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RESEARCH

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Physiological and subjective burden when wearing fire protective boots between 3.2 and 5.3 kg

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Abstract

This study investigated the effects of weight increase of firefighters' boots on physiological and psychological strain. Seven young males (70.9 ± 4.8 kg in body mass, BM) participated in the following four boot conditions while wearing standard firefighting personal protective equipment: 3.2, 3.9, 4.6, and 5.3 kg (4.5, 5.5, 6.5, and 7.5%BM). The results showed that the four boot conditions resulted in no differences in rectal temperature, mean skin temperature, energy expenditure and overall thermal comfort during walking, while increments in heart rate were greater for 5.3 kg than for other three conditions ($P < 0.05$). Subjects felt less warm and had less uncomfortable feet during exercise for the 3.2 kg condition compared to the three other heavier conditions ($P < 0.05$). These results indicate that psychological strain due to the load carried on the feet appeared earlier (between 4.5 to 5.5%BM) than physiological strain in terms of heart rate (between 6.5 to 7.5%BM). We finally suggest a 5% body mass upper limit for boot weight because subjective strain of the feet may be a valuable preliminary alarm for the physiological strain of firefighters wearing heavy boots.

Keywords: Fire protective boots, Physiological strain, Weight thresholds, Firefighters, Core temperature

Introduction

Firefighters engage in strenuous tasks such as searching and rescuing victims, climbing ladders and stairs, holding and dragging fire hoses, carrying equipment, ceiling overhauls, and breaking doors or windows for forcible entry. Those firefighting tasks require an oxygen consumption (VO_2) of around 44 ml min^{-1} kg^{-1} (Gledhill and Jamnik 1992; Holmer and Gavhed 2007; von Heimburg et al. 2006), 47 to 88% of maximal oxygen consumption (VO_{2max}) (Bilzon et al. 2001; Lemon and Hermiston 1977; von Heimburg et al. 2006), 90 to 94% of maximum heart rate (HR_{max}) (O'Connell et al. 1986; Williams-Bell et al. 2009). Such highly demanding metabolic costs are associated with heavy and multiple-layered firefighting protective equipment (PPE) as well as the strenuous task itself. A typical firefighting PPE including self-contained breathing apparatus (SCBA) weighs ~ 30 kg (Barr et al. 2010) and their thermal insulation are about ~ 2.44 clo (Holmer et al. 2006). PPE increased rectal temperature by 2.24 °C when compared to the increase of 0.23 °C in a standard uniform (Skoldstrom 1987), and firefighting PPE induced 58% greater sweat rate (1.9 l h^{-1}) compared to the unclothed condition (1.2 l h^{-1}) (Fogarty et al. 2004).

The physically demanding facet of wearing PPE has been well documented in terms of metabolic cost. Even though some figures in the results are not in agreement with each other because of a number of external or internal factors, such as exercise intensities/duration/type, PPE characteristics (materials/design/layer/weight distribution), subject characteristics (fitness/age/sex/adaptation), or environmental conditions (temperature/humidity/radiation/ground/field), it is agreed that heavier and bulkier PPE causes greater metabolic cost to workers. For example, 15% increase in $VO_{2\_}$ when wearing firefighting PPE without SCBA (Graveling and Hanson 2000), 9–16% increase in VO_2 during stepping (9.1–10.8 kg in PPE vs. 5.9 kg in the control) (Duggan 1988), 16% increase in VO_2 with fire suits (7.0 kg heavier than control) (Dorman and Havenith 2009), 13–18% increase in VO_2 with 9.3 kg military PPE (Patton et al. 1995), 11–21% increase in VO_2 with firefighter PPE compared with the light clothing condition, 36%, 37% and 47% increase in VO_2 with firefighting PPE (19.9 kg) during bench stepping, stair-climbing and steady state walking, respectively (Taylor et al. 2012), 33% increase when wearing firefighting PPE with SCBA (Davis and Santa-Maria 1975) and 33% increase when wearing firefighting PPE with SCBA during submaximal exercise (Lee et al. 2013). On the other hand, maximal oxygen consumption (VO_{2max}) decreased by 4–20% when wearing fire protective clothing and/or SCBA (Dreger et al. 2006; Lee et al. 2013; Louhevaara 1984; Louhevaara et al. 1995; Raven et al. 1977). These studies indicate that increases in firefighters' metabolic cost, due to heavy and multi-layered PPE, damage their maximal performance capability. Finally, the increases in metabolic cost have been 1% per kg of added load (Givoni and Goldman 1971) to 3% per kg (Rintamaki 2005). Those increments in metabolic costs reflect both load carriage and hobbling/friction effects due to layering or bulkiness. Several studies quantified the separated contributions of added weight, per se (Pandolf et al. 1977), and effects of multiple clothing layers on the metabolic cost (Teitlebaum and Goldman 1972).

