Effect of Personal Protective Equipment on the Physiological Responses of Different Body Weight Groups of Firefighters

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Abstract

This study analyzed two firefighter groups, the heavy bodyweight (HBW) and the light body weight (LBW) groups. The main aim was to evaluate the physiological responses of these two groups during the personal protective equipment standard test. Furthermore, the differences in the physiological responses between the two groups were hypothesized. All groups performed a 5.5 km∙hr⁻¹ treadmill exercise under 0.967 Kg sports attire as a control condition (CON) and 18.974 Kg personal protective equipment as the PPE condition (PPE), at air temperatures (T_a) of 32°C and 60% relative humidity (RH), respectively. The result showed that the hypothesis was rejected since no differences in physiological responses were found between HBW and LBW groups. The differences only occurred within each group when PPE or control clothing was used. The physical condition of the volunteers was similar due to their daily structured exercise despite differences in body weight between both groups. Therefore, the bodyweight of volunteers is not a relevant issue, provided they are well trained for the standard PPE test.

Keywords: firefighter, personal protective equipment (PPE), physiological responses, body weight

1. Introduction

This study explicitly addresses the volunteer’s body weight and the relationship with physiological responses during a standard Personal Protective Clothing (PPC) test. This test enhances the understanding of the ideal volunteer. A volunteer group with a lighter bodyweight may significantly impact physiological responses relative to a group with a heavier bodyweight. In contrast, body height may not significantly impact physiological responses during exercise in a specific protocol. For example, wearing and carrying PPE weighing a total of 20 Kg may have different effects with an average body weight of 90 Kg relative to a group of 60 Kg. This is because the Light Body Weight (LBW) group will experience a load of about 33.3% of their body weight. In comparison, the Heavy Body Weight (HBW) will only have approximately 22.2% of their body weight.

Studies investigating the physiological burden caused by the load placed on the trunk using a backpack are well documented. Furthermore, Taylor et al. (2016) noted that heart rates and Borg scores (Devroey et al., 2007) increased remarkably for the heaviest loads. Chatterjee et al. (2018) and Holewijn (1990) found that heart rate and oxygen uptake were significantly influenced by the mass carried while walking. Li et al. (2019) and Knapi et al. (1996) showed that the energy cost of walking with backpack loads progressively increased with load mass, body mass, walking speed, or grade. In addition, some laboratory and simulation work has been performed to understand the combined weight effect of PPC and Self-Contained Breathing Apparatus (SCBA) on firefighters. However, no investigation has been conducted on the physiological responses of a heavy load carried by a heavier bodyweight volunteer relative to a lighter bodyweight...
volunteer. Following the context of the Personal Protective Equipment (PPE) standard test for firefighters, it is essential to confirm whether all firefighters can be accepted as volunteers or when a group with specific body weights can only be used for such a test.

This study addressed the bodyweight issue by experimenting with two different groups with a difference of more than 20 kg. Furthermore, it evaluates the physiological responses of these two groups during the PPE standard test. It was hypothesized that their differences lie in the physiological responses between the two groups.

2. Methods

2.1. Volunteers

Two groups of volunteers, the HBW and LBW groups consisting of eight professional firefighters for each group, participated in this study (Table 1). According to the Latin Square design, the experiment was balanced across subjects to avoid partial heat acclimatization due to prevailing environmental circumstances during testing. In addition, the volunteers completed a health status questionnaire and signed a written informed consent form before participating.

2.2. Experimental design and procedures

The maximum oxygen consumption (\(V_{O2max}\)) test was performed a week prior to the main test session. First, volunteers performed a graded exercise test using a treadmill in a climatic chamber at an air temperature \((T_a)\) of 25°C and relative humidity (RH) of 50%. They wore shorts, a round-necked T-shirt, socks, and running shoes and were required to start walking at 2.74 km⋅hr\(^{-1}\) on a 10% slope. According to the Bruce treadmill protocol (Bruce, 1977), the speed and inclination angle of the treadmill was gradually increased every 3 min until the exercise was stopped due to volitional exhaustion. During the test, expired gases were continuously collected by an automatic respirometer (AE-300S, Minato Medical Science, Japan), and \(V_{O2max}\) was calculated by averaging the data for the 30 seconds before they became exhausted.

The Institutional Review Board of Kyushu University approved this study (#80). Written informed consent was obtained from all volunteers after a full explanation of the study requirements and the risk involved.

