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The Impact of Firefighter Personal Protective Equipment and Treadmill Protocol on Maximal Oxygen Uptake

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This study investigated the effects of firefighter personal protective equipment (PPE) on the determination of maximal oxygen uptake (VO_{2max}) while using two different treadmill protocols: a progressive incline protocol (PIP) and a progressive speed protocol (PSP), with three clothing conditions (Light-light clothing; Boots-PPE with rubber boots; Shoes-PPE with running shoes). Bruce protocol with Light was performed for a reference test. Results showed there was no difference in VO_{2max} between Bruce Light, PIP Light, and PSP Light. However, VO_{2max} was reduced in Boots and Shoes with shortened maximal performance time (7 and 6 min reduced for PIP Boots and Shoes, respectively; 11 and 9 min reduced for PSP Boots and Shoes, respectively), whereas the increasing rate of VO_2 in Boots and Shoes during submaximal exercise was greater compared with Light. Wearing firefighter boots compared with wearing running shoes also significantly affected submaximal VO_2 but not VO_{2max} . These results suggest that firefighters' maximal performance determined from a typical VO_{2max} test without wearing PPE may overestimate the actual performance capability of firefighters wearing PPE.

Keywords clothing weight, graded exercise test, maximal oxygen uptake, personal protective equipment, protective boots

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INTRODUCTION

It is generally recognized that a maximal oxygen uptake (VO_{2max}) characterizes the functional limits of the cardiovascular system to transport oxygen from air to tissues to meet aerobic requirements of the body.⁽¹⁾ It is the single best physiological indicator of muscular capacity for sustained work.⁽²⁾ Various exercise protocols are used to determine VO_{2max} for assessment of individual cardiovascular fitness, prescribed training intensity, and to evaluate the effects

of physical training. In an occupational setting, the assessment of VO_{2max} helps to determine workers' cardiovascular health and physical capability required to perform their duties safely and effectively.

Fire fighting is one of the most physically demanding occupations, with a considerably high rate of on-duty fatalities worldwide. Recent reports showed 34 cases (2007–2011) in South Korea,⁽³⁾ 10 cases (2004–2008) in Japan,⁽⁴⁾ and 427 cases (2007–2011) in the United States⁽⁵⁾ of on-duty firefighter fatalities. Wearing firefighter personal protective equipment (PPE) along with self-contained breathing apparatus (SCBA) provides an effective barrier of protection against hazardous materials, but the heavy weight and increased thermal insulation from PPE and SCBA result in the premature onset of muscle fatigue and impaired thermoregulation (elevation of body temperature), which consequently leads to a significant reduction in work capability and duration.^(6–12) Previous studies revealed a significant reduction in the attainment of VO_{2max} ranging from 17 to 20% when PPE and SCBA are worn.^(10,13) While a minimum level of aerobic fitness for firefighters of 40 to 45 mL/kg/min is suggested,^(8,9,14) such a significant reduction in VO_{2max} attributed to wearing PPE and SCBA leads firefighters to failure or prolonged task duration in executing some of the most metabolically demanding activities, such as victim rescue and stair/ladder climbing with hose, or tool carrying (40–44 mL/kg/min).^(8,11,14)

In this context, the question arises as to how the aerobic fitness level of firefighters should be determined to evaluate their work capability while wearing PPE and SCBA. A typical method to determine VO_{2max} in a fitness setting would involve wearing light gym clothing. However, this does not account for the added metabolic demands resulting from PPE and SCBA and thus would likely overestimate actual VO_{2max} achieved in the PPE condition (Shoes and Boots). Also, some testing protocols with large increments in work load (e.g., Bruce protocol) or specific modes of exercise (e.g., cycling) would

not be appropriate due to premature muscle fatigue stopping exercise prior to reaching $\text{VO}_{2\text{max}}$, and attenuated weight-carrying effects on a wearer, respectively. Further, replacing firefighter boots with running shoes in PPE-involved exercise tests and/or firefighting simulation studies is often practiced to prevent any gait-disturbing incidents and/or to promote comfort even though studies^(15,16) have shown increased metabolic burden with wearing firefighter boots. Thus, there could be differences in VO_2 responses during tests.

To our knowledge, there is no guideline for a test protocol or clothing configuration universally accepted for firefighters in South Korea, Japan, or the United States. One European standard⁽¹⁷⁾ provides a protocol for determination of the standard activity level of firefighters exercising at 90% of anaerobic threshold while wearing PPE; however, this test is still based on $\text{VO}_{2\text{max}}$ results from a typical test in light gym clothing. Thus, the purpose of our study was (1) to evaluate the effects of firefighter PPE and SCBA on the determination of $\text{VO}_{2\text{max}}$ while using two different treadmill exercise protocols: progressive incline protocol (PIP) and progressive speed protocol (PSP), and (2) to examine the impact of wearing firefighter boots on submaximal VO_2 responses and $\text{VO}_{2\text{max}}$ compared with wearing running shoes during the exercise test.

METHODS

Subjects

Ten healthy males free of known cardiovascular and respiratory dysfunction participated in the study. Their physical characteristics were 26.5 ± 4.0 years in age; 175.9 ± 4.8 cm in height; 69.1 ± 7.5 kg in body weight; $17.2 \pm 5.2\%$ in total body fat (%BF) (mean \pm SD). Their $\text{VO}_{2\text{max}}$ determined from the initial reference trial (Bruce protocol) was 46.7 ± 6.5 mL/kg/min. This level of aerobic fitness could not be categorized into a group of highly trained individuals but was comparable with a reported range of $\text{VO}_{2\text{max}}$ in professional firefighters.^(8,11,12)

All tests were conducted from August to September 2011. Prior to providing written informed consent, subjects were fully informed of the purpose and potential risks of the present study. The study was approved by the Institutional Review Board of Kyushu University.

Experimental Protocols and Procedures

Subjects visited a laboratory on seven occasions at the same time of day for one reference $\text{VO}_{2\text{max}}$ and six experimental trials. They were instructed to abstain from alcohol and strenuous exercise for 48 hr, as well as food and caffeine for 3 hr, prior to their scheduled tests. Each visit was separated by at least 48 hr; the seven trials were completed within 4 weeks. All $\text{VO}_{2\text{max}}$ tests were performed on a motorized treadmill (Aeromill; Nihon Kohden, Tokyo, Japan) in a laboratory where air temperature and relative humidity were maintained at 23°C and 40%, respectively. The subjects began each trial with a 15-min rest on a chair for stabilization and then warmed up (walking at a speed of 3 km/hr without incline) for 5 min.

Following the warm-up period, each treadmill protocol described below was initiated followed by a 15-min recovery period on a chair after cessation of exercise. During the tests, subjects were encouraged to perform as well as they could; however, the tests were terminated when they reached volitional fatigue or 95% of age-predicted maximum heart rate (HR_{max}). Each test was retrospectively examined and confirmed as a true maximal test when two of the following criteria were met:^(18,19) (1) plateau or increase in oxygen uptake ≤ 2.1 mL/kg/min with an increased work load; (2) respiratory exchange ratio (RER) ≥ 1.10 ; (3) $\text{HR} \geq 95\%$ of age-predicted HR_{max} ($220 - \text{age in yrs}$); (4) ratings of perceived exertion (RPE) ≥ 18 ; and (5) post-exercise blood lactate concentration ≥ 8 mmol/L.

The conditions of the seven $\text{VO}_{2\text{max}}$ trials are shown in Figure 1. The Bruce protocol consisted of seven stages with progressive increases of speed and incline every 3 min starting from 2.74 km/hr at a 10% incline (about 6°), with the subjects wearing light clothing. This test served as initial health screening of the subjects and a reference trial for the comparison of $\text{VO}_{2\text{max}}$ with those measured from the PIP and PSP protocols. The PIP consisted of stages with a 1% increase in grade every minute at a constant speed of 5.3 km/hr. The PSP consisted of stages with 1 km/hr increase in speed every minute starting from 4 km/hr without incline. The maximum increase in incline for PIP and speed for PSP was 20% and 12 km/hr, respectively, due to the operation limit of the treadmill.

Three clothing conditions were assigned to each protocol: *Light* (shorts, t-shirts, socks, and 0.7 kg running shoes; 1.0 kg in total mass); *Boots* (6.0 kg-PPE with 11.0 kg SCBA and 2.2 kg-rubber boots; 19.2 kg in total mass); and *Shoes* (6.0 kg-PPE with 11.0 kg SCBA and 0.7 kg running shoes; 17.7 kg in total mass). The PPE consisted of a short-sleeved t-shirt, shorts, socks, duty uniform of long-sleeved shirt and pants, a waist belt, a bunker jacket, pants with a bunker belt, work gloves, and a helmet with its neck cover (standard PPE of the Tokyo Fire Department). The facepiece of the SCBA was replaced by a respirator mask connected to the gas exchange analyzer so that respiratory gases could be collected. Condition Boots was designed to examine the effect of the PPE and SCBA on oxygen uptake in comparison with condition Light. Condition Shoes aimed to examine the direct effect of wearing firefighter boots on oxygen uptake in comparison with Condition Shoes, as well as to test the practicality of wearing athletic shoes instead of firefighter boots in PPE-involved tests. To minimize any order effect, the test order of the six experimental trials (2 protocols \times 3 clothing) was balanced across the subjects using a Latin square design.

Measurements

Before and after each trial, subjects' seminude body weight was measured on a calibrated scale with 1-gram resolution (ID2; Mettler-Toledo, Albstadt, Germany). In all trials, gas exchange variables such as oxygen uptake (VO_2), carbon dioxide production (VCO_2), ventilation (V_E), respiratory exchange ratio (RER), and respiratory frequency (R_f) were continuously