However, the above values reflect the effects of PPE on the whole body not on specific body regions. Datta and Ramanathan (1971) compared seven modes of carrying 30 kg: using the head, rucksack, double pack on the trunk, rice bag, Sherpa, yoke, and hands during walking at 5 km h^{-1}. As a result, they found that the double pack mode over the trunk was the best and carrying by hands was the worst method (44% greater in energy expenditure than the double pack mode). Among the head, hands and feet, the most inefficient location for load carriage was the feet and load carriage on the feet was about 6.3 times greater than by the torso (Soule and Goldman 1969). Similar results were found in Myers and Steudel (1985) and Legg and Mahanty (1986). Taylor et al. (2012) distinguished fractional contributions of each PPE item on metabolic cost of wearers and found that the footwear elicit the greatest metabolic cost during both walking and bench stepping, being 8.7 and 6.4 times greater per unit mass than those values for wearing the breathing apparatus. Taken together, it is agreed that load carriage on the feet elicit greater relative metabolic cost compared adding loads to other body regions. This information suggests that locating the load as closer to the body center results in the lower energy cost, and that the metabolic cost of adding a mass to body extremities is greater than adding the same mass to the center of the body (Myers and Steudel 1985).

In this regard, it is a question whether or not the 1–3% increases in metabolic cost per kg of added load on the whole body corresponds to the feet as well. The answer provided by of a number of studies is that, while the type of task, gender of participant, additional protective clothing, etc., the metabolic burden is higher for loads placed on the feet than the same load place on another body region. During walking or exercising at a speed of 4–14 km h^{-1}, VO_2 per kg of added load to the feet increased by around 3–13% (Caltlin and Dressendorfer 1979; Frederick et al. 1980; Jones et al. 1984; Jones and Knapik 1986; Knapik et al. 2004; Martin 1985; Miller and Stamford 1987; Neeves et al. 1989; Turner et al. 2010).

As cooperated by many studies, it is reasonable to posit that heavy footwear results in higher metabolic cost compared wearing running shoes. Because most studies, with the exception of Miller and Stamford (1987), used footwear weighing less than 3 kg per pair, whether such rates of increase can be extrapolated to include firefighters' boots heavier than 3 kg has yet to be explored. That is to say, it seems clear that a certain amount of weight added to the feet causes a rise in metabolic cost when over that of wearing light shoes, but it is not certain whether additional weight increase to the heavy footwear induce a similar proportional increase in metabolic cost. Strydom et al. (1968) stated that increasing the weight of boots from 1.85 to 2.95 kg per pair had no significant effect on the energy cost of walking at normal speed. In particular, firefighting protective boots often become heavier than their original mass due to fire water and the mud accumulation. In addition, there are wearable technologies which are currently trying to be integrated into fire protective boots. Last but not least, while most studies on load carriage have focused on metabolic cost, the thermoregulatory and psychological burden due to the wearing heavy boots still needs to be explored. In this light, the present study aimed to investigate the impact of weight increases (in fire protective boots over 3 kg per pair while wearing firefighting PPE) on thermoregulatory, cardiovascular and psychological burden. We hypothesized (1) energy expenditure would increase as the weight load on the feet increases from 4.5 to 7.5% body mass (3.2 to 5.3 kg in boots weight); (2) A weight load on the feet inducing physiological strain would differ from the weight load inducing psychological strain.

