

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-

ments so as to fulfill their duties and are exposed to physical and psychological fatigue. In addition to firefighting, firefighters' duties include rescue operations and emergency medical services. In fact, the frequency of rescue and emergency medical services that firefighters provide is high, and various motions are performed during these tasks. The personal protective equipment (PPE) that firefighters wear comprises a turnout jacket and pants, a self-contained

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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 equipment¹. 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 performance². Friction caused by station uniforms worn under the PPE becomes damp due to sweat or hosing water, which also negatively affects the mobility of firefighters³.

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 PPE⁴. 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 firefighters⁶; 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 mobility⁹. 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 slips⁹. In addition, U.S firefighters have reported that wearing PPE restricted jumping, running, and squatting movements and impeded mobility when bending, lifting, and pushing¹.

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 strain¹³⁻¹⁶, fluctuation of thermal responses^{17, 18} during simulated firefighting activities (SFA), and decreased work performance¹⁹. 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 size²¹⁻²³. ISO 13688²³, BS 8469²⁴, and ASTM F3031-17²⁵ 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 site⁹. 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^{20, 32, 33}. In order to evaluate physiological responses with PPE, a treadmill or ergometer exercise is often used to simulate a workload that applies to firefighting^{15, 18, 34}. 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.*² 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 stability³⁵. 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.*³⁵ 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 movement 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 illness³⁵. 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.*³⁶ 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^{12, 37} (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 PPE³⁷.

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 mobility²⁴. 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 window-sill 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 strain⁹. 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 - Full set of PPE	- Don in cab simulation, glove doff/don, walking, ladder raise, windowsill obstacle, hose rolling, stretching, crawl	- The performance time - SE for arm mobility, comfort, discomfort, vision, fit, interactions, and flexibility	- TC >200% of BC: #1 - TC >150% of BC: #2 - TC >110% of BC: #3 - TC <110% of BC: #4
Coca <i>et al.</i> (2008)	- 8 participants: healthy adults (5 males, 3 females) - 5 clothing conditions	- 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 <i>et al.</i> (2010)	- 8 participants: healthy adults (5 males, 3 females), three of whom were fire fighters - 2 conditions	- 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 <i>et al.</i> (2013)	- 57 male firefighters (divided two groups) - 2 conditions	- 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 <i>et al.</i> (2019)	- 8 firefighters (7 males, 1 females) - 5 clothing conditions	- 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, vertical jump, 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 <i>et al.</i> (2016)	- 24 participants: firefighters (23 males, 1 females) - PPE condition without mask	- 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

Table 1. Continued

Reference	Participants and clothing conditions	SFA	Mobility assessments	Main outcomes
Son <i>et al.</i> (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.

that ‘stair climbing’ and ‘carrying a heavy object or person’ should be included as SFA for testing mobility; thus, the following five tasks for evaluating mobility while wearing PPE were assessed in our study^{9, 26}.

- Step-up: for 1 min, go up and down on a 45 cm step 20 times
- Side jump: for 20 s, as often as possible
- Crawl: 10 m, back and forth
- Object drag: 10 m dragging a 20 kg object back and forth
- Obstacle stride: 12 m, move back and forth three times (six times crossing the 70 cm obstacle, six times passing under-neath the 100 cm obstacle).

Son *et al.* reported that SFA used in their research are effective in measuring the impaired mobility of PPE users²⁶. In particular, the change in heart rate during the step-up task and performance time in the obstacle stride task showed significant differences between the clothing conditions in both the non-firefighter and firefighter groups (Table 2). Restriction in mobility associated with wearing PPE often presents as increased performance time as well as a #3 or #4 rating based on the criteria of BS 8469^{24, 26}. For the SFA, multiple variables such as performance time and heart rate or performance errors may exist according to the dynamic movement. Participants try to move their bodies as fast as possible and as much as possible to achieve good performances. While this does improve the performance, the heart rate or performance error may increase owing to the PPE load and physical fatigue. For the authors’ studies, heart rate was not recorded when measuring the completion time or number of performances (e.g., side jump, crawl, object drag, and obstacle stride). Moreover, there were errors in the participants’ performances, and these errors