During the control condition (CON) test, the volunteers only wore shorts (81 ± 6 g) and a round-necked T-shirt (204 ± 31 g) and running shoes (682 ± 124 g). For the PPE test, they wore shorts, a round-necked T-shirt, a long-sleeved shirt (374 ± 14 g), long pants (347 ± 23 g), and a waist belt (98 ± 1 g) as undergarments, a bunker jacket (1,832 ± 254 g), bunker pants (1,217 ± 177 g), bunker belt (768 ± 0 g), gloves (121 ± 11 g), helmet (941 ± 2 g), socks (53 ± 6 g), and boots (2,223 ± 99 g). \(T_a\) of the experimental chamber was set at 32°C with 60%RH and minimal air velocity to represent the hot environment of the firefighters’ working conditions.

Volunteers were given 200 ml drinks before the test to achieve a hydrated state. They were then weighed on a calibrated body scale (ID2, Mettler-Toledo, Germany; resolution of 1 gram) while wearing only shorts. In addition, every undergarment and PPE was weighed in a dry state before being donned by the volunteers. After obtaining their weight, temperature sensors and a heart rate (HR) monitor were placed on the volunteers. They then put on the experimental clothing in the preparation room, maintained at a \(T_a\) of 22-24°C. The rectal temperature was confirmed within normal ranges (37.0 ± 0.4°C), and the volunteers were escorted to the experimental chamber. In this chamber, they sat on a stool, wore an 11 kg SCBA, and started a stabilization period of 10 min. The respiration gas collector mask was used for expired gas analysis instead of an SCBA full-piece mask. Volunteers then performed 30 min exercises on a treadmill without a slope. The initial speed was 3.5 km⋅hr\(^{-1}\) and gradually increased to an exercise speed at 5.5 km⋅hr\(^{-1}\) in 2 min and maintained until the end. After the exercise, they were asked to sit down for a 20 min-recovery period where the SCBA and gas collector masks were removed. During the test, they were prohibited from drinking. The test was terminated when their rectal temperature and heart rate reached 39.5°C and 95% of their maximal heart rate or when any volunteer cannot continue the exercise. After completing the session, they were directed to the

| Height (cm) | 178.0 ± 7.4 | 174.7 ± 4.1 |
| Weight (kg) | 92.0 ± 8.6 *** | 71.6 ± 6.0 |
| Body Fat (%) | 24.6 ± 4.0 * | 17.8 ± 5.0 |
| Body Surface Area (m\(^2\)) | 2.1 ± 0.08 | 1.9 ± 0.04 |
| Age (years) | 31 ± 5 | 31 ± 5 |
| \(V_{O2max}\) (ml⋅kg\(^{-1}\)⋅min\(^{-1}\)) | 53.6 ± 7.7 | 57.7 ± 2.4 |

* Untrained volunteers were significantly lower than trained volunteers (P<0.05)
*** Untrained volunteers were significantly lower than trained volunteers (P<0.001)
preparation room to remove all the experimental clothing, except their pants. After removing the temperature sensors and HR monitor, they were weighed on the same body scale used before the experiment. In addition, the undergarments and PPE pieces were also weighed again.

2.3. Measurements and calculations

Rectal temperature (T<sub>r</sub>) was measured every second using a logger (LT-8A, Gram Corporation, Japan) and a temperature probe (LT-ST08-00, Gram Corporation, Japan; resolution of 0.01°C) inserted 16 cm beyond the anal sphincter. ΔT<sub>r</sub> is the increase in T<sub>r</sub> from baseline T<sub>r</sub> to the peak (T<sub>r</sub>-peak) per hour. T<sub>r</sub>-peak is the 3 min average value during the last 30 min of exercise. The T<sub>r</sub> time lag represents the time from the end of the exercise period until T<sub>r</sub> becomes increased or decreased. Skin temperature probes were attached to 12 sites: head, chest, abdomen, back, forearm, upper arm, hand, mid-finger, thigh, calf, foot, and toe. The measurement was conducted every second using the thermistors that were used to assess T<sub>r</sub>. The weighted mean skin temperature (T<sub>sk</sub>) was calculated according to a modified version of Hardy and DuBois’s 7-point formula (Hardy et al., 1938).

Body surface area was estimated according to the method of Lee et al. (2008). Total body fat (%BF) was assessed using a bioelectrical impedance method (Karada Scan HBF-354, OMRON Co., Ltd., Japan). Skinfold thickness was determined using a caliper (Eiyoken-group, Meikosha Co., Ltd., Japan) on the chest, upper arm, forearm, upper back, abdomen, thigh, and calf while volunteers were standing and relaxed. The same investigator took three readings at each site, and the mean was used.

The volume of expired gas was continuously measured throughout the trial using an automatic respirometer (AE-300S, Minato Medical Science, Japan). Meanwhile, the Oxygen Uptake (VO<sub>2</sub>) and the respiratory exchange ratio (RER) were averaged every minute. The HR was measured every second using an HR monitor (RS400, Polar Electro, Finland).

2.4. Statistics

All quantitative data are expressed as the mean for the last 3 min of each period and standard deviation (mean±SD). In addition, a paired t-test was used to identify differences in the physiological responses of the volunteer groups. All statistical analyses were performed with the statistical package SPSS v. 17.0 (SPSS Inc, Chicago IL, USA), and the significance level was set at P < 0.05.

3. Results

3.1. Oxygen uptake (VO<sub>2</sub>)

VO<sub>2</sub> was similar for the CON and PPE tests in HBW and LBW groups during stabilization at the rest period. However, after 30 min exercise, VO<sub>2</sub> in HBW and LBW groups using the PPE test was remarkably higher than the CON test. For example, VO<sub>2</sub> of the HBW group was 22.0 ± 0.9 ml·kg<sup>-1</sup>·min<sup>-1</sup> using the PPE test and 15.6 ± 0.5 ml·kg<sup>-1</sup>·min<sup>-1</sup> using the CON test (P < 0.001) (Figure 1). On the other hand, the VO<sub>2</sub> in the LBW group was 23.1 ± 2.0 ml·kg<sup>-1</sup>·min<sup>-1</sup> using the PPE test and 15.6 ± 1.3 ml·kg<sup>-1</sup>·min<sup>-1</sup> using the CON test (P < 0.001) (Figure 1b). However, VO<sub>2</sub> was not significantly different between HBW and LBW groups.

3.2. Heart rate (HR)

There was a slight variation in the HR of volunteers in HBW and LBW groups before the initiation of exercise using the CON and PPE test. However, at the end of the exercise, the HR of HBW and LBW groups using the PPE test was higher than using the CON test. For example, within the HBW group, the HR of volunteers was 153 ± 18 bpm and 106 ± 11 bpm using PPE and CON tests (P < 0.001) (Figure 2a), respectively. Similar results were obtained within the LBW group where the HR of volunteers was 145 ± 15 bpm and 97 ± 7 bpm using PPE and CON tests (P < 0.001; Figure 2b), respectively.

After a 20 min recovery, the HR of HBW and
LBW groups was reduced, however, PPE test was still markedly higher than CON test ($P < 0.001$). Although the HR of the HBW group was slightly higher than the LBW group using the PPE test, it was not significantly different.

The highest HR reached during the experiment (HRpeak) showed that differences in HR were only observed within, but not between groups. For example, the HRpeak of the HBW group using PPE and CON tests was 159 ± 16 bpm and 126 ± 38 bpm, respectively, while the HRpeak in the LBW was 145 ± 15 bpm and 108 ± 3 bpm, respectively.

### 3.3. Rectal ($T_r$)

The $T_r$ from the CON test was slightly higher than that from the PPE test at the end of the rest period for both HBW and LBW groups. However, there were no significant differences observed. Significant differences in $T_r$ were in the middle of the exercise period. In the end, the $T_r$ of HBW and LBW groups using the PPE test was significantly higher than that using the CON test. However, no significant differences were observed between groups (Figures 3). The $T_r$ of the HBW group at the end of the exercise using PPE and CON tests was $38.2 ± 0.3°C$ and $37.6 ± 0.2°C$ ($P < 0.001$), respectively. In the LBW group, the $T_r$ was $38.1 ± 0.3°C$ and $37.4 ± 0.2°C$ ($P < 0.001$) using PPE and CON tests, respectively. At the end of the recovery, the $T_r$ of HBW and LBW groups using the CON test were relatively similar to the $T_r$ of HBW and LBW groups at the end of the exercise.

The $T_r$ of HBW and LBW groups using the PPE test rose until the recovery period, and $T_r$ was significantly higher than the exercise period. Using the PPE test, HBW and LBW groups ended the whole experimental protocol with a $T_r$ of $38.7 ± 0.3°C$ and $38.6 ± 0.3°C$, respectively ($P < 0.001$). The $T_r$ differences from the initial time of the rest to the end of the exercise period ($\Delta T_r$) in the HBW group using PPE and CON tests were $1.0 ± 0.2°C\cdot h^{-1}$ and $0.2 ± 0.2°C\cdot h^{-1}$, respectively. On the other hand, $\Delta T_r$ in the LBW group using PPE and CON tests were $1.1 ± 0.2°C\cdot h^{-1}$ and $0.3 ± 0.2°C\cdot h^{-1}$, respectively ($P < 0.001$). Figure 4 showed that there were no $\Delta T_r$ differences between HBW and LBW groups.

![Figure 2](image1.png)  
(a) Heart rate of volunteer groups during experiment using: (a) Control Test; (b) PPE Test;

![Figure 3](image2.png)  
(a) Rectal temperature of volunteer groups during experiment using: (a) Control Test; (b) PPE Test;

![Figure 4](image3.png)  
$\Delta T_r$ differences from baseline to the end of The exercise period ($\Delta T_r$) between volunteer groups using different types of tests; ($\$\$significant differences at $P < 0.001$)
3.4. Total Sweat Rate (TSR)

After a one-hour experiment, the Total Sweat Rate (TSR) of the HBW group using PPE and CON tests was 600.8 ± 124.8 g·m⁻²·h⁻¹ and 184.0 ± 63.1 g·m⁻²·h⁻¹, respectively (P < 0.001). Similar results were obtained within the LBW group, where the TSR using the PPE test was markedly higher than using the CON test (Figure 5). This group’s TSR using PPE and CON tests was 654.7 ± 143.3 g·m⁻²·h⁻¹ and 184.5 ± 29.6 g·m⁻²·h⁻¹, respectively (P < 0.001).

![Figure 5. The total sweat rate (TSR) during the experiment; §significant differences at P < 0.05 using a t-test](data:image/png)

4. Discussion

The physiological responses of the subjects that wore PPE were significantly higher than those that wore control clothing. This result is consistent with numerous previous reports, where SCBA can lead to an additional burden on the wearer to increase oxygen consumption, heart rate, and body core temperature. For example, Dreger et al. (2006) reported that oxygen consumption in graded exercise treadmill tests using heavy PPE was 13% higher than light clothing. In addition, Bruce-Low et al. (2007) showed that HR and aural temperature were markedly higher during a 10 min exercise using PPE+SCBA than only gym clothing. Previously, conducted study provided similar evidence that the combination of heavy PPE and hot temperatures potentially increase the heat stress factor on volunteers (Bakri et al., 2012). Furthermore, study by Kesler et al. (2018) underlined the SCBA users’ physiological burden.

Rodahl (1989) described that the physiological responses of volunteers on average will be similar with comparable work and load intensities. However, lighter bodyweight volunteers will experience a more significant burden with the same work and load intensities than those experienced by heavy bodyweight volunteers after wearing similar PPE. Volunteers with lighter body weights exercising in hot environments using the complete set of PPE, including SCBA, experienced similar cardio-respiratory and body core temperature responses with heavy bodyweight volunteers. One possible reason for this was that both groups receive high-intensity, structured daily exercises as professional firefighters to fit such a standard PPE test. Even though the well-known clinical finding of body fat, surface area, and body weight showing high coefficients of correlation with oxygen consumption (Bray et al., 1970) have been found, the participants in both groups performed in oxygen consumption during a workout despite wearing similar heavy PPE. The volunteer groups’ heart rate responses and body temperature regulation were modified in a good direction due to their acclimation status. In addition, Selkirk & McLellan (2004) stated that the significant advantage attributed to a higher aerobic fitness level was the ability of volunteers to tolerate a higher core temperature at exhaustion.

Another explanation can be given from the total weight of PPE relative to body weight. The total weight of PPE (attire + SCBA) worn by LBW and HBW groups was 18.4 Kg and 19.6 Kg, respectively. These weights were 25.7% and 21.3% of the bodyweight of these groups. Therefore, the difference in the load received by the groups due to PPE was about 4.4%. The body fat percentage of volunteers can also be a factor. Compared to the LBW group, the HBW group carried almost 10 kg additional load in fat. This negative factor is balanced because the LBW group suffered a more significant burden than the HBW due to the heavy PPE.

The lean body mass can be calculated when the body fat is neglected, meaning that volunteers’ body mass consists only of muscle. However, the body weight differences between the two groups were more than 20 Kg since the lean body mass differences were only 10 Kg. Therefore, while combining the PPE weight with the body fat, the difference in the load received by both groups relative to body weight was only about 2% (43.5% for LBW vs. 45.9% for HBW). This value can significantly cause differences in physiological responses.

5. Conclusions

The hypothesis of this study was rejected since no differences in physiological responses were found between HBW and LBW groups. The differences only occurred within each group when volunteers used PPE or control clothing. In addition, the physical condition of these volunteers was similar due to their daily structured exercise despite differences in body weight between both groups. For the standard PPE test, the bodyweight of volunteers is not a relevant issue as long as they are well trained.
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