Methods

Subjects

Seven young males, without any medical condition and orthopedic issues in the ankles, participated in this study (mean ± SD: 24.0 ± 2.9 year in age, 171.6 ± 4.5 cm in height, 70.9 ± 4.8 kg in body weight, 24.1 ± 1.5 kg m^{-2} in BMI, 1.83 ± 0.07 m^2 in body surface area, 48.8 ± 3.8 ml min^{-1} kg^{-1} in VO_{2max}, 197 ± 7 bpm in maximum heart rate (HR_{max}) and 261 ± 10 mm in foot length). Body surface area was estimated using the formula of Lee et al. (2008). There were no subjects with flat feet or malformation of the feet. Subjects were instructed to abstain from alcohol and strenuous exercise for 48 h, along with food and caffeine for 3 h prior to scheduled tests. Prior to obtaining written informed consent, the subjects were informed of the purpose and potential risks of the present study. This study was approved by the Institutional Review Board of Seoul National University (IRB #SNU 18-07-014).

Characteristics of personal protective equipment (PPE)

All subjects wore undershorts (100% cotton, 72 g), long-sleeved T-shirts (100% cotton, 200 g), long trousers (100% cotton, 360 g), and socks (100% cotton, 52 g), firefighting turnout jacket and pants (out layer_PBI 40% and para-aramid 60%, 3.2 kg in total), fire-protective hood (aramid 100%, 70 g), fire-protective helmet (PEI, 1.2 kg), fire-protective rubber boots (2.4–2.6 kg) and self-contained breathing apparatus (SCBA, empty) (45-min duration, 7.05 kg) (14.6–14.8 kg in total PPE mass; total clothing insulation that directly measured using a thermal manikin, Newton, $I_T = 1.6$ clo). Five of the seven subjects wore the 255 mm boots (2.4 kg) and the other two subjects wore the 270 mm boots (2.6 kg). Based on interviews with firefighters, other firefighting boot weights (e.g. 3.2 kg for USA) and a pilot test with young males, we set the minimum and maximum weights of boots per pair at 3.2 and 5.3 kg, respectively. As addressed in the introduction, most previous studies were conducted with ~ 3 kg boots and we explored the impact of heavier boots than the usual. Over 5.3 kg load on the feet was abandoned because of subjects' complaints during the pilot tests. Then, the total range was divided into the four values by successively adding 700 g starting from the 3.2 kg boots (3.2, 3.9, 4.6 and 5.3 kg). To increase the weight of boots, a certain mass of rubber clay was attached to the top of the feet and the front side of the ankle evenly on the right and left boots as illustrated in Fig. 1. Any clay was not added on the back side of the ankles not to avoid walking on the treadmill.

Experimental procedure

All subjects performed a preliminary trial with 2.5 kg-boots to familiarize themselves with the whole test procedure. Then, they participated in the following four experimental conditions: 3.2 kg-boots, 3.9 kg-boots, 4.6 kg-boots and 5.3 kg-boots. Experimental order was counterbalanced to avoid any familiarization effect and each condition was conducted on separated days at an identical morning time (A. M. 09:00–12:00). For all conditions, subjects wore the firefighting hood, helmet, turnout jacket and pants and SCBA along with under clothes.

Trials of subjects were separated by at least 48 h interval (Jan to Feb in 2018). The daily air temperature of the experimental days were on average -4.8 ± 5.6 °C, -3.8 ± 4.6 °C,

Fig. 1 Fire protective boots with weight added in the present study. The weight were added to the right and left boot evenly. The 3.2, 3.9, 4.6 and 5.3 kg demonstrate the total sum of right and left boot mass

