, arms, elbows, wrists, waist, thighs, knees, ankles, pelvis, and hips) and wearer comfort by answering seven questions ("How comfortable does the clothing fit?"; "How comfortable do you feel when you bend the body wearing this ensemble?"; "How comfortable do you feel when moving with this ensemble?"; "How comfortable do you feel when you lift your arms with this ensemble?"; "How comfortable do you feel when you lift your legs with this ensemble?"; "How comfortable is the bulkiness of this ensemble?"; and "How comfortable is the weight of this ensemble?") on a 7-point scale from 1 (very difficult to move or uncomfortable) to 7 (very easy to move or comfortable) after the functional balance and ROM tests.

### Statistical analysis

The non-subjective changes in mobility according to the PPE load were calculated as percentages of the relative changes by PPE ensemble compared to baseline values (BS8469, 2007; Son et al., 2010). The absolute values of each test result were statistically processed using SPSS (version 23.0, SPSS Inc. Chicago), and four conditions were compared. One-way analysis of variance was conducted to assess the effects of the three ensembles of PPE. Tukey's post-hoc test was used to determine statistically significant differences in the results. Statistical significance was set at $p < 0.05$. For the subjective evaluation results, tests for normality indicated that the assumption of normality was unmet; thus, the Kruskal–Wallis test was used for the analysis. Dunn's pairwise tests were carried out for the six pairs of the conditions. Statistical significance was set at $p < 0.05$.

## Results

### Physical performance test

The results of the physical performance tests are presented in Table 2. Significant differences were found between the four conditions in the performance time of the obstacle course and heart rate after step-ups. The performance time on the obstacle course under the condition was significantly shorter than that under the three PPE conditions (PPC: $p < 0.01$; L-SCBA and H-SCBA: $p < 0.001$). In addition, the performance time increased with the increased weight of clothing. Statistically, a significant difference in obstacle course performance time was found between PPC and H-SCBA conditions ($p < 0.001$). However, no significant difference was observed between the PPC and L-SCBA conditions. The heart rate of participants after step-ups was higher for all PPE conditions (PPC, L-SCBA, and H-SCBA: $p < 0.001$) than that at the baseline. The relative increase in the physical performance from the baseline to the PPC, L-SCBA, and H-SCBA conditions were 15%, 22%, and 30%, respectively.

### Functional balance test

The results of the functional balance tests are shown in Table 3. Significant differences were found among the four conditions for the FRT and TUG tests. The scores were not significantly different between the baseline and PPC conditions. However, the FRT score for the PPE with SCBA conditions were statistically less than that in the baseline condition ($p < 0.001$). Moreover, wearing additional L-SCBA or H-SCBA reduced arm reach distance compared with wearing only PPC (L-SCBA, $p < 0.05$ and H-SCBA, $p < 0.001$). No significant differences were found between the L-SCBA and H-SCBA conditions. In the TUG test, the mean score for the baseline conditions was significantly lower than that in any of the PPE conditions (PPC and L-SCBA, $p < 0.05$; H-SCBA, $p < 0.001$). However, there were no significant differences between the three PPE conditions (Table 3). In the WPT test, no significant differences were found. The relative increase in functional

**Table 2** Physical performance test

| | Baseline | PPC | L-SCBA | H-SCBA | *F* | *p* | Tukey test |
|---|---|---|---|---|---|---|---|
| Crawl (s) | 28.0 ± 8.0 | 31.0 ± 7.0 | 33.0 ± 7.0 | 36.0 ± 6.0 | 2.3 | 0.098 | |
| Obstacle course (s) | 16.0 ± 2.0 | 21.0 ± 3.0 | 23.0 ± 2.0 | 26.0 ± 3.0 | 22.3 | < 0.001 | a < b < c, d |
| Side-to-side jumps (times/20 s) | 39.0 ± 9.0 | 37.0 ± 5.0 | 35.0 ± 6.0 | 33.0 ± 5.0 | 1.6 | 0.210 | |
| Heavy-object drag (s) | 42.0 ± 8.0 | 43.0 ± 6.0 | 45.0 ± 4.0 | 45.0 ± 7.0 | 0.5 | 0.695 | |
| Heart rate after step-ups (bpm) | 107.0 ± 13.0 | 131.0 ± 8.0 | 135.0 ± 9.0 | 138.0 ± 11.0 | 15.9 | < 0.001 | a < b, c, d |

Results are presented as mean ± standard deviation

a: Baseline, b: PPC, c: L-SCBA, d: H-SCBA

*PPC* personal protective clothing; *L-SCBA* light self-contained breathing apparatus; *H-SCBA* heavy self-contained breathing apparatus

**Table 3** Functional balance test

| | Baseline | PPC | L-SCBA | H-SCBA | *F* | *p* | Tukey test |
|---|---|---|---|---|---|---|---|
| FRT | 36.4 ± 6.8 | 32.3 ± 3.8 | 25.8 ± 4.3 | 22.5 ± 4.7 | 13.9 | *p* < 0.001 | a, b > c, d |
| TUG | 7.2 ± 0.9 | 8.4 ± 0.9 | 8.4 ± 0.8 | 9.2 ± 0.8 | 7.9 | *p* < 0.001 | a > b, c, d |
| WPT | 7.0 ± 1.1 | 7.2 ± 1.3 | 7.9 ± 1.5 | 8.4 ± 1.3 | 1.8 | 0.168 | |

The values are presented in seconds (s)

Results are presented as mean ± standard deviation

a: Baseline, b: PPC, c: L-SCBA, d: H-SCBA

*PPC* personal protective clothing; *L-SCBA* light self-contained breathing apparatus; *H-SCBA* heavy self-contained breathing apparatus; *FRT* functional reach test; *TUG* timed up and go; *WPT* wooden plank time

**Table 4** Range of motion test

| | Baseline | PPC | L-SCBA | H-SCBA | *F* | *p* | Tukey test |
|---|---|---|---|---|---|---|---|
| *Shoulder* | | | | | | | |
| Adduction | 45.2 ± 11.9 | 33.2 ± 12.5 | 13.2 ± 6.0 | 12.6 ± 4.5 | 26.3 | < 0.001 | a > b > c, d |
| Abduction | 135.3 ± 11.0 | 110.4 ± 15.3 | 91.3 ± 19.5 | 81.6 ± 11.5 | 23.3 | < 0.001 | a > b > c, d |
| Flexion | 112.2 ± 8.2 | 96.9 ± 13.2 | 82.2 ± 6.8 | 84.6 ± 7.1 | 20.1 | < 0.001 | a > b > c, d |
| Extension | 49.9 ± 13.6 | 43.9 ± 9.3 | 45.2 ± 5.9 | 39.8 ± 9.4 | 1.0 | 0.386 | |
| Horizontal adduction | 51.5 ± 8.0 | 48.3 ± 13.8 | 42.6 ± 15.3 | 38.4 ± 14.0 | 1.5 | 0.226 | |
| Horizontal abduction | 145.2 ± 8.6 | 137.8 ± 9.6 | 136.1 ± 12.9 | 135.1 ± 12.4 | 1.8 | 0.168 | |
| *Lumbar* | | | | | | | |
| Flexion | 98.8 ± 21.5 | 97.8 ± 20.6 | 87.0 ± 25.7 | 81.5 ± 23.6 | 1.2 | 0.318 | |
| Extension | 63.2 ± 22.9 | 61.8 ± 21.9 | 53.7 ± 16.9 | 48.2 ± 14.5 | 1.2 | 0.327 | |
| Rotation | 86.8 ± 12.3 | 84.8 ± 17.7 | 67.8 ± 15.7 | 59.0 ± 12.6 | 6.8 | 0.001 | a, b > c, d |

The values are presented in degrees

Results are presented as mean ± standard deviation

a: Baseline, b: PPC, c: L-SCBA, d: H-SCBA

*PPC* personal protective clothing; *L-SCBA* light self-contained breathing apparatus; *H-SCBA* heavy self-contained breathing apparatus

balance from the baseline to the PPC, L-SCBA, and H-SCBA conditions were 11%, 20%, and 29%, respectively.

## ROM test

The ROM of the joint angles decreased with PPE use (Table 4). Significant differences among the four conditions were found in shoulder adduction, abduction, flexion, and lumbar rotations. In shoulder adduction, the baseline conditions showed the highest ROM values among all conditions (PPC, $p < 0.05$; L-SCBA and H-SCBA, $p < 0.001$). Wearing additional L-SCBA or heavy H-SCBA decreased the ROM of the joint angles compared with the PPC condition ($p < 0.001$). In shoulder abduction, the baseline conditions showed higher ROM values compared to the other conditions (PPC, $p < 0.01$; L-SCBA and H-SCBA, $p < 0.001$). Participants in the PPC condition were more likely to move the shoulder joint than those in the L-SCBA ($p < 0.05$) and H-SCBA ($p < 0.01$) conditions. In shoulder flexion, reductions in ROM values were observed when comparing

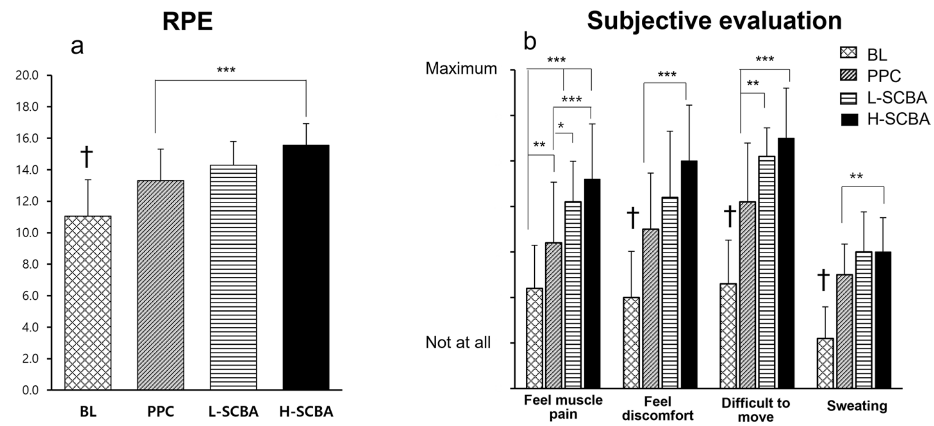



**Fig. 3** Participants rated perceived exertion, and subjective evaluation in four personal protective equipment conditions. **a** Rated perceived exertion; **b** Muscle fatigue, discomfort, movement, and sweat sensation. Cross marks indicate statistically significant differences between baseline and PPE conditions (PPC, L-SCBA, and H-SCBA, $p < 0.001$). Asterisks indicate conditions showing statistically significant differences when comparing experimental conditions (* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$). BL: baseline; PPC: personal protective clothing; L- SCBA: light self-contained breathing apparatus; H-SCBA: heavy self-contained breathing apparatus; RPE: rate of perceived exertion

the baseline and other conditions (PPC, $p < 0.01$; L-SCBA and H-SCBA, $p < 0.001$). The ROM of the PPC condition was higher than that of the L-SCBA ($p < 0.01$) and H-SCBA ($p < 0.05$) conditions. In the lumbar motions, we found differences in rotation due to SCBA wearing. The ROM values in the H-SCBA condition were lower than those in the baseline and PPC conditions ($p < 0.01$). The mean values of the relative decrease in the ROM all over the body from the baseline to the PPC, L-SCBA, and H-SCBA conditions were 8%, 22%, and 28%, respectively.

## Subjective evaluation

When self-evaluating their RPE and muscle fatigue, discomfort, movement, and sweat sensation after the physical performance test, participants reported significantly worse rates under the baseline condition compared to the PPE conditions ($p < 0.01$). Furthermore, wearing additional H-SCBA increased the RPE and decreased the subjective evaluation values (PPC vs H-SCBA, $p < 0.01$, Fig. 3). In addition, there were significant differences in muscle fatigue ($p < 0.05$) and movement ($p < 0.01$) between the PPC and L-SCBA conditions. Almost all participants indicated that their body's regional mobility while wearing any type of PPE was significantly worse than that while wearing the baseline clothing (PPC, $p < 0.05$; L-SCBA, $p < 0.01$; H-SCBA, $p < 0.001$). Participants in the H-SCBA condition reported a statistically lower rating of waist mobility than those in PPC condition ($p < 0.05$). Participants reported that wearing a full set of PPE ensemble was significantly more uncomfortable than the baseline condition (L-SCBA, $p < 0.01$; H-SCBA, $p < 0.001$). For bulkiness, there were significant differences between the baseline and PPC conditions ($p < 0.05$).

## Discussion

### How do differences in weight and combination of PPE affect wearer mobility?

Wearer mobility was better in the non-PPE than in the PPE conditions and worse in the H-SCBA condition than in the other PPE conditions. The physical performance, functional balance, and ROM were gradually decreased as participants wore 8.7 kg of PPC, 15.6 kg of L-SCBA, and 21.8 kg of H-SCBA, indicating that increasing total equipment weight leads to a significant decline in the ability of wearers to perform movement. In general, stiff and bulky PPC and heavy SCBA cause strain, fatigue, and restricted joint angles and reduce physical performance and balance ability (Coca et al., 2008, 2010; Hur et al., 2013; Son et al., 2010, 2014).

While the effect of PPC on wearer mobility has seldom been evaluated, some previous studies have reported findings similar to those of the present study. Kong et al. (2012) reported that firefighters walk slowly while wearing PPC to maintain their balance. Son (2018) used the ROM test to evaluate decreased mobility due to wearing PPC. The participants wore 3 kg of PPC without a helmet, gloves, and boots; ROM values were significantly decreased by approximately 13%. In the present study, statistically significant differences were observed between baseline and PPC conditions, and the decreased mobility due to wearing 8.7 kg of PPC was verified on physical performance, functional balance, ROM, and subjective evaluation. These results indicate that even when wearing PPC only, heavy bulky designs limit wearer mobility.

The objective quantitative differences in the test results between the different SCBA weights, such as performance time, errors, and parameters of balance ability, have been confirmed in our study, which are consistent with the findings of previous research (Hur et al., 2015; Kesler et al., 2018). Son et al. (2010) found a 13.7% decline in ROM while wearing an additional 10 kg of SCBA, which is similar to the findings of our study. Over 20% of reduced mobility when additionally wearing light SCBA (15.6 kg) or heavy SCBA (21.8 kg) were observed in terms of physical performance, functional balance, and ROM tests.

### Which test method is effective for evaluating wearers' mobility for PPE?

An important finding in this study is that the test method consisting of physical performance, functional balance, ROM tests, and subjective evaluation can be used to measure and validate PPE wearer mobility. In the physical performance test, a decline in mobility due to wearing PPE was shown through the longer performance time for the obstacle course and the increased heart rate in the step-ups. In particular, the obstacle course scores under the H-SCBA condition showed a longer performance time compared with the PPC condition. Son et al. (2014) assessed physical performance for two types of PPE similar to that in the present study and in a comparable participant group. They concluded that firefighters are a suitable participant group for the mobility test method; however, statistical differences were found in the obstacle course and the step-ups tasks under the group of non-firefighters, similar to that in the present study (Son et al., 2014). The obstacle course and step-ups tasks were used for mobility assessment when wearing PPE (BS8469, 2007; Hur et al., 2013; Petrucci et al., 2016; Son et al., 2014), and BS 8469 (2007) established four mobility levels based on the relative performance time changes due to PPE. In each task, performance times > 200%, > 150%, > 110%, and < 110% of the performance times in the baseline conditions were rated as 1, 2, 3, and 4, respectively. Thus, these two tasks are suitable as simple physical performance tests to measure PPE mobility.

As the final outcome, significant differences were observed among the different experimental conditions in the FRT and TUG tests, but not in the WPT test. Previous studies have determined that wearing PPE reduced the reach distance measured in FRT tests (Coca et al., 2008, 2010; Son et al., 2014). The reach distance reported in previous studies presented reductions when wearing PPE, wet PPE, and heavy SCBAs compared to ordinary sportswear and improved PPE (Coca et al., 2008, 2010, 2011). Similar results were shown in the present study. FRT test results showed significant differences between the SCBA and non-SCBA conditions (baseline and PPC vs. L-SCBA and H-SCBA), which further declined as the PPE weights increased. In a study by Son et al. (2014), it was difficult to assess mobility according to the different designs and similar weights of PPEs. Moreover, it was not possible to evaluate the effect of PPC on wearer mobility in the FRT test; however, restricted mobility due to the weight of additional SCBAs increased, although the participants were non-firefighters. Therefore, the FRT test, a simple method for evaluating the deteriorated mobility which reflects the center of pressure (Kage et al., 2009), appears to be a suitable measurement of mobility with PPE.

The TUG test is typically used to compare balance ability among different ages; however, the participants included in this study were all healthy and young. Despite this, we found that TUG performance times increased with increasing PPE weight while wearing PPC, H-SCBA, and L-SCBA components compared with the baseline condition. Since a high TUG score indicates low balance ability (Steffen et al., 2002), it follows that wearing PPE has a negative effect on mobility. Son et al. (2014) compared pre- and post-TUG test scores of participants performing a suppression task; however, statistical differences were observed under one PPE condition only when the participants were firefighters. In the present study, statistically significant differences in TUG scores were observed when comparing the baseline and PPE conditions, although the participants did not perform any strenuous physical tasks. This suggests that the TUG test may be a reasonable method for measuring mobility variation depending on whether the participant is wearing PPE.

Punakallio et al. (2003) reported that PPE causes deterioration of WPT scores, namely decreased balance ability, in both young and old firefighters. Moreover, another study reported that firefighters walked slowly while performing the WPT test with PPE (Kong et al., 2012). However, significant differences were not observed in the present study when comparing the non-PPE and PPE conditions. In the case of Hur et al. (2013), the WPT test was assessed for evaluating mobility with PPE when combined with an obstacle stride. The walking speed decreased during firefighting while wearing PPE. Thus, using WPT in combination with an obstacle stride would have a higher validity as a mobility test method than when used alone.

PPE wearer mobility was affected by the design and materials of the PPE, and ROM was a significant measurement (Ciesielska-Wróbel et al., 2017; Son, 2019). In the present study, ROM differences between PPE and non-PPE conditions were found to be statistically significant for shoulder adduction, abduction, and flexion. In addition, restricted mobility due to light or heavy SCBAs was shown in our study, and an increase in 10 kg of SCBA weight was associated with a 13.7% reduction in ROM in a previous study (Son et al., 2010). Moreover, lumbar rotation under SCBA conditions was significantly smaller than that under regular exercise clothing and PPC conditions. The weight and harness system of PPE may reduce the joint angles of the shoulder and lumbar region, and we found that the ROM test is an appropriate way to test wearer mobility.

Subjective evaluation following dynamic or static test has previously been used to evaluate wearer mobility (Coca et al., 2011; Orr et al., 2019; Park & Langseth-Schmidt, 2016; Son et al., 2010, 2014). The objective scoring of the physical performance of participants shows similar tendencies regarding their comfort and restricted body areas (Orr et al., 2019; Park & Langseth-Schmidt, 2016). The subjective ratings of comfort while wearing PPE have also been reported by other researchers (Coca et al., 2008, 2011). However, Coca et al. (2010) mentioned that it is difficult to examine the effect of PPE by subjective evaluation only. In the present study, almost all participants responded that their mobility was significantly worse while wearing any type of PPE than while wearing none. Most of the subjective evaluations on PPE conditions, especially when wearing a SCBA, revealed that participants perceived high levels of RPE, discomfort, difficulty of movement, and restrictions in body joint mobility while wearing the equipment, as well as decreased mobility during physical performance tests. In addition, participants perceived significantly more discomfort when bending forward with a combination of PPC and SCBA than when wearing PPC alone. Son et al. (2014) reported that subjective mobility evaluation by firefighters may be an effective way to measure mobility, due to their familiarity with PPE. Although the participants in our study were not firefighters, we found statistically significant differences in the subjective evaluations. The subjective opinions and perceptions of PPE wearers when performing heavier exercise and more complex movement are also important. Therefore, including subjective evaluations in the test methods for wearer mobility may be an appropriate measure when examining PPE safety and efficacy.

### Study limitations

In the present study, statistically significant effects may have been limited by the fact that the participants were not firefighters and thus had no physical training and expertise in using PPE. Additionally, this study was conducted among Japanese males, and we tested the firefighter PPE commonly used in Japan. Hence, we cannot determine whether the test methods proposed in the present study can be applied regardless of the race, country, sex, and PPE design. Therefore, to increase the reliability of the proposed test methods for evaluating PPE wearer mobility, additional validation will be necessary to consider race, sex, and firefighter status.

## Conclusions

The results of our study show that increasing PPE weight leads to a decline in mobility of the wearer which is indicated by decreased physical performance, functional balance ability, and angular movement. Among the five tasks in the present performance test, the obstacle course and step-ups are considered validated test methods for measuring mobility, even when participants are not used to wearing PPE. The functional balance tests are effective measurements for assessing mobility among PPE wearers, especially the FRT and TUG tests, which are more convenient and reliable than the other measurements. The validity of the WPT test was not confirmed in this study; however, its combination with an obstacle stride would likely have increased its validity as a test method compared to that when used alone. Moreover, ROM is a relatively simple method to test mobility depending on the design and weight of PPE, as well as the effect of wearing PPE itself. Subjective evaluation potentially provides supplementary measurements of mobility when assessed after a dynamic movement. The subjective opinions and perceptions of PPE wearers are important evaluation criteria, even if the wearers are not firefighters. The findings from this study may provide a guide for researchers and firefighters in the evaluation of PPE mobility as well as manufacturers in the development of enhanced, comfortable PPE.

**Abbreviations**

| | |
|---|---|
| FRT | Functional reach test |
| H-SCBA | Heavy self-contained breathing apparatus |
| L-SCBA | Light self-contained breathing apparatus |
| PPC | Personal protective clothing |
| PPE | Personal Protective equipment |
| ROM | Range of motion |
| RPE | Rate of perceived exertion |
| SCBA | Self-contained breathing apparatus |
| TUG | Timed up and go |
| WPT | Wooden plank time |

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**Author contributions**
SYS participated in the experiment and analyzed data and drafted the manuscript. SM participated in the discussion and manuscript preparation. YT conceptualized the entire research and designed the study plan and participated in the discussion and manuscript preparation. All authors read and approved the final manuscript.

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## Declarations

**Competing interests**
The authors declare that they have no competing interests.

**Ethics and consent to participate**
This research was conducted under the approval and supervision of Kyushu University Institutional Review Board (IRB Approval No.: #H24-129) regarding ethical issues including consent to participate.

**Availability of data and materials**
The datasets used and/or analysed during the current study are available from the corresponding author on reasonable request.

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**References**

Ciesielska-Wróbel, I., DenHartog, E., & Barker, R. (2017). Measuring the effects of structural turnout suits on firefighter range of motion and comfort. *Ergonomics, 60*(7), 997–1007. https://doi.org/10.1080/00140139.2016.1229044

BS 8469. (2007). Personal Protective Equipment for Firefighters. Assessment of ergonomic performance and compatibility. In: Requirements and test methods. British Standard Institute.

Coca, A., Kim, J. H., Duffy, R., & Williams, W. J. (2011). Field evaluation of a new prototype self-contained breathing apparatus. *Ergonomics, 54*(12), 1197–1206. https://doi.org/10.1080/00140139.2011.622797

Coca, A., Roberge, R., Shepherd, A., Powell, J. B., Stull, J. O., & Williams, W. J. (2008). Ergonomic comparison of a chem/bio prototype firefighter ensemble and a standard ensemble. *European Journal of Applied Physiology, 104*(2), 351–359. https://doi.org/10.1007/s00421-007-0644-z

Coca, A., Williams, W. J., Roberge, R. J., & Powell, J. B. (2010). Effects of fire fighter protective ensembles on mobility and performance. *Applied Ergonomics, 41*(4), 636–641. https://doi.org/10.1016/j.apergo.2010.01.001

EN 469. (2020). Protective clothing for firefighters – Performance requirements for protective clothing for firefighting activities. European Standards.

Hur, P., Park, K., Rosengren, K. S., Horn, G. P., & Hsiao-Wecksler, E. T. (2015). Effects of air bottle design on postural control of firefighters. *Applied Ergonomics, 48*, 49–55. https://doi.org/10.1016/j.apergo.2014.11.003

Hur, P., Rosengren, K. S., Horn, G. P., Smith, D. L., & Hsiao-Wecksler, E. T. (2013). Effect of protective clothing and fatigue on functional balance of firefighters. *Journal of Ergonomics*. https://doi.org/10.4172/2165-7556.S2-004

International Organization for Standardization. (2013). *Protective clothing - General requirements (ISO Standard No. 13688:2013)*. https://www.iso.org/standard/51449.html

International Organization for Standardization. (2015). *PPE for firefighters - Test methods and requirements for PPE used by firefighters who are at risk of exposure to high levels of heat and/or flame while fighting fires occurring in structures - Part 2: Compatibility (ISO Standard No. 11999-2:2015)*. https://www.iso.org/obp/ui#iso:std:iso:ts:11999:-2:ed-1:v1:en

Kage, H., Okuda, M., Nakamura, I., Kunitsugu, I., Sugiyama, S., & Hobara, T. (2009). Measuring methods for functional reach test: Comparison of 1-arm reach and 2-arm reach. *Archives of Physical Medicine and Rehabilitation, 90*(12), 2103–2107.

Kesler, R. M., Deetjen, G. S., Bradley, F. F., Angelini, M. J., Petrucci, M. N., Rosengren, K. S., Horn, G. P., & Hsiao-Wecksler, E. T. (2018). Impact of SCBA size and firefighting work cycle on firefighter functional balance. *Applied Ergonomics, 69*, 112–119. https://doi.org/10.1016/j.apergo.2018.01.006

Kong, P. W., Suyama, J., Cham, R., & Hostler, D. (2012). The relationship between physical activity and thermal protective clothing on functional balance in firefighters. *Research Quarterly for Exercise and Sport, 83*(4), 546–552. https://doi.org/10.1080/02701367.2012.10599144

Lee, J. Y., Park, J., Park, H., Coca, A., Kim, J. H., Taylor, N. A., Son, S. Y., & Tochihara, Y. (2015). What do firefighters desire from the next generation of personal protective equipment? Outcomes from an international survey. *Industrial Health, 53*(5), 434–444. https://doi.org/10.2486/indhealth.2015-0033

Orr, R., Simas, V., Canetti, E., Maupin, D., & Schram, B. (2019). Impact of various clothing variations on firefighter mobility: A pilot study. *Safety, 5*(4), 78. https://doi.org/10.3390/safety5040078

Park, J., & Langseth-Schmidt, K. (2016). Anthropometric fit evaluation of firefighters' uniform pants: A sex comparison. *International Journal of Industrial Ergonomics, 56*, 1–8. https://doi.org/10.1016/j.ergon.2016.08.011

Petrucci, M. N., Horn, G. P., Rosengren, K. S., & Hsiao-Wecksler, E. T. (2016). Inaccuracy of affordance judgments for firefighters wearing personal protective equipment. *Ecological Psychology, 28*(2), 108–126. https://doi.org/10.1080/10407413.2016.1163987

Punakallio, A., Lusa, S., & Luukkonen, R. (2003). Protective equipment affects balance abilities differently in younger and older firefighters. *Aviation, Space, and Environmental Medicine, 74*(11), 1151–1156.

Punakallio, A., Lusa, S., & Luukkonen, R. (2004). Functional, postural and perceived balance for predicting the work ability of firefighters. *International Archives of Occupational and Environmental Health, 77*(7), 482–490. https://doi.org/10.1007/s00420-004-0536-z

Son, S. Y. (2018). Measurements of range of motion and surface electromyography for analysis of wearer mobility with firefighter protective clothing. *Journal of Korean Living Environment System, 25*(5), 620–632. https://doi.org/10.21086/ksles.2018.10.25.5.620

Son, S. Y. (2019). Effect of different types of firefighter station uniforms on wearer mobility using range of motion and electromyography evidence. *Fashion & Textile Research Journal, 21*(2), 209–219. https://doi.org/10.5805/SFTI.2019.21.2.209

Son, S. Y., Bakri, I., Muraki, S., & Tochihara, Y. (2014). Comparison of firefighter and non-firefighter and the test methods used regarding the effects of personal protective equipment on individual mobility. *Applied Ergonomics, 45*(4), 1019–1027. https://doi.org/10.1016/j.apergo.2013.12.006

Son, S. Y., Xia, Y., & Tochihara, Y. (2010). Evaluation of the effects of various clothing conditions on firefighter mobility and the validity of those measurements made. *Journal of the Human-Environment System, 13*(1), 15–24. https://doi.org/10.1618/jhes.13.15

Steffen, T. M., Hacker, T. A., & Mollinger, L. (2002). Age-and gender-related test performance in community-dwelling elderly people: Six-minute walk test, berg balance scale, timed up & go test, and gait speeds. *Physical Therapy, 82*(2), 128–137. https://doi.org/10.1093/ptj/82.2.128

Thrane, G., Joakimsen, R. M., & Thornquist, E. (2007). The association between timed up and go test and history of falls: the Tromsø study. *BMC Geriatrics*. https://doi.org/10.1186/1471-2318-7-1

Tochihara, Y., Fujita, M., & Ogawa., T. (2005). Protective Clothing – Related Heat Stress on Firefighters in Japan. In I. Holmer, K. Kuklane, & C. Gao (Eds.), *Environmental ergonomics XI* (pp. 137–139). Lund University.


## Publisher's Note