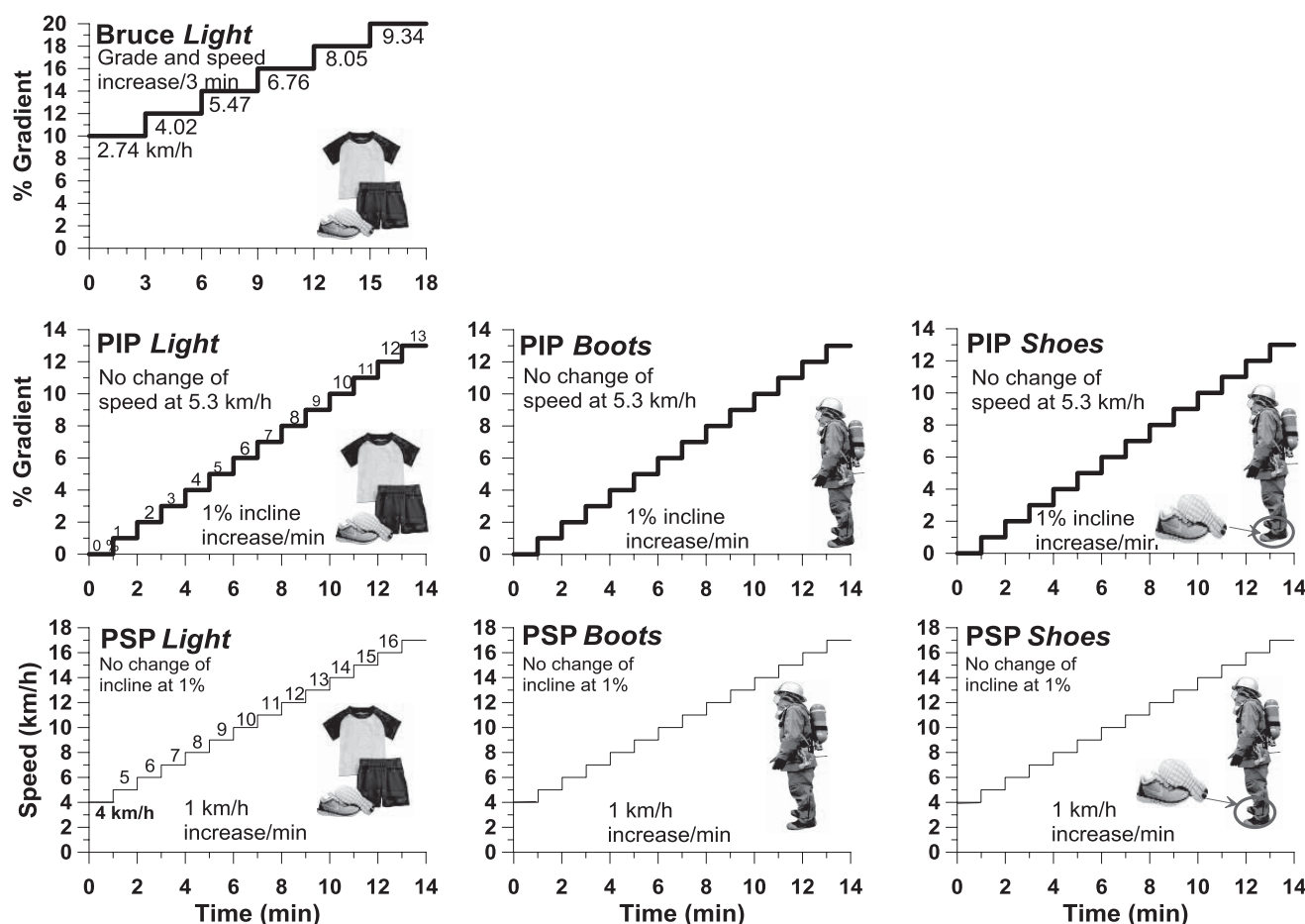


FIGURE 1. Seven maximal oxygen uptake (VO_{2max}) treadmill test protocols. (For PSP graphs, the stair lines represent the gradual increase in treadmill speed, whereas the stair lines in PIP and the Bruce protocol represent the gradual increase in treadmill incline. Light, Boots, and Shoes represent the conditions with light clothing, PPE with rubber boots, and PPE with running shoes, respectively).

measured at a sampling interval of 10 sec throughout the rest, exercise, and recovery periods using an automatic respirometer (AE-300S; Minato Medical Science, Tokyo, Japan). Prior to each trial, the respirometer was calibrated using room air and standard gas mixture (5.03% CO_2 , 15.00% O_2 , balance nitrogen) along with a volume calibration using a 2-L syringe. Heart rate (HR) was recorded every second using a HR monitor (RS400; Polar Electro, Kempele, Finland). Gas exchange and HR data during the last 30 sec of exercise period were averaged and considered the maximal values. To measure blood lactate concentration, capillary blood samples were collected from the tip of the middle finger at rest and 5 min after the cessation of exercise, then analyzed using a portable lactate analyzer (Lactate Pro/LT1710; Arkay KDK Corporation, Kyoto, Japan). Subjects were also asked to provide their ratings of perceived exertion (RPE; Borg's 6–20 scale) every 2 min.

Data Presentation and Statistical Analysis

Values were presented as mean and standard deviation (SD). Data from the Bruce protocol served as a reference VO_{2max}

for the comparison with VO_{2max} values from PIP Light and PSP Light. The effect of the PPE factor was analyzed both in comparison with the reference test and within the PIP/PSP conditions. All comparisons between the Bruce protocol, PIP Light, and PSP Light were presented as "Protocol" in tables and figures, while the comparisons between Light, Boots, and Shoes in PIP or PSP were expressed as "LBS" in tables and figures. Data from the first 7 min of exercise were analyzed to compare differences in submaximal responses to each clothing condition within the PIP and PSP, as all subjects completed at least the first 7 min of each trial. For statistical analysis, repeated measures analysis of variance (ANOVA) was carried out to identify the differences in gas exchange, HR, lactate concentration, and performance time variables between protocols and clothing conditions. Tukey's post hoc test was employed for the variables that showed a significant difference in ANOVA. Pearson's correlation coefficients were calculated to assess the association among continuous variables. A level of statistical significance was set at $P < 0.05$, and all analyses were performed using a statistical software package (version 19.0; IBM SPSS Statistics, Somers, N.Y.).

RESULTS

Time-to-Exhaustion

The group mean of time-to-exhaustion was 11.9 ± 1.8 min for Bruce Light, 21.0 ± 3.8 min for PIP Light, and 18.2 ± 10.3 min for PSP Light, showing a significant difference between the three protocols ($P < 0.001$) (Figure 2). In the PPE condition, the group mean of time-to-exhaustion was 13.9 ± 3.5 min (PIP Boots), 15.2 ± 3.0 min (PIP Shoes), 7.3 ± 1.5 min (PSP Boots), and 8.9 ± 2.3 min (PSP Shoes). Decrease in time-to-exhaustion in Shoes due to the extra load of PPE (16.7 kg) was greater in PSP Shoes [9.3 ± 8.2 min (43%)] than in PIP Shoes [6.0 ± 1.8 min (28%)]. Similarly, decrease in time-to-exhaustion in Light due to the extra load of PPE + boots (18.2 kg) was greater in PSP Boots [10.9 ± 9.2 min (52%)] than PIP Boots [7.3 ± 0.9 min (35%)] (Figure 2, Table I). Based on these results, it was estimated that time-to-exhaustion decreased by 0.5 min for every 1.5 kg of additional weight over the body in PIP Shoes and 0.8 min in PSP Shoes, whereas when the additional 1.5 kg loaded on the feet, time-to-exhaustion decreased by 1.3 min in PIP Boots and 1.6 min in PSP Boots (Table I).

Oxygen Uptake

VO_{2max} showed slightly greater in Bruce Light (46.7 ± 6.5 mL/kg/min) than in PIP Light (43.8 ± 7.2) and PSP Light (42.4 ± 9.0) without a statistical significance. However, VO_{2max} obtained in PPE conditions was significantly less than the reference VO_{2max} (Figure 2). VO_{2max} obtained from PIP Boots and Shoes was 12% lower than the reference VO_{2max} and from PSP Boots and Shoes was 8% and 11% lower than the reference VO_{2max} . Table II shows the percentages of VO_{2max} from PIP and PSP corresponding to the reference VO_{2max} from Bruce Light. VO_2 responses during the first 7 min of exercise in PIP and PSP are shown in Figure 3. Submaximal VO_2 was 33% and 25% greater in PIP Boots and Shoes compared with PIP Light, and 22% greater in PSP Boots and Shoes compared with PSP Light ($P < 0.05$). The differences between the Boots and Shoes conditions were not significant for PIP or PSP protocols. It was estimated that the increasing rate of VO_2 per time-to-exhaustion was 47% and 102% greater in PIP Boots and the PSP Boots, respectively, compared with PIP Light and PSP Light ($P < 0.05$). Also, the rate of increase in VO_2 was greater in the PSPs than in the PIPs ($P < 0.001$) (Figure 4). In addition, wearing rubber boots exerted a significantly greater

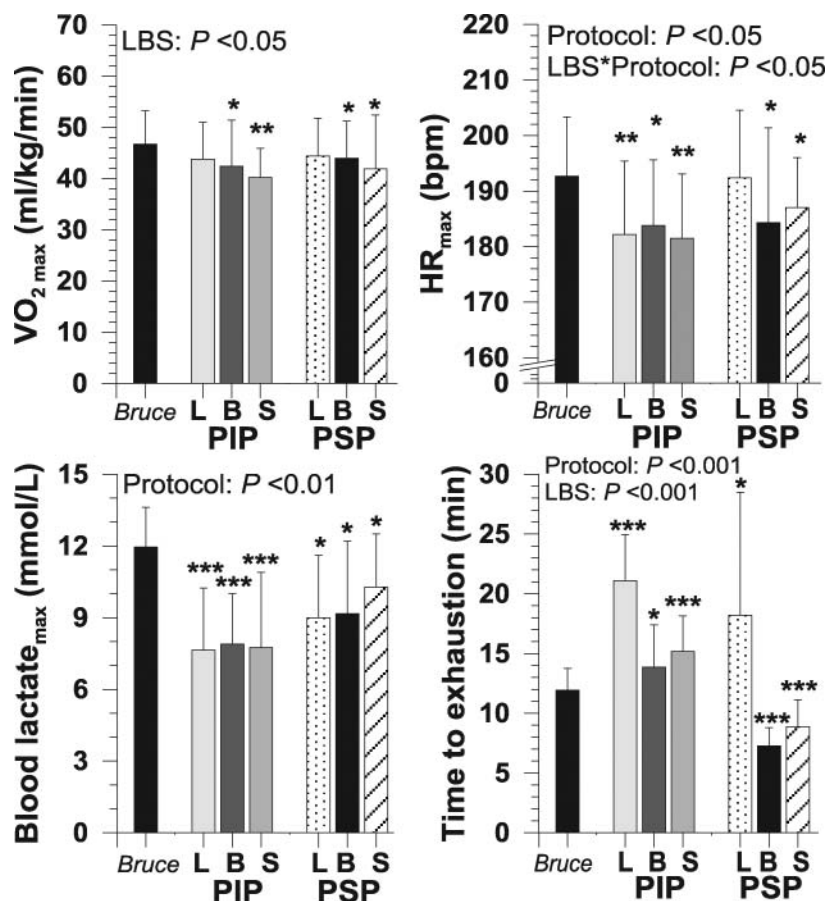


FIGURE 2. Maximal oxygen uptake (VO_{2max}), maximal heart rate (HR_{max}), maximal lactate concentration and time-to-exhaustion; L, B and S represent the conditions with light clothing (Light), PPE with rubber boots (Boots), and PPE with running shoes (Shoes), respectively. Note: *, **, and *** display significant differences compared with the Bruce protocol at levels of 0.05, 0.01, and 0.001, respectively.

TABLE I. Changes in Time-to-Exhaustion According to PPE Weight Worn

Protocol	Condition Light vs. Shoes			Light vs. Boots	
	An additional 16.7 kg on the whole body (measured)	1.5 kg added on the whole body (estimated)	18.2 kg added on the whole body (estimated)	An additional 18.2 kg on the whole body (measured)	Shoes vs. Boots An additional 1.5 kg on the feet (measured)
Progressive Incline (PIP)	-6.0 (1.8) min 28 (6)%	-0.5 (0.2) min	-6.5 (1.9) min	-7.3 (0.9) min 35 (6)%	-1.3 (1.5) min 9 (10)%
Progressive Speed (PSP)	-9.3 (8.2) min 43 (17)%	-0.8 (0.7) min	-10.2 (8.9) min	-10.9 (9.2) min 52 (18)%	-1.6 (1.3) min 17 (12)%

Note: Light, Shoes, and Boots represent Light clothing, PPE with shoes, and PPE with boots, respectively. Data is expressed in mean SD.

VO₂ than wearing running shoes during submaximal exercise ($P < 0.05$).

Other Gas Exchange Variables (VCO₂, V_E, RER, and R_f)

VCO_{2max} was significantly lower in PIP Light and PSP Light compared with the reference value from Bruce Light ($P < 0.05$), but there was no significant difference in VCO_{2max} between PIP and PSP in any clothing condition (Table III). For V_{E max}, PIP Boots and Shoes displayed significantly lower V_{E max} than the reference value from the Bruce protocol ($P < 0.05$), whereas the differences in V_{E max} between the Bruce protocol and all the PSPs were not significant (Table III). RER_{max} was significantly lower in PIP Light, Boots, Shoes, and PSP Light, when compared with the reference value from the Bruce protocol. R_{f max} showed no significant difference

between Light, Boots, and Shoes. However, R_{f max} tended to be greater in PSP compared with PIP ($P < 0.05$).

Heart Rate (HR)

HR_{max} was lower in PIP Light (182 ± 13 bpm) than in the reference value from Bruce Light (193 ± 11 bpm) and PSP Light (192 ± 12 bpm) ($P = 0.026$; Figure 2). HR_{max} in the PPE conditions of PSP and PIP were all significantly lower than in the reference value from the Bruce protocol (184 ± 12 bpm for PIP Boots and 182 ± 12 bpm for PIP Shoes; 184 ± 17 bpm for PSP Boots; and 187 ± 9 bpm for PSP Shoes). However, there was no significant difference in HR_{max} between Boots and Shoes for both PIP and PSP. During submaximal exercise, HR was significantly greater in PIP Boots and Shoes than in PIP Light (112 ± 10 , 142 ± 15 , and 132 ± 11 bpm for PIP Light, Boots, and Shoes, respectively; $P < 0.001$) and in PSP ($158 \pm$

TABLE II. Percentages of VO_{2max} in PIP and PSP Corresponding to %VO_{2max} from Bruce Protocol

VO _{2max} Bruce	Progressive Incline Protocol (PIP)						Progressive Speed Protocol (PSP)						P-values††		
	Light		Boots		Shoes		Light		Boots		Shoes				
	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Mean	SD	Factor 1 (PIP*PSP)	Factor 2 (Light*Boots*Shoes)	F1*F2
100%	108	15	115*	17	117**	11	106	13	107*	8	117†	24	0.876	0.117	0.492
90%	98	13	104*	15	105**	10	96	12	96*	7	105†	22			
80%	87	12	92*	14	93**	9	85	10	86*	6	93†	20			
70%	76	10	81*	12	82**	8	75	9	75*	6	82†	17			
60%	65	9	69*	10	70**	7	64	8	64*	5	70†	15			
50%	54	7	58*	9	58**	6	53	7	54*	4	58†	12			
40%	43	6	46*	7	47**	4	43	5	43*	3	47†	10			
30%	33	5	35*	5	35**	3	32	4	32*	2	35†	7			
20%	22	3	23*	3	23**	2	21	3	21*	2	23†	5			
10%	11	2	12*	2	18**	1	11	1	11*	1	12†	2			

Notes: Light, Shoes, and Boots represent light clothing, PPE with shoes, and PPE with boots, respectively. †, *, and ** indicate differences from the Bruce values at $P < 0.01$, 0.05, and 0.01. †† P-values from repeated measures ANOVA.

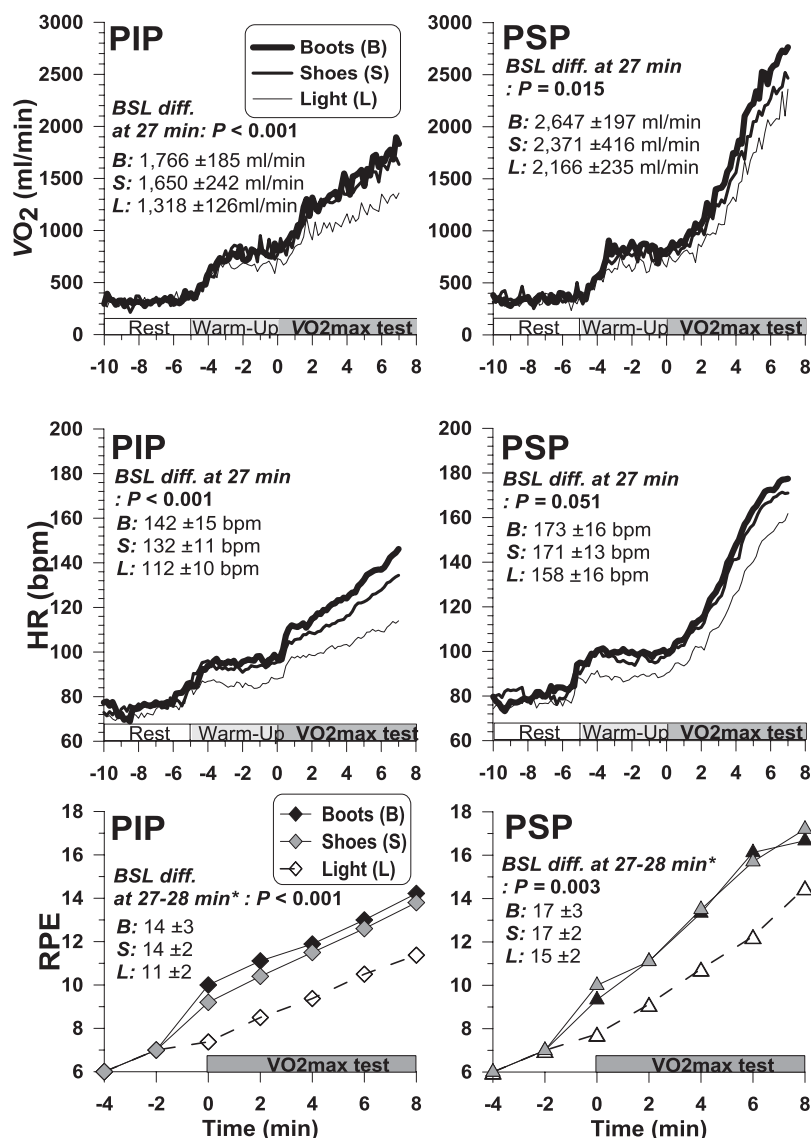


FIGURE 3. Oxygen uptake (VO₂), heart rate (HR) and ratings of perceived exertion (RPE) until the 7th min of exercise; Boots(B), Shoes(S), and Light(L) represent the conditions with light clothing, PPE with rubber boots, and PPE with running shoes, respectively. *Note:* For the RPE, the last values were obtained at 7–8th min.

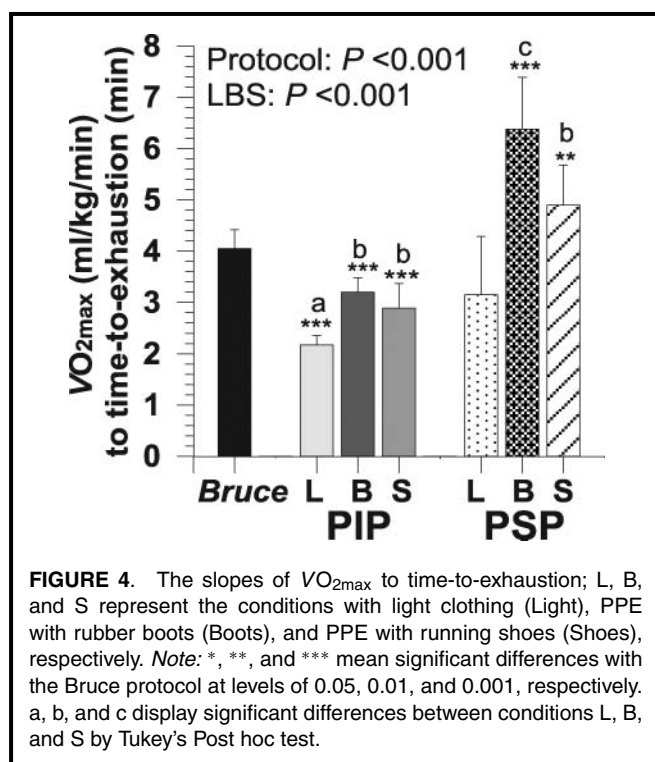
16, 173 ± 16 , and 171 ± 13 bpm for PSP Light, Boots, and Shoes, respectively; $P < 0.05$). HR_{max} showed significantly positive correlation to both VO_{2max} and V_{E max} in all seven protocols ($P < 0.05$).

Blood Lactate Concentration

Blood lactate concentration at exhaustion was significantly greater in Bruce Light (12.0 ± 1.7 mmol/L) than in the other six protocols (7.6 ± 2.6 , 7.9 ± 2.1 , and 7.7 ± 3.1 mmol/L for PIP Light, Boots, and Shoes, respectively; 9.0 ± 2.6 , 9.2 ± 3.0 , and 10.3 ± 2.2 mmol/L for PSP Light, Boots, and Shoes, respectively) (Figure 2). Also, there was a significant difference in lactate concentration between PIP and PSP ($P = 0.006$) but no difference between any clothing conditions.

Ratings of Perceived Exertion (RPE)

RPE at exhaustion (RPE_{max}) was significantly greater in Bruce Light (18.5 ± 0.7) than PIP Light (17.6 ± 1.4) and PSP Light (17.3 ± 1.9) ($P < 0.05$), but there was no statistical difference between PIP and PSP (17.9 ± 1.9 and 18.3 ± 1.1 for PIP Boots and Shoes, respectively; 17.6 ± 1.4 and 18.3 ± 0.5 for PSP Boots and Shoes). Also, there was no difference between Boots and Shoes in either PIP or PSP. During submaximal exercise, RPE was significantly greater in Boots and Shoes than in Light for PIP (11 ± 2 , 14 ± 3 , and 14 ± 2 for Light, Boots, and Shoes, respectively; $P < 0.001$) and PSP (15 ± 2 , 17 ± 3 and 17 ± 2 for Light, Boots, and Shoes, respectively; $P < 0.05$), but there was no difference between Boots and Shoes in either PIP or PSP. RPE_{max} had significant relationships with HR_{max}, RER_{max},



V_{Emax} , RER_{max} , and blood lactate concentration ($P < 0.05$), but the relationships with time-to-exhaustion, total sweat rate, and VO_{2max} were not significant.

DISCUSSION

Time-to-Exhaustion

It has been reported that the use of SCBA alone decreases maximal performance time by approximately 20%.⁽²⁰⁾ One of the main findings in the present study was that maximal performance time decreased by approximately 35% during uphill walking (decreased by approximately 7 min) and 52% during running on a treadmill without incline (decreased by approximately 11 min) due to wearing the firefighter PPE (including SCBA). This indicates that the significant effect of wearing PPE on the maximal performance time was greater in fast running on a flat level than with uphill walking. It seems that the decrease in maximal performance time in the present study was attributed primarily to the increase in metabolic burden due to wearing PPE and SCBA. Considering that the total time of firefighting in an operation is generally limited to 30 min due to the capacity limit of SCBA,⁽⁶⁾ the reduction in time to exertion in Boots (7 min decrease in PIP and 11 min decrease in PSP) could be of significant importance in a real-life operation.

Effects of PPE on Oxygen Uptake

Another interesting finding is that wearing firefighter PPE increased VO_2 during submaximal exercise by 33% and 22% but reduced VO_{2max} by 5% and 3% in PIP and PSP, respectively. When compared with the reference value from Bruce

Light, VO_{2max} decreased by 12% and 8% due to wearing firefighter PPE in PIP Boots and PSP Boots, respectively. Both the increased VO_2 and decreased VO_{2max} indicate that firefighter PPE imposes a greater metabolic burden on a wearer during exercise but also impedes the body's maximal ability to use oxygen, which led to the premature cessation of the exercise before reaching the subject's true VO_{2max} . It has been reported that VO_2 demands in actual or simulated firefighting operations ranges between 62% and 84% VO_{2max} ^(9,21,22) and often reach near VO_{2max} .⁽⁸⁾ As shown in Table III, however, it is critical to note if the minimal work load standard required for firefighter applicants is set at 70–80% VO_{2max} measured from a typical exercise test, firefighters wearing PPE and SCBA would perform at approximately 80–90% VO_{2max} , which may require different strategies for task shift and work duration as well as for safety practices.

A series of investigations have reported added burdens of wearing heavy PPE on energy costs during work. The energy cost of walking and/or running increased by 13–18% with 9.3 kg military PPE⁽²³⁾ and 11–21% with firefighter PPE⁽⁷⁾ compared with the energy cost of wearing light clothing. On the other hand, studies have found significant decreases in VO_{2max} by 10–17% wearing SCBA alone,^(24,25) 17–20% with wearing PPE and SCBA.^(10,20,26) It seems that increased submaximal VO_2 and decreased VO_{2max} due to the use of PPE are attributable to a number of factors, including heat stress inside the semi-impermeable firefighter PPE,^(6,8) a hobbling/binding effect caused by bulkiness and stiffness that can interfere with joint movements and/or the frictional resistance that results from clothing layers sliding over one another,⁽²³⁾ tight SCBA harness impeding ventilation and tidal volume,^(24,27) and the direct effect of PPE weight.

In particular, we need to concentrate the influences of heat stress on the performance of firefighters wearing PPE. Firefighters complained much more about heat stress from bad ventilation and sweat inside PPE rather than from the heavy PPE when worn in the line of duty.⁽²⁸⁾ Peak heart rate during exercise wearing firefighter PPE (19 kg) was significantly greater at an air temperature of 32°C than at 22°C (180 ± 17 and 168 ± 18 bpm, respectively).⁽⁶⁾ Thus, air temperature should be considered when suggesting a standard test method for the VO_{2max} of firefighters wearing PPE. When compared with our results, one may find a wide variation in the changed values, even with similar weight PPE. This is primarily accounted for by different exercise protocols across studies, but it is important to note that there is a non-linear relationship between PPE weight and energy cost as exercise intensity increases.⁽²⁹⁾

Wearing firefighter boots did not have a statistically significant impact on VO_{2max} , whereas the rate of increase in VO_2 was noticeably greater in Boots than in Shoes, especially in PSP (Figure 4). It is well documented that walking/running while wearing the boots increases energy expenditure by 0.5–1.2% per 100 g shoes mass.^(15,30–32) The energy cost of weight load on the feet relative to other parts of the body has been reported as twice greater than that of the same load on the thigh,⁽³³⁾ 5.8 times on the torso,⁽³²⁾ 6.4 times on the back,⁽³¹⁾

TABLE III. Gas Exchange Variables

		Bruce Light	PIP			PSP			P-values [†]		
			Light	Boots	Shoes	Light	Boots	Shoes	Factor 1 (2 Protocols)	Factor 2 (3 PPE)	F1*F2
VO ₂ max (mL/kg/min)	Mean	46.7	43.8	42.4*	40.2	44.4	44.0*	41.9*	0.682	0.238	0.234
	SD	6.5	7.2	9.0	5.7	7.4	7.2	10.5			
VO ₂ max (L/min)	Mean	3.20	2.99	2.83*	2.82**	3.04	2.95*	2.85*	0.682	0.238	0.234
	SD	3.81	4.02	5.34	3.86	4.29	4.31	6.20			
VCO ₂ max (L/min)	Mean	3.89	3.28*	3.21***	3.21**	3.24**	3.45*	3.30*	0.809	0.754	0.308
	SD	5.25	5.00	6.39	5.15	4.16	5.91	6.51			
V _E max (L/min)	Mean	118	105	103*	103*	110	112	111	0.050	0.659	0.811
	SD	16.7	22.5	20.2	14.8	14.4	23	15			
RER _{max}	Mean	1.21	1.10**	1.13*	1.14*	1.08*	1.17	1.17	0.455	0.327	0.677
	SD	0.07	0.07	0.09	0.1	0.15	0.1	0.06			
RER _{recovery}	Mean	1.47	1.32**	1.28**	1.28**	1.27 ^{a,*}	1.42 ^A	1.38 ^B	0.126	0.847	0.041
	SD	0.06	0.12	0.09	0.17	0.19	0.14	0.14			
R _f max (frequency/min)	Mean	49.7	45.0	46.5	45.3	51.7	50.5	50.1	0.076	0.872	0.703
	SD	10.6	9.9	10.2	9.3	13.8	12.5	13.1			
R _f recovery (frequency/min)	Mean	34.6	32.7	37.2	36.7*	36.5	39.2*	39.2**	0.269	0.155	0.521
	SD	8.0	4.5	8.3	7.8	6.8	8.5	10.4			

Notes: Light, Shoes, and Boots represent light clothing, PPE with shoes, and PPE with boots, respectively. *, **, and *** indicate significant differences from the Bruce values at P < 0.05, 0.01 and 0.001, respectively. ^A and ^B indicate significant differences between the three PPE conditions. [†]P-values from repeated measures ANOVA. A recovery value averaged the data of initial 5 min in the recovery session.

and 1.9–4.7 times over the whole body.⁽³⁴⁾ Recently, Taylor and colleagues⁽¹⁶⁾ determined the fractional contributions of firefighter PPE on VO_2 and revealed that footwear exerted the greatest relative metabolic load during walking (more than clothing, helmet, or SCBA). Turner and colleagues⁽¹⁵⁾ examined the effects of firefighter rubber boots (3.9 kg) and leather boots (2.4 kg) on gait characteristics and VO_2 during a simulated obstacle walking. They reported a greater metabolic burden and VO_2 when subjects wore the heavier rubber boots. Similarly, results of the present study also show that wearing a firefighter rubber boots negatively affects performance by increasing VO_2 and HR during submaximal exercise (Figure 3). In terms of boot weight, it was estimated from present study results that a reduction in the boots' weight by 1.5 kg could possibly increase maximal performance (Table I). That is, firefighters could save 1–2 min if the weight of footwear were reduced by 1.5 kg. However, perturbations on biomechanics and/or ergonomics of walking/running while wearing the boots could also have contributed to the performance time, together with the direct weight effect.

Selection of Exercise Protocol

Selection of an appropriate exercise protocol may depend on the purpose of the study. However, an exercise protocol with large incremental changes such as the Bruce protocol would be too demanding for the determination of $\text{VO}_{2\text{max}}$ in PPE condition, while a certain mode of exercise that supports body weight, such as cycling, would compensate PPE weight effects on a wearer. In terms of a test duration, a protocol that elicits $\text{VO}_{2\text{max}}$ at up to 10 ± 2 min is generally thought optimal, while a long duration protocol ($>$ about 13–14 min) may negatively affect the attainment of $\text{VO}_{2\text{max}}$ due to a lower maximal cardiac output and stroke volume and/or the alteration of HR_{max} .^(35–37)

Previous studies^(35,37) report no significant differences in the attainment of $\text{VO}_{2\text{max}}$ and HR_{max} between the Bruce protocol and other progressive incline protocols, such as the Balke protocol. Results from the present study for $\text{VO}_{2\text{max}}$ from the Light conditions (Bruce Light, PIP Light, and PSP Light) are in line with previous results, but HR_{max} was slightly lower in PIP Light compared with those values from Bruce Light or PSP Light. In particular, RER, V_E , and blood lactate concentration at exhaustion in PIP Boots and Shoes were not as high as those values in PSP Boots and Shoes, which indicates the work load of PIP was not sufficiently high enough to elicit maximal demands. As for RER, it is generally agreed that an increased RER is indicative of an increased level of anaerobic metabolism.⁽³⁸⁾ As CO_2 production increases, V_E and RER increase.⁽¹⁸⁾ The high level of VCO_2 reflects elevated bicarbonate buffering of hydrogen ions resulting in part from increased lactate metabolism during high levels of muscle tension.⁽³⁹⁾ Therefore, smaller RER_{max} in PIP represents less anaerobic metabolism during maximal performance tests. In addition, PIP Boots and Shoes demonstrated average values of lactate concentration less than 8 mmol/L, which suggests that the work load was not high enough for recruiting active muscle fibers and caused cellular fatigue. The lower lactate production may

be attributed, in part, to an enhanced clearance due to the long performance time at submaximal level⁽⁴⁰⁾ and/or the relatively lower exhaustive work load. Collectively, PSP, which is similar to the protocol described for PPE performance testing,⁽¹⁷⁾ seems to be more appropriate to determine $\text{VO}_{2\text{max}}$ in PPE condition compared with PIP in the present study.

Study Highlights and Limitations

In summary, the significant effect of wearing PPE on maximal performance was greater in fast running on a flat level than in walking uphill, but reduction in boot weight could possibly increase maximal performance. Another important issue is that if the minimal work load standard required for firefighter applicants is from a typical $\text{VO}_{2\text{max}}$ test with subjects wearing light clothing, firefighters wearing PPE would perform at a higher level of $\%\text{VO}_{2\text{max}}$, which is important for establishing safety practices. Alternatively, the present study reports Japanese males' responses while wearing standard Japanese firefighting PPE. In general, however, Caucasian males are taller and heavier than Asian males. Nakanishi and Nethery⁽⁴¹⁾ reported that young Caucasian males are, on average, 9 cm taller (181 cm vs. 172 cm) and 17 kg heavier (79 kg vs. 62 kg) than young Japanese males. The energy cost of treadmill exercise is closely related to body weight, and the absolute $\text{VO}_{2\text{max}}$ is generally higher in heavier subjects.⁽⁴²⁾ With the data above, it is important to note a 20 kg firefighter PPE represents approximately 32% and 25% of body weight for Japanese and Caucasian males, respectively. This difference may indicate that lighter subjects face greater metabolic demands than heavier subjects due to the identical weight of PPE loaded. Thus, one may consider individual body physique and shape as one of the factors that affects oxygen uptake of individuals wearing heavy PPE.

CONCLUSION

Three conclusions can be drawn from this study:

- (1) Assessment of aerobic capacity in firefighters may need to be conducted with subjects wearing light clothing as a typical aerobic fitness test, and while wearing firefighter PPE. While the former test provides a reference to firefighters' fitness combined with other health screening tests, the latter test helps determine their actual work capability in performing a task while wearing PPE. This is mainly due to a significant difference in the attainment of $\text{VO}_{2\text{max}}$ between the two clothing conditions, as present study results showed a significant reduction in $\text{VO}_{2\text{max}}$ by $10 \pm 2\%$ in PPE condition.
- (2) Wearing rubber firefighter boots during the tests showed no significant difference in $\text{VO}_{2\text{max}}$ compared with wearing running shoes. However, the rate of increase in VO_2 was greater in Boots conditions, especially for PSP, which suggests that wearing firefighter boots exerts additional metabolic burden on a wearer during running. Future studies are warranted to investigate

biomechanical and physiological effects of wearing firefighter boots on physical performance.

- (3) PIP as performed in the present study seems to be disadvantageous for the accurate determination of $\text{VO}_{2\text{max}}$, especially in PPE condition. The drawbacks of this protocol may include a longer performance time to complete a test and greater muscle fatigue due to continuous uphill walking while carrying additional weight (e.g., PPE and SCBA), which, nonetheless, provides insufficient work load to reach $\text{VO}_{2\text{max}}$.

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