− 2.5 ± 3.9 °C and − 8.3 ± 3.4 °C for the 3.2 kg, 3.9 kg, 4.6 kg and 5.3 kg boot conditions, respectively. They were required to maintain their hydration state at a normal level 24 h prior and were prohibited from any drinking 2-h prior to participation. As soon as they arrived, subjects drank 300 ml water and rested in a preparation room. At rest at the room, rectal temperature (T_{re}), heart rate and urine gravity were checked and the trial was started only when rectal temperature was within the normal range of 37.0 ± 0.5 °C, heart rate was below 80 bpm and urine gravity was below 1.020. After checking that these criteria were within the normal range, subjects were equipped with other measurement sensors. All trials were performed in a climate chamber at an air temperature of 28 °C and at a relative humidity of 50%. Trials consisted of a 10-min rest on a stool followed by 30-min walking at 5.5 km h^{-1} on a treadmill and a 20-min recovery in a sitting position on the stool. Subjects put on the helmet and SCBA just before starting exercise and took them off as soon as exercise was finished. Subjects weighed their bodies in a seminude state three times on a scale before and after the 60-min trial. Total mass of the dry and wet PPE were weighed on the scale twice. Trials were terminated when rectal temperature reached 39.2 °C, heart rate (HR) reached 95% of their maximal heart rate, or if any subject felt unable to continue the exercise.

Measurements

Prior to participation, all subjects took part in a maximal fitness test to evaluate maximal oxygen consumption (VO_{2max}) and maximal heart rate (HR_{max}) using a modified Bruce protocol. Subjects had VO_{2max} of 48.8 ± 3.8 ml min^{-1} kg^{-1} and HR_{max} of 197 ± 7 bpm. Rectal temperature (T_{re}) was recorded every 5 s using a data logger (LT-8A, Gram Corporation, Japan) which was inserted to a depth of 16 cm beyond the anal sphincter. Energy expenditure was calculated with oxygen consumption which was measured for 3 min at rest and at the end of exercise (Quark CPET, COSMED, ITALY). Subjects weighed themselves on a calibrated body scale (ID2, Mettler-Toledo, Germany; resolution of 1 g) before and after each trial to estimating total body mass loss. We also weighed the experimental clothing before and after each trial to estimate evaporative sweat rate as one part of the total body mass loss. Heart rate was measured on the chest every 1 s throughout the trial using a chest belt and a watch (RC3 GPS™, Polar, Finland). Blood pressure was measured 3 times at the 0th, 41st and 59th min using a digital blood pressure monitor and a cuff (HEM-7200, OMRON, Japan).

Thermal sensation, thermal comfort, sweat sensation and thirst sensation were recorded every 10 min at the 5th, 19th, 29th, 39th, 49th and 59th min using the following categorical scales: 9-point thermal sensation with 9 categories (4 very hot, 3 hot, 2 warm, 1 slightly warm, 0 neutral, − 1 slightly cool, − 2 cool, − 3 cold, and − 4 very cold); 7-point thermal comfort (3 very comfortable, 2 comfortable, 1 a little comfortable, 0 not both, − 1 a little uncomfortable, − 2 uncomfortable, − 3 very uncomfortable), 7-point sweat sensation (3 very dry, 2 dry, 1 a little dry, 0 neither, − 1 a little wet, − 2 wet, − 3 very wet) and 7-point thirst sensation with 4 categories (0 no thirsty, 0.5, 1 a little thirsty, 1.5, 2 thirsty, 2.5, 3 very thirsty). Overall and foot thermal sensation, thermal comfort and sweat sensations were recorded. During exercise, ratings of perceived exertion (RPE) which ranged from score 6 (no exertion at all) to 20 (maximal exertion) (Borg 1982) were recorded every 10 min at the 19th, 29th, 39th min. Subjects chose the score that they

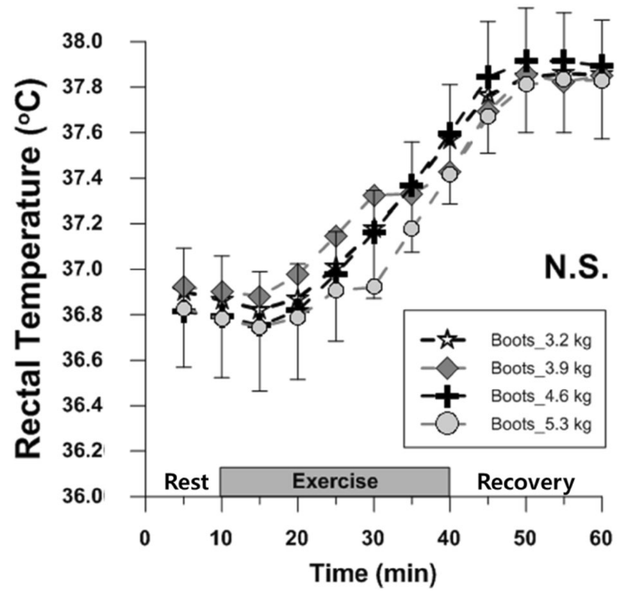

Fig. 2 The time courses of rectal temperature. $*P<0.05$, $**P<0.01$, and $***P<0.001$. N.S represents not significant