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^{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 measures 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^{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 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 (8) -	131 (10) * #3	133 (10)** #3	139 (10)** #3
Side jump (times/20 s)	39.9 (8.7) -	35.8 (4.2) #3	35.1 (5.4) #3	35.1 (5.7) #3
Crawl (sec)	24.8 (4.2) -	29.7 (4.9) #3	29.9 (4.4) #3	29.9 (4.5) #3
Object drag (sec)	20.2 (6.0) -	20.6 (4.3) #4	22.2 (6.6) #4	21.3 (5.0) #4
Obstacle stride (sec)	53.4 (5.5) -	69.5 (8.5)*** #3	67.52 (6.9)*** #3	68.0 (7.5)*** #3

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)

while performing firefighter tasks can negatively affect postural sway. For example, in a study by Kincl *et al.*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.*^{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 sway⁴⁴⁻⁴⁶⁾. Brown *et al.*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.*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.*²⁶⁾ investigated PPE user mobility by measuring postural sway as a mobility assessment and found no indications of impairments or improvements in postural sway depending upon the PPE design.

While postural sway may be used as an assessment to determine the mobility restriction caused due to wearing PPE by firefighters^{39, 44)}, cognizance is raised to the fact that although postural sway indeed changes with the addition of PPE, it does not necessarily mean that the PPE will cause mobility changes. The measurement of postural sway may not be the best test method for mobility as it requires costly devices for measuring the effects of PPE and is difficult to define the mechanisms underlying these effects remains challenging, as observed in a previous study²⁶⁾.

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^{26, 40, 41, 43, 45, 47, 48)}. 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^{40–42)}. Using the wooden plank time test, Punakallio *et al.*⁴³⁾ 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.*⁴⁸⁾ 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.*³⁶⁾ 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 ability⁴⁷⁾. 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.*²⁶⁾, no significant reduction in functional balance ability was observed; however, there was a tendency for impaired

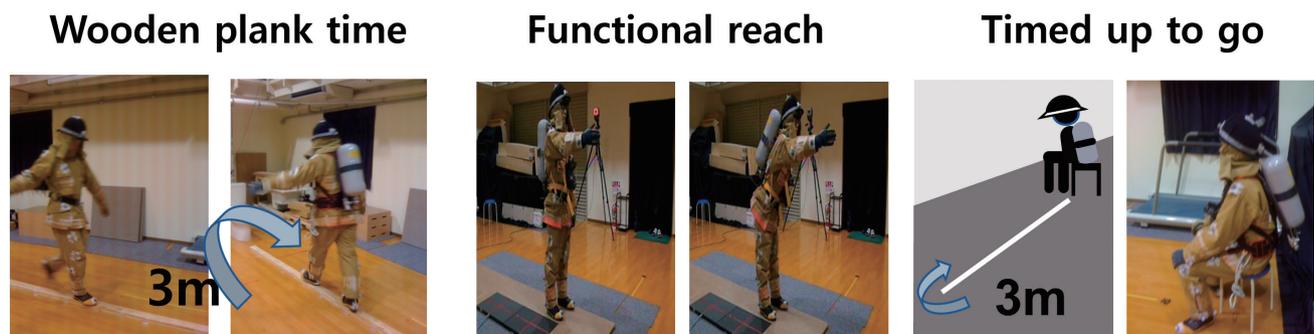


Fig. 1. Functional balance test

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^{41, 43}.

The functional reach test was designed to assess balance abilities due its similarity with postural sway excursion⁴⁹. 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^{12, 37, 50}. 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.*²⁶ 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.*¹² 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 (Fig. 1). The time it takes to complete the task is considered the score of this test^{51, 52}. Son *et al.* attempted to examine mobility using the timed up and go test and obtained notable outcomes²⁶. 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 PPE³¹.

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 weight²⁶. 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^{3, 10–12, 26, 37, 50, 53}. ROM, measured using a goniometer, flexometer, and electro-goniometer, 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^{3, 53}. 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 complicated³. 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 designs¹⁰. 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 Huck¹¹. The different PPE designs, such as modified sleeves and varied 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 measurements¹². 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-

tached electrogoniometers to measure ROM while participants wore different designs of PPE⁵⁴). They succeeded in evaluating the ergonomically restrictive design of PPE under experimental clothing conditions. The PPE, which had an increased number of fabric layers, and the bulkiest design, which had additional materials in the sleeves, significantly reduced the ROM values.

The aforementioned studies focused on variations in the PPE design and materials; however, other studies have evaluated the effect of PPE use itself on mobility. For example, the effect of PPE use compared with that of light clothing on users' mobility was tested by measuring ROM³⁷). Static ROM consisted of flexion/extension/abduction movements of the joints of the elbows, shoulder, neck, hip, knees, ankles, and wrists and was measured both with and without PPE. The authors concluded that wearing PPE had no significant influence on overall mobility compared with wearing light clothing. However, some of the ROM measurements were shown to be significantly reduced in 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 motions²⁹). Coca *et al.* suggested that their test method, consisting of ROM, should be considered as a standard method for the assessment of PPE³⁷).

The authors of the present study investigated mobility when wearing various types of PPE clothing and evaluated the effectiveness of these measurements³). 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^{29, 30}). A previous study hypothesized that the different materials and design of station uniforms worn under PPE may influence the improvement of users' mobility³⁰). 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 up-gradation 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 PPE²⁵). 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 mobility²⁵). 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^{25, 26}).

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^{13, 17, 27}). Furthermore, psychological responses have been used as supportive data of physiological responses⁵⁵); 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 comfort⁵⁶).

Ciesielska-Wróbel *et al.* assessed the comparison of similar designs of PPE to verify SE measurements⁵⁴). 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 areas³⁵. 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^{12, 37, 50}. 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^{3, 26}. 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^{3, 26}. In addition, significant differences in the mass of PPE were observed in the perceived mobility and comfort results³¹.

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^{29, 30, 37, 57}.

A few studies have reported comparisons of efficiency results while wearing PPE between firefighter and civilian participants^{26, 58}. 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 trials⁵⁸. 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^{26, 27}. 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 environments²⁷. 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 participants⁵⁹.

We also investigated the suitability of standard participants for the assessment of mobility with PPE²⁶. 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 methods²⁶. 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^{10, 11, 47, 54}. However, objective mobility assessments and tests accompanied by SE may increase the precision of test participated by firefighters²⁶. 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^{12, 26, 35, 37}. ASTM F3031-17 describes that a minimum of eight different participants (firefighters or non-firefighters) are allowed for standard practice²⁵. Furthermore, at least six professional firefight-

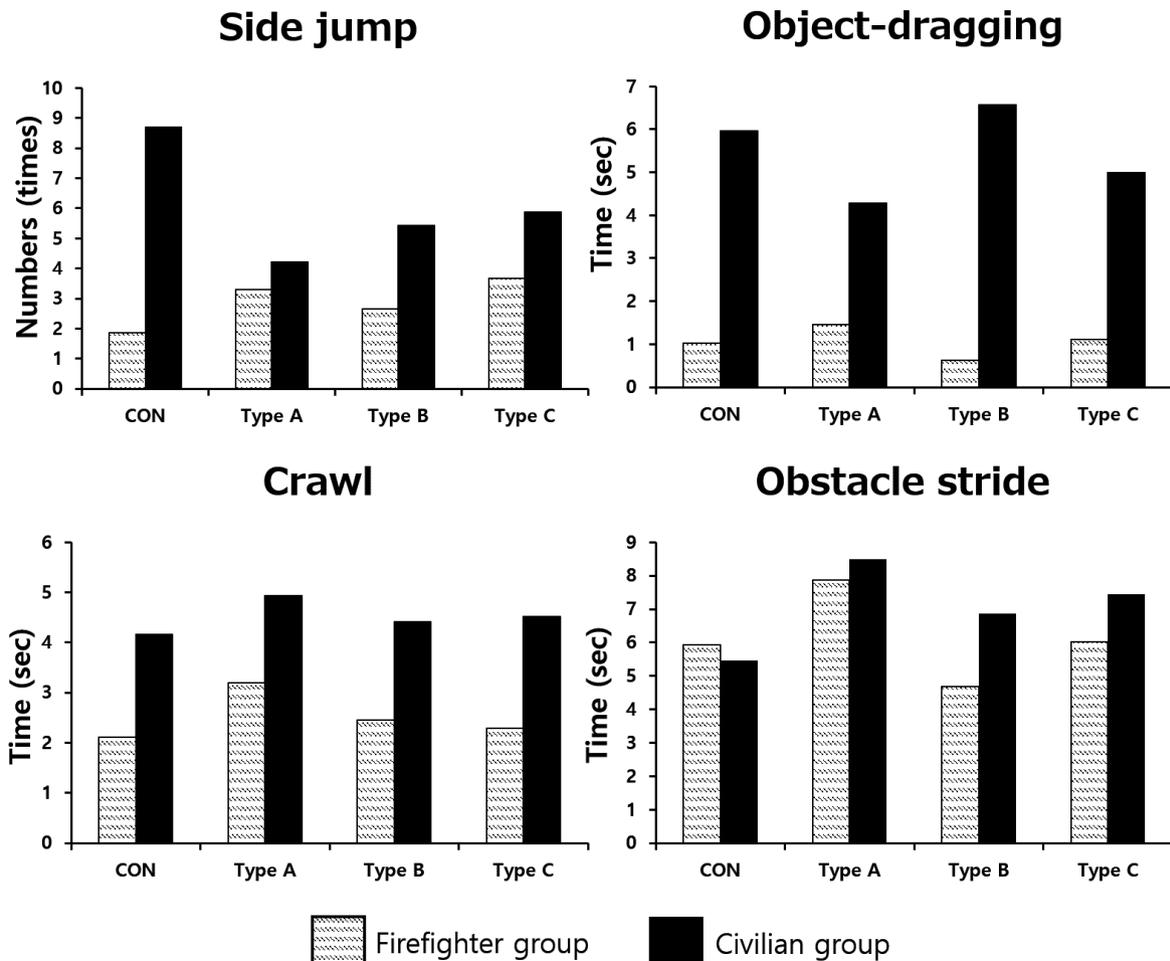


Fig. 2. The comparison of standard deviation between firefighter and civilian groups under the simulated firefighting activities. The figure was adapted from Son *et al.* (2014) : (partially modified).

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.

ers are required for mobility assessment under BS 8469²⁴). Therefore, more than eight professional firefighters will be required for increased precision of the standardized mobility test.

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 cloth-

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 PPE³¹). 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 time²⁴), 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-

Table 3. The simplicity and ergonomic judgment possibility of test methods for mobility assessment

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.

ous studies, the degree of simplicity, and ergonomic judgment possibility we established three grades: small, middle, and great. Simplicity was based on an evaluation being simple to operate/perform as well as the supply and demand of the devices needed. The ergonomic judgement possibility was based on the number of significant results in previous studies.

However, there are several limitations to this review. First, the majority of research assessing the reduction in mobility associated with PPE use has been performed by a select number of researchers. Therefore, in order for the suggested test methods to be standardized internationally, further research from various countries evaluating these methods is required. Second, almost all of the participants in previous studies related to PPE were firefighters; hence, a relatively small number of studies were focused on civilian groups. Although the suggested test methods require that firefighters should participate in the test for more significant results, future research focusing on civilian groups is required to extend the findings to the volunteer fire brigade as well as broader public in terms of mobility.

Conclusions

To the best of our knowledge, this article is the first review highlighting the most useful test methods for assess-

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.

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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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