A review of test methods for evaluating mobility of firefighters wearing personal protective equipment

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Abstract: This review aimed to suggest useful, potential measurements as standard test methods for evaluating the mobility of structural firefighters wearing personal protective equipment (PPE). Based on our previous research on Japanese firefighters’ activities related to mobility as well as previous literature results, the findings were categorized (e.g., simulated firefighting activities, test method for mobility assessment, and participants groups), and discussed. We identified four categories that can be used to test and evaluate mobility: (1) simulated firefighting activities consisting of step-ups, obstacle strides, crawling, dragging, and jumping; (2) in terms of balance ability, the postural sway and functional balance tests (functional reach and timed up and go) were useful measurements; (3) range of motion can be used to estimate the mobility associated with the various designs of PPE, as well as the effect of wearing the PPE itself; and (4) subjective evaluations of individuals wearing PPE were available for the mobility assessments. Professional firefighters who were familiar with wearing PPE were suitable for the suggested test method. This review provides useful information for firefighters, researchers, and PPE manufacturers that can be used to develop more comfortable and safer PPE.

Key words: Firefighters, Personal protective equipment, Protective clothing, Mobility, Test method

Introduction

Firefighters work in high-risk and strenuous environ-
breathing apparatus (SCBA), gloves, boots, a face mask, and personal tools. Importantly, the full set of PPE weighs approximately 20 kg, which causes significant physical burden and impaired mobility due to the heavy weight and bulkiness of the equipment\(^1\). The overall weight and location of the center of mass of firefighters equipped with PPE change according to those of the components, thereby affecting firefighters’ work performance\(^2\). Friction caused by station uniforms worn under the PPE becomes damp due to sweat or hosing water, which also negatively affects the mobility of firefighters\(^3\).

In a Japanese survey study, firefighters responded that wearing PPE resulted in restriction of mobility. They ranked ease of movement (mobility) higher than comfort and protection, thereby making it evident that mobility is the first priority of firefighters who wear PPE\(^4\). Another study by Huang et al.\(^5\) reported that a large percentage of firefighters experienced discomfort with mobility during firefighting. These results highlight the importance of mobility among PPE users.

Maintaining appropriate body balance while wearing PPE in the field is critical for preventing injury and promoting healthy work abilities in firefighters\(^6\); furthermore, it is an important aspect of mobility. In the United States (U.S.), almost half of the injuries occurred while carrying out firefighters’ duties. The leading causes of injuries (over 20\%) were falls, slips, and jumps\(^7\), \(^8\). A survey previously assessed the impact of different PPE materials and designs on Japanese firefighters’ degree of mobility\(^9\). The respondents reported that the leading cause of muscle fatigue and injuries when performing work in PPE was a deterioration in balance ability leading to increased falls, jumps, trips, and slips\(^9\). In addition, U.S. firefighters have reported that wearing PPE restricted jumping, running, and squatting movements and impeded mobility when bending, lifting, and pushing\(^1\).

A number of studies that investigated the mobility reduction associated with PPE use have assessed the limitations in joint angles due to heavy and bulky PPE\(^10\), \(^11\). Furthermore, previous studies have investigated the range of motion (ROM) and work performance associated with differences in the design and conditions of various PPE\(^3\), \(^12\). A number of studies have been conducted over the years to assess physiological responses to PPE, including increased cardiovascular strain\(^13\)–\(^16\), fluctuation of thermal responses\(^17\), \(^18\) during simulated firefighting activities (SFA), and decreased work performance\(^19\). Other studies have focused on firefighters’ mobility related to wearing PPE and their movements at the fireground\(^1\), \(^4\), \(^9\), \(^20\).

Although there are international standards for the evaluation of PPE, most of them are related to physical properties, such as heat, flame, water-resistance or ergonomic design, and PPE size\(^21\)–\(^29\). ISO 13688\(^23\), BS 8469\(^24\), and ASTM F3031-17\(^25\) mention instructions for mobility while wearing PPE; however, detailed test methods using standardized measurements have not been perfectly established. Without a standard test method for assessing mobility while wearing PPE, assessment results from various research groups using different methods may lead to inaccurate interpretations\(^17\), \(^26\).

To bridge this gap in knowledge, we conducted a large-scale questionnaire survey of Japanese firefighters, titled “Development of standard test methods for evaluating heat strain and mobility of firefighters wearing personal protective equipment” in order to investigate the actual working conditions and work style at a structural firefighting site\(^9\). Furthermore, the test method details for evaluating heat strain and the wearer’s mobility have been previously examined through several laboratory experiments\(^3\), \(^9\), \(^14\), \(^17\), \(^26\)–\(^31\).

The purpose of this review was to determine potentially useful measurements for evaluating the mobility of firefighters with PPE that can be used as standard test methods based on our study results as well as those of previous studies. To that end, we will review and discuss these methods in three parts: SFA, test methods for mobility assessment, and participant groups. The test methods and measurements for mobility were categorized as follows: balance ability, ROM, and subjective evaluations (SE). All experimental studies from the authors’ research group were conducted at the Experimental House for Living Space Design and the Research Center for Human Environmental Adaptation of Kyushu University in Fukuoka, Japan. Our studies were approved by the Institutional Review Board of Kyushu University, and written informed consent was obtained from all volunteers after providing full explanation of the study requirements and the risks involved.

**Methods**

This paper systematically reviewed the existing test methods and drew conclusions from effective results related to mobility while wearing PPE. We searched for published studies on relevant electronic databases such as ‘PubMed’ and ‘Web of Science’, with reference to Google Scholar. The search strategy involved the following keywords: ‘personal protective equipment’, ‘protective clothing’, ‘firefighter’, ‘firefighting’, ‘mobility’, ‘movement’, ‘balance’, ‘gait’, and ‘range of motion’. The initial litera-
ture search was performed on February 27, 2021, with the following search terms: ‘personal protective equipment’ or ‘protective clothing’) AND (firefighter OR firefighting) AND (movement OR mobility OR balance OR ‘range of motion’ OR gait OR ‘motor control’). There were no restrictions on the publication date of the papers. However, only papers published in the English language were included. The selection criteria for this review were: full publications based on the original results of mobility while using PPE. However, conference abstracts and publications for which the full text could not be accessed were excluded. The authors retrieved full publications by screening titles and abstracts. In addition, we manually searched all relevant reference lists in the selected studies.

Simulated Firefighting Activities (SFA)

A high level of physical performance involving aerobic capacity, muscular strength, and endurance is required by the firefighters who work in extreme environments. In order to evaluate physiological responses with PPE, a treadmill or ergometer exercise is often used to simulate a workload that applies to firefighting. In contrast, several studies have assessed the use of SFA as a test method for evaluating the mobility impeded by heavy and bulky PPE. Table 1 summarizes important articles simulating firefighting activities and mobility assessment.

Petrucci et al. examined the obstacle crossing abilities of firefighters during simulated fire suppression, such as crossing over, under, and through different obstacles while wearing PPE (Table 1). This obstacle stride was designed to stimulate the participants’ balance ability and mobility when wearing PPE. However, the experimental clothing conditions were only designed for a full set of PPE, and there was no baseline clothing, such as normal sportswear. Therefore, this study was unable to confirm that the mobility of firefighters was reduced due to wearing PPE of different mass and designs, although wearing PPE resulted in a decline in obstacle crossing performance based on poor affordance judgments.

The functional movement screen test includes overhead squats, hurdle steps, in-line lunges, shoulder mobility, active straight leg raises, push-ups, and rotary stability. These tasks can be used to assess the firefighters’ mobility while wearing different types of PPE. In addition, reach height, vertical jump, and simulation tasks that included stepping and crawling were also assessed by Orr et al. The objective results, such as the functional movement screen test score, showed significant differences among several PPE types (Table 1). Although the experimental clothing conditions did not include SCBA or helmets, the use of protective clothing led to decreased performance in many participants due to reduced mobility, thereby increasing the risk of injury. Wearing clothing that allows for greater mobility than experimental clothing could help to mitigate the impact of equipment and reduce the overall injury risk. The results from the functional movement screen test and vertical jump test suggested that clothing variation was associated with an increased risk of injury and/or illness. They found that the clothing conditions offering the least impact on lower limb power and the least restriction in functional movements reduced injury risk the most.

Another study by Hur et al. investigated the effects of wearing PPE on fatigue during SFA using test methods to prevent the maintenance of body posture during stair climbing, forcible entry, room search, and hose advancement (Table 1). The performance time in the SFA was increased by workload and PPE weight; however, the effects of wearing PPE with a cooling system and external circulating hose on firefighter mobility were not assessed. Moreover, variations in mobility with PPE were tested using objective measures of user mobility, such as SFA consisting of ladder pickup, crawling over and under objects, mannequin drag, and solid object lift (Table 1). They also observed slightly greater mobility in job-related tasks (one-arm search distance and time when wearing PPE) in participants with PPE than in those without PPE. Coca et al. suggested that the reason for these findings was that the participants might have felt more comfortable and protected when wearing PPE.

In British standards, the requirements and test methods used for the assessment of ergonomic performance and compatibility for firefighters’ PPE have been suggested. However, BS 8469 is the only British standard for assessment of PPE user mobility. To date, it has been proposed that the best SFA for assessing the restriction of movement caused by PPE are: walking, the ladder raise, the windowsill obstacle, hose rolling, and crawling (Table 1). The time required to execute these tasks is measured, and the impairment of mobility is rated as follows: complete time of each task >200%, >150%, >110%, and <110% of baseline conditions, which are rated as 1, 2, 3, and 4, respectively. In the Japanese survey, firefighters were asked the motions during firefighting that cause them the most physical strain. The ‘stair climbing’ task was chosen as the greatest physical strain (21% of 3,687 responses), followed by ‘carrying a heavy object or person’ (19%). Based on this, we suggest...
Table 1. Summary of participants and clothing conditions, simulated firefighting activities, mobility assessments, and main outcomes of previous research on mobility with PPE.

| Reference            | Participants and clothing conditions | SFA | Mobility assessments                                      | Main outcomes                                                                 |
|----------------------|--------------------------------------|-----|----------------------------------------------------------|-------------------------------------------------------------------------------|
| BS 8469 (2007)       | At least 6 firefighters               | Don in cab simulation, glove doff/don, walking,stretching, crawl | The performance time, SE for arm mobility, comfort, interactions, vision, fit, and flexibility | TC >200% of BC: #1, TC >150% of BC: #2, TC >110% of BC: #3, TC <110% of BC: #4 |
| Coca et al. (2008)   | 8 participants: healthy adults (5 males, 3 females) | Job-related tasks: donning/doffing, one-arm search, ladder pick-up, crawl over and under objects, mannequin drag, and object lift | Performance time and distance of job-related tasks, SE for comfort and discomfort | The PPE design features to enhance protection does not decrease the wearer’s mobility, The participants perceived more comfortable wearing the standard PPE compared to the PPE with enhanced protection |
| Coca et al. (2010)   | 8 participants: healthy adults (5 males, 3 females), three of whom were fire fighters | Job-related tasks: donning/doffing, one-arm search, ladder pick-up, crawl over and under objects, mannequin drag, and object lift | Time and number of strides to complete task | The time and stride of tasks of baseline were significantly slower than PPE condition |
| Hur et al. (2013)    | 57 male firefighters (divided two groups) | Stair climb, forcible entry, room search, and hose advancement (A total 18 min of activity) | HR, Functional balance test score (performance time, index, major error, and minor error) of before and after simulated work, The obstacle stride was performed for functional balance test | Wearing PPE significantly impaired functional balance by slowing down movement speed and increasing errors, The enhanced PPE lighter than standard PPE was not found to be effective in mobility |
| Orr et al. (2019)    | 8 firefighters (7 males, 1 females)   | Functional movement screen (the overhead squat, hurdle step, in-line lunge, shoulder mobility, active straight leg raise, push-up, and rotary stability), Standing reach height and vertical jump, step-up and crawl | The score of functional movement screen, Vertical jump heights, Overhead reach score, SE for functional movement screen, SE for comfort and tasks, SE for comfort and discomfort area | The military clothing was more comfortable than firefighters’ PPE to have improved their ability to perform in the functional movement screen and vertical jump |
| Petrucci et al. (2016) | 24 participants: firefighters (23 males, 1 females) | Three obstacle strides (under, over, through) with perception action (to prevent success or failure in the action trials from influencing the judgments) | Participants’ affordance thresholds (perception and action), Perceptual judgment error | Firefighters make poor affordance judgments while wearing PPE when faced with obstacles, Participants made significant judgment errors for obstacles with PPE |
were not included in the measurement. In the step-up task, variables other than heart rate were controlled by assigning a fixed amount of physical load (20 step-ups) per minute to all participants\textsuperscript{26, 31}).

In summary, numerous assessments using SFA have been published in the field of PPE research. Previous studies utilized SFA such as obstacle movement, walking, crawling, climbing, and jumping. It is possible to replace SFA with treadmill or ergometer exercises that cause physical fatigue. However, there is a limitation in evaluating physical burden using the abovementioned aerobic exercises, in that it is difficult to measure dynamic movements. Therefore, it is necessary to select activities that can provide reliable results among the various tasks for evaluating the mobility of PPE users.

### Test Methods for Mobility Assessment

#### Balance ability

Postural sway

Mobility assessment, which changes in balance ability while wearing several types of PPE, is typically assessed using biomechanical test methods. Many researchers have studied reduced user mobility through tests of postural sway, which refer to movement of the center of mass or the persons’ pattern of movement\textsuperscript{26, 36, 38–42).}

Postural sway can be used to assess the effect of PPE on user mobility by measuring a participant’s ability to maintain an upright posture while wearing PPE, that is, the sway area and length and the mediolateral and anterior-posterior excursion are measured to analyze postural sway. The participants are required to maintain a double-leg or single-leg stance on a device, such as a force plate available for tracking the center of pressure. Importantly, the use of PPE

Table 1. Continued

| Reference         | Participants and clothing conditions | SFA                                | Mobility assessments                              | Main outcomes                              |
|-------------------|--------------------------------------|------------------------------------|---------------------------------------------------|--------------------------------------------|
| Son et al. (2014) | - 18 participants (9 professional male firefighters, 9 healthy males untrained for firefighting) - 4 clothing conditions | - Grip test and sit and reach - SFA: step-up, side jump, crawl, object dragging, obstacle striding | - The performance time and HR of SFA - The performance time and distance for functional balance test - SE for comfort and mobility | - PPE conditions from firefighters revealed significantly worse results in the performance time and HR, and SE compared to the baseline condition |

HR: heart rate; ROM: range of motion; SE: subjective evaluations, TC: time to complete, BC: benchmark condition; PPE: personal protective equipment, SFA: simulated firefighting activities.
while performing firefighter tasks can negatively affect postural sway. For example, in a study by Kincl et al.\textsuperscript{39}, variations in postural sway due to different levels of PPE were measured using a force plate system and the sway length was found to be the most sensitive parameter. In particular, the measurement of sway length with participants who closed their eyes was correlated with heat stress. Other studies by Punakallio et al.\textsuperscript{40,41,43} focused on the analysis of postural sway associated with different PPE. They found that the use of additional SCBA led to an increase in postural sway parameters. The slip, fall risk, and body sway results of firefighters who wore PPE were compared by age and slip distances.

Studies have shown that the heavier the PPE is, the more it impacts postural sway\textsuperscript{44–46}. Brown et al.\textsuperscript{44} analyzed the effects of weight on fatigue across different combinations of PPE use, including conditions of normal sports clothing, PPE with or without SCBA, and a full set of PPE (i.e., the addition of a face mask). They measured participants’ anterior-posterior and medial-lateral tilts and calculated stability indices for anterior-posterior, medial-lateral, and overall. The negative impact of wearing the additional PPE components as well as an SCBA and face mask on postural sway was significantly indicated during the dynamic balance test presented by higher scores in the overall stability index, suggesting a small amount of postural stability. The balance ability in all directions was further deteriorated by wearing the full set of PPE. The equipment that impairs dynamic balance the most is the face mask. Hur et al.\textsuperscript{45} examined the effect of SCBAs of several different sizes and cylinder shapes on postural sway and found it significantly increased excursion in the medial-lateral direction. They suggested that the causes of significant variations in medial-lateral postural sway were from immovable stance widths for each clothing condition trial and a lean forward posture caused by the heavy weight of the SCBA. Son et al.\textsuperscript{46} evaluated mobility of firefighters wearing PPE using a force plate system and found that the heavier the PPE is, the more it impacts postural sway.

Table 2. Changes in simulated firefighting activities results in non-firefighter groups

|                          | CON  | Type A | Type B | Type C |
|--------------------------|------|--------|--------|--------|
| Cotton T-shirts          |      |        |        |        |
| Cotton shorts            |      |        |        |        |
| Running shoes            |      |        |        |        |
| Step-up (bpm/60 s)       | 116  | 131\textsuperscript{*} | 133\textsuperscript{**} | 139\textsuperscript{***} |
| Side jump (times/20 s)   | 39.9 | 35.8\textsuperscript{*} | 35.1\textsuperscript{**} | 35.1\textsuperscript{*} |
| Crawl (sec)              | 24.8 | 29.7\textsuperscript{*} | 29.9\textsuperscript{**} | 29.9\textsuperscript{**} |
| Object drag (sec)        | 20.2 | 20.6\textsuperscript{*} | 22.2\textsuperscript{**} | 21.3\textsuperscript{***} |
| Obstacle stride (sec)    | 53.4 | 69.5\textsuperscript{***} | 67.52\textsuperscript{***} | 68.0\textsuperscript{***} |

Values are represented as mean (SD). Significant differences between CON and the other conditions (*p<0.05, **p<0.01, ***p<0.001). BS 8469 (2007) rating: #1: >200%, #2: >150%, #3: >110%, #4: <110%.

CON: The ordinary exercise clothing, Type A: 19.2 kg of Japanese PPE, Type B: 19.4 kg of aluminized coated PPE from Japan, Type C: 20.8 kg of European PPE.

The table was adapted from Son et al. (2014) (partially modified)
al. also used the wooden plank time test to investigate functional balance ability while wearing PPE and found that firefighters walked slowly while wearing PPE to maintain their balance. In addition, participants’ errors increased under PPE clothing conditions. They suggested that both completion time and the number of errors may be considered as provisions of functional balance tests.

Hur et al. designed a novel functional balance test assessing participants’ ability to maintain balance body posture while performing tasks such as stepping up, stepping down, turning, walking along a beam, and passing under an obstacle. This functional balance test consisted of a combination of the wooden plank time and obstacle stride tests. In order to investigate the effects of wearing PPE, major and minor performance errors and completion time were recorded, and a composite performance index was calculated. Regardless of the PPE design, wearing PPE significantly impaired functional balance by slowing down movement speed and increasing errors. The firefighters’ performance speed decreased following firefighting activity. However, these slower performance speeds were affected by wearing PPE and strenuous firefighting activity, and not by the PPE design. There were no significant differences in the test outcomes when comparing regular PPE with lighter and more breathable enhanced PPE. Another study using a similar test method that focused on mobility affected by different designs and sizes of SCBA hypothesized that wearing a larger or heavier SCBA and increased duration of firefighting activities cause impairments in functional balance ability. According to their results, wearing a larger or heavier SCBA led to more errors and a longer completion time in the wooden plank time test. Moreover, the participants completed the test with a decreased number of errors and shorter completion time while wearing an improved design of SCBA, which had no air bottle. In the case of Son et al., no significant reduction in functional balance ability was observed; however, there was a tendency for impaired mobility.

Functional balance test

Unlike the measurement of postural sway, which is measured using a force plate and computerized system, there is a simpler but more commonly used measurement method for mobility. A number of research groups have designed a functional balance test method for evaluating mobility with PPE using a dynamic balance parameter. In this method, the subject is asked to walk along as quickly as possible and return to the starting position on 3 m of narrow wooden plates (Fig. 1), and performance time is measured. Falling off of the wooden plates is considered an error. Using the wooden plank time test, Punakallio et al. assessed functional balance by evaluating the slip and fall risk of firefighters due to PPE use. In particular, they analyzed the association between firefighters’ muscular strength, age, and balance ability. According to their study, wearing Nordic PPE impaired functional balance ability in both young and old groups of firefighters. Furthermore, each component of PPE, including protective clothing, the mask, and SCBA negatively affected completion time in the wooden plank time test. Importantly, SCBA impacted performance on this task the most. In another study, Kong et al. also used the wooden plank time test to investigate functional balance ability while wearing PPE and found that firefighters walked slowly while wearing PPE to maintain their balance. In addition, participants’ errors increased under PPE clothing conditions. They suggested that both completion time and the number of errors may be considered as provisions of functional balance tests.

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![Fig. 1. Functional balance test](image-url)
balance due to PPE. Punakallio et al. discussed the utility of this test method for mobility, recommending more studies be performed to promote firefighters’ health and work performance.

The functional reach test was designed to assess balance abilities due to its similarity with postural sway excursion. In this test, participants are asked to stand in the measuring position and raise their right arm horizontally. After the starting sign, the participants extend their right arm forward as far as possible. The movement distance of the extended arm is measured using the functional reach test score (Fig. 1). Coca et al. used the functional reach test to compare different and improved designs of PPE. The reach distance had a tendency to decline when wearing wet or dry PPE, standard PPE, and large and heavy SCBAs compared to when wearing ordinary sportswear and PPE with improved design. Son et al. also used the functional reach test to assess PPE mobility and discussed the validity of this method. The test results were similar to those reported by Coca et al. That is, arm movement distance was decreased when wearing PPE. However, it was insufficient to support the idea that variations in mobility are due to the different designs of the PPE. Nevertheless, the functional reach test is simple, reasonable, and useful for evaluating the changes in mobility associated with PPE use. Therefore, it may be useful as a standard test method for assessing mobility for those reasons.

For the prediction of risk of fall and slip injury in elderly or handicapped persons, the timed up and go test is commonly used to detect decreases in mobility, with older individuals typically displaying lower scores. In this test, the participants are asked to sit on an armchair or stool at the start of the measurement. After the start sign, they are asked to stand up and walk forward for 3 m and return to the start position. The time it takes to complete the task is considered the score of this test. Son et al. attempted to examine mobility using the timed up and go test and obtained notable outcomes. The participants scores were significantly reduced by PPE, which included an aluminum-coated and stiff fire jacket. Moreover, the authors’ research group verified the decrease of over 20% in the timed up and go score due to wearing PPE.

In summary, the wooden plank time, functional reach, and timed up and go tests are frequently used functional balance tests; these are simple and convenient tests for measuring mobility, have good performance, and are low in cost. In particular, the timed up and go and functional reach tests are useful for evaluating mobility affected by PPE weight. The wooden plank time test is a promising tool for measuring mobility if it can be combined with SFA such as the obstacle stride.

Range of motion (ROM)

Standard methods for measuring mobility while wearing PPE using ROM values have yet to be established in international standards, but the validity of using ROM as an assessment of mobility has been evaluated in several studies. ROM, measured using a goniometer, flexometer, and electrogoniometer, is a simple and reasonable measurement and suitable for the assessment of joint angles in the laboratory. However, measuring ROM using goniometers, flexometers, and electrogoniometers is very time-consuming and technically challenging due to the complexity of the procedures involved. Generally, measuring ROM while wearing PPE is not easy, and it is difficult to identify the measurement points covered by the PPE. In addition, it is difficult for experimental motions to be more complicated. Hence, it requires extremely experienced researchers to accurately measure changes in ROM.

A previous study used the ROM test to assess changes in mobility associated with wearing PPE of different designs. To that end, the ROM values of eight motions while wearing PPE were evaluated, and the restriction of participants’ movements was measured using a flexometer. Among the eight experimental movements, shoulder and trunk lateral movements were significantly affected by the PPE design. Similar results were reported by Huck. The different PPE designs, such as modified sleeves and variated liner configurations, were evaluated using four restricted upper-body movements. Participants’ ROM was measured to clarify the restricted mobility associated with different PPE designs, and significant differences were found among the experimental conditions. Two types of PPE, the standard U.S. PPE and modified PPE (improved vapor resistant component and design of opening parts of PPE, e.g., interfaces of sleeve-glove, hood-face mask, and boot-pants), were evaluated using static and dynamic ROM measurements. The static ROM was measured using a goniometer while participants carried out several motions, such as flexion, extension, and abduction of body joints. There were no significant differences among experimental clothing conditions, and the authors mentioned that the reason for these results was the similar platform of the design of the two types of PPE. However, the important outcome of their study was the success in measuring the joint motions recorded over bulky and heavy PPE using ROM and identifying ergonomic differences due to changes in the design points of the PPE. Ciesielska-Wróbel et al. used body-at-
performed the experimental joint motions. Coca values were decreased when participants who wore PPE mobility with and without PPE and reported that the ROM parameter for measuring mobility. A previous study assessed the PPE users; hence, ROM was validated as a possible parameter for measuring mobility. A previous study assessed mobility with and without PPE and reported that the ROM values were decreased when participants who wore PPE performed the experimental joint motions. Coca et al. suggested that their test method, consisting of ROM, should be considered as a standard method for the assessment of PPE.

The authors of the present study investigated mobility when wearing various types of PPE clothing and evaluated the effectiveness of these measurements. The effects of wearing PPE, especially the additional mass associated with a SCBA and increased friction due to wetting of PPE by sweat significantly affected objective joint angle measures. The relative restriction rates of ROM were approximately 14% and 10%, respectively. These tendencies for decreased ROM by PPE were also observed in previous studies. A previous study hypothesized that the different materials and design of station uniforms worn under PPE may influence the improvement of users’ mobility. For this study, the ROM when wearing experimental PPE conditions was assessed through the following five joint motions: shoulder flexion/extension, shoulder adduction/abduction, shoulder rotation, hip flexion/extension, and hip adduction/abduction. Significantly increased ROM values, which indicated enhanced mobility, were observed in the joint motions due to changes in the materials under the uniform and upgrading of their design to a stretched and compressive one. The effects of increased mass and volume by different designs of PPE components on user mobility were indicated as statistical variation in the ROM values.

For the ASTM standard, ROM was used as the primary mobility measurement for participants while wearing PPE. Using this standard, the negative ergonomic impact of PPE on the wearer was established as ergonomic measurements for eight static ROMs: shoulder flexion, shoulder abduction, cervical rotation, cervical flexion and extension, trunk flexion, trunk extension, and trunk lateral flexion. Furthermore, a calculation of the ratio of ROM changes due to wearing different PPEs was suggested. In addition, using the ASTM standard, the sit-and-reach test was used as a flexibility test for measuring mobility. This test showed a similar motion to ROM, especially for trunk flexion. As the assessment requires simple devices, it prevents measurement errors by inexperienced researchers. Furthermore, a deterioration of flexibility was noted due to wearing PPE. Therefore, the sit-and-reach test may be a supportive measurement to the ROM.

In summary, our study succeeded in determining significant outcomes using ROM measurements of the user’s mobility while wearing PPE of various designs and masses. Consequently, the ROM test has been recommended as a standard test method because it is a sensitive and valid test method for evaluating mobility with various equipment. However, the measurement of ROM while wearing PPE requires careful operations by researchers with sufficient experimental experience in measuring ROM.

Subjective evaluations (SE)

Psychological fatigue is caused by strenuous firefighting with PPE in a hot and humid environment, which may be a risk factor for injuries to firefighters. In the thermal responses research field, thermoregulatory responses as well as psychological responses such as thermal sensation, comfort, and sweat sensation while wearing PPE have been studied. Furthermore, psychological responses have been used as supportive data of physiological responses; thus, the SE of mobility is an important parameter in PPE research. McQuerry reported that improper fitting of PPE affects mobility, which causes an increased burden and restricted motion among users, has a significant effect on the perception of comfort.

Ciesielska-Wróbel et al. assessed the comparison of similar designs of PPE to verify SE measurements. The ease of movement, overall comfort of the outfit, and mobility perception of PPE (e.g., fit, arm and leg lift, and stiffness) were included in their questionnaire. The experimental clothing conditions had very similar designs, but the number of PPE layers and sleeves designs were different. There
were significant differences in the SEs of mobility, and the PPE conditions with the worst objective scores also had the worst responses. According to their results, the bulkiness of the PPE had a greater effect on the SE than the mass of the PPE. Another study by Orr et al. used a visual analog scale with questionnaires to measure the perceived impact of clothing on the performance of given tasks, comfort, and restricted body areas. The objective scoring of the physical performance of the participants was generally related to their SE, which refers to the perceived effects of PPE variants on SFA and clothing comfort. The subjective ratings of comfort while wearing PPE have also been reported by other studies. However, it is difficult to determine which elements of PPE affect SE without an in-depth evaluation.

Our previous studies conducted assessments using several evaluations associated with the mobility of various PPE clothing conditions. For this study, SE was assessed using detailed questionnaires on users’ comfort and body mobility. The questions on body mobility associated with PPE were organized by the following body parts: head/neck, arms, elbows, wrists, waist, thighs, knees, ankles, and hip/pelvis. The users’ comfort was evaluated by six questions on the fit of the PPE, bending or moving a body while wearing PPE, lifting arms or legs, and the bulkiness and heaviness of the PPE. The questionnaires were validated to indicate the differences between wearing PPE, condition of the PPE (wet or not), and influence of different PPE designs. In addition, significant differences in the mass of PPE were observed in the perceived mobility and comfort results.

In summary, SE is a principal supportive method for measuring both physiological and kinesiological responses while wearing PPE. Several previous studies assessed SE to test the satisfaction, perception of protection and performance, comfort, and mobility associated with PPE and pointed out that SE is a sensitive measurement for evaluating the users’ mobility and could be part of the standard test method for PPE mobility.

**Participants: firefighters or non-firefighters**

Most studies included in the literature review were on professional firefighters who volunteered as participants in experiments. However, some studies have reported significant differences in the mobility assessed in male civilian participants. A few studies have reported comparisons of efficiency results while wearing PPE between firefighter and civilian participants. Firefighters and civilians participated in postural balance assessments including the sensory organization test and motor control test, while wearing PPE in rest conditions; the two groups performed similarly across most of the trials. In our previous studies, we compared responses in the heat strain test and mobility test with PPE between firefighter and civilian (consisting of non-firefighters) groups. In the heat strain study, firefighters demonstrated a higher VO2 max and smaller interindividual differences than civilians. Their core temperature was also lower than that of civilians when performing treadmill exercise wearing PPE in hot and humid environments. Based on these results, firefighters were considered suitable participants for the PPE heat strain test, where an extremely high-intensity workload such as treadmill or ergometer exercises, in hot and humid environments was required to evaluate physiological responses. Therefore, firefighters, who demonstrated better results than civilians in the aerobic field tests were designated as participants.

We also investigated the suitability of standard participants for the assessment of mobility with PPE. The firefighter group demonstrated significantly different results in SFA, functional balance tests, and SE related to movement and mobility with PPE; that is, firefighters showed significantly better physical performance in most tasks, with a smaller standard deviation than the civilian group (Fig. 2). These results are expected as the civilian group had individuals with different physical performance levels. Thus, firefighters may be more appropriate as the standard participant group for mobility test methods. Although the firefighters showed significant differences in the objective test values between PPE wearing and non-wearing conditions, few studies have indicated significant differences between PPE with different designs, materials, and weight, although these studies were conducted in firefighters. However, objective mobility assessments and tests accompanied by SE may increase the precision of test participated by firefighters. We hypothesize that the reason for these results was either the insufficient physical ability and experience in donning/doffing PPE by non-firefighters or that firefighters are more sensitive to comfort and mobility when wearing PPE.

In previous studies mentioned in this review, 8 to 135 firefighters or members of the general population participated as experimental research subjects. Significant differences were found even in some studies in which few numbers of subjects participated. ASTM F3031-17 describes that a minimum of eight different participants (firefighters or non-firefighters) are allowed for standard practice. Furthermore, at least six professional firefight-
ing stipulations\(^{25, 26}\). According to the results of the authors’ unpublished study, mobility, which was evaluated using SFA, the functional balance test, and ROM analysis, decreased with an increase in the weight of PPE\(^{31}\). The comparison between the baseline (T-shirt and shorts) and full set of PPE conditions revealed that the SFA result, functional balance ability, and ROM decreased by 30%, 29%, and 28%, respectively, after a 20-kg increase in the weight of clothes. Although the aforementioned results were obtained from only nine participants, they can be presented as a reference for the evaluation criteria of mobility assessment in PPE conditions. However, while BS8469 leveled mobility according to the increase or decrease in completion time\(^{24}\), the authors’ previous and current studies could not establish PPE evaluation criteria. Therefore, we consider that this should be an important task for future research, and further examination will be required. Based on previ-

**Suggestions and limitations**

Ultimately, we suggest the following mobility assessments as the most reliable test methods for mobility, which have simple and ergonomic measurements: postural sway, functional balance tests (wooden plank time, function reach, and timed up and go), ROM, and SE (Table 3). More than eight firefighters should be used for evaluation. For comparison of mobility with different PPE components, more than two clothing conditions are required: baseline and PPE conditions. T-shirts and shorts can be the basic items used for the baseline in the absence of specific clothing stipulations\(^{25, 26}\). According to the results of the authors’ unpublished study, mobility, which was evaluated using SFA, the functional balance test, and ROM analysis, decreased with an increase in the weight of PPE\(^{31}\). The comparison between the baseline (T-shirt and shorts) and full set of PPE conditions revealed that the SFA result, functional balance ability, and ROM decreased by 30%, 29%, and 28%, respectively, after a 20-kg increase in the weight of clothes. Although the aforementioned results were obtained from only nine participants, they can be presented as a reference for the evaluation criteria of mobility assessment in PPE conditions. However, while BS8469 leveled mobility according to the increase or decrease in completion time\(^{24}\), the authors’ previous and current studies could not establish PPE evaluation criteria. Therefore, we consider that this should be an important task for future research, and further examination will be required. Based on previ-

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**Fig. 2.** The comparison of standard deviation between firefighter and civilian groups under the simulated firefighting activities. The figure was adapted from Son et al. (2014): (partially modified). CON: The ordinary exercise clothing; Type A: 19.2 kg of Japanese PPE; Type B: 19.4 kg of aluminized coated PPE from Japan; Type C: 20.8 kg of European PPE; PPE: personal protective equipment.
ing firefighters’ mobility with PPE. Furthermore, it highlights the need to develop novel more effective test methods for evaluating the mobility of firefighters while wearing PPE. We discussed the most promising potential measurements for mobility based on the results of previous studies including our own study’s results. The measurements suggested as a reliable test method for the evaluation of mobility are presented in Table 3. SFA included step-up, obstacle strides, crawling, dragging, and jumping. The postural sway and functional balance tests are useful measurements for monitoring the PPE users’ mobility. In particular, the timed up and go and functional reach tests are very convenient methods that are significantly affected by the mass of PPE. The wooden plank time test may also be useful when combined with SFAs, such as the obstacle stride. ROM can be used to estimate the user’s mobility depending on the various designs and masses of PPE, as well as the effect of wearing PPE itself. However, measuring ROM requires careful operations by researchers with sufficient experimental experience, although relatively simple devices can be used. In addition to the above objective measurements, SE in terms of comfort and movement of PPE users are useful for the assessment of mobility, and if the participants are professional firefighters who are familiar with PPE, the variation in their mobility would be perceived to be more sensitive.

| Measurements       | Simplicity | Ergonomic judgment possibility | Note                                                                 |
|--------------------|------------|-------------------------------|----------------------------------------------------------------------|
| Postural sway      | +          | +                             | Sway excursion should be tested before and after of SFA               |
| Wooden plank time  | ++         | +                             | Combination with the obstacle stride is needed                       |
| Functional reach   | +++        | ++                            |                                                                     |
| Timed up and go    | +++        | ++                            |                                                                     |
| ROM                | ++         | +++                           | Careful measurement by skilled researchers is needed                  |
| SE                 | +++        | +                             | Firefighters have more susceptibility in subjective comfort and mobility |

+ indicates the degree of simplicity and ergonomic judgment possibility; +: small, ++: middle, +++: great.

ROM: range of motion, SE: Subjective evaluations, SFA: Simulated firefighter activities.

Conclusions

To the best of our knowledge, this article is the first review highlighting the most useful test methods for assessing firefighters’ mobility with PPE. Furthermore, it highlights the need to develop novel more effective test methods for evaluating the mobility of firefighters while wearing PPE. We discussed the most promising potential measurements for mobility based on the results of previous studies including our own study’s results. The measurements suggested as a reliable test method for the evaluation of mobility are presented in Table 3. SFA included step-up, obstacle strides, crawling, dragging, and jumping. The postural sway and functional balance tests are useful measurements for monitoring the PPE users’ mobility. In particular, the timed up and go and functional reach tests are very convenient methods that are significantly affected by the mass of PPE. The wooden plank time test may also be useful when combined with SFAs, such as the obstacle stride. ROM can be used to estimate the user’s mobility depending on the various designs and masses of PPE, as well as the effect of wearing PPE itself. However, measuring ROM requires careful operations by researchers with sufficient experimental experience, although relatively simple devices can be used. In addition to the above objective measurements, SE in terms of comfort and movement of PPE users are useful for the assessment of mobility, and if the participants are professional firefighters who are familiar with PPE, the variation in their mobility would be perceived to be more sensitive.
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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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