felt every 10 min and experimenters filled in their responses on experimental sheets. We interviewed subjects for demographic and health information, such as smoking/drinking/sleeping habits and also considered any relevant information they provided in their self-health evaluation.

Data analysis

Physiological strain index (PSI) was calculated using Moran et al. (1999)'s equation: $PSI = 5(T_{ret} - T_{re0}) \times (39.5 - T_{re0})^{-1} + 5(HR_t - HR_0) \times (180 - HR_0)^{-1}$. The PSI values were calculated from score 0 (no strain) to 10 (maximal strain). All quantitative data were expressed as the mean for the last 5 min of each period and standard deviation of the mean (mean ± SD). Repeated-measures analyses of variance (ANOVA) were used to identify differences in physiological responses among the four weight conditions. Tukey's post hoc test was used to assess the parameters that displayed significant differences in ANOVA. Analysis of the rating scale measures (thermal, sweat and thirst sensation, thermal comfort, and RPE) was carried out using Friedman test and Kendall test. Statistical analyses were performed with SPSS 23.0. Significance was set at $P<0.05$.

Results

Rectal temperature (T^{re})

There were no significant differences in T_{re} for the four conditions, at rest, during exercise and recovery. We found rectal temperatures of 37.6 ± 0.3 °C, 37.7 ± 0.2 °C, 37.6 ± 0.2 °C and 37.7 ± 0.3 °C at the end of exercise for the 3.2, 3.9, 4.6 and 5.3 kg condition, respectively (Fig. 2a).

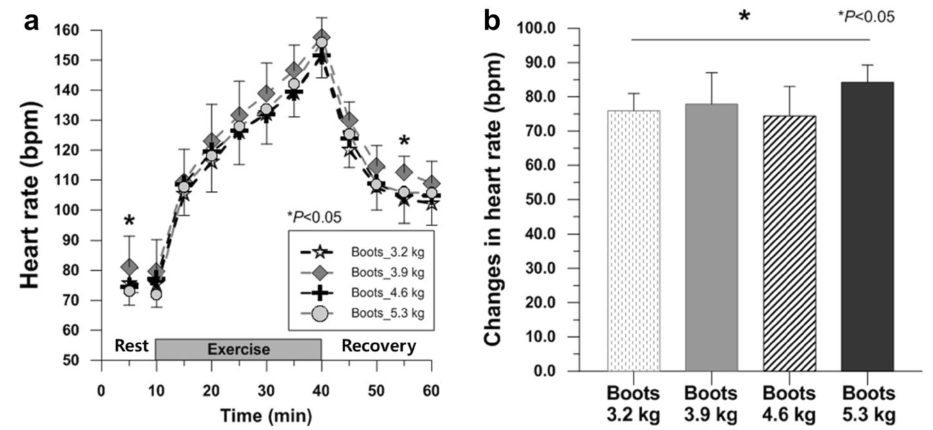

Fig. 3 Time courses of heart rate (**a**) and changes in heart rate (**b**) during exercise. *$P < 0.05$, **$P < 0.01$, and ***$P < 0.001$

Oxygen consumption, heart rate and blood pressure (VO^2, HR, and BP)

There was no differences in VO_2 at rest among the four conditions, showing that VO_2 was 386 ± 113 ml min^{-1}, 359 ± 66 ml min^{-1}, 354 ± 101 ml min^{-1} and 317 ± 101 ml min^{-1} for the four conditions, and VO_2 at the end of exercise there were no significant differences among the four conditions (1559 ± 224 ml min^{-1}, 1805 ± 190 ml min^{-1}, 1616 ± 250 ml min^{-1}, and 1702 ± 358 ml min^{-1} for the 3.2, 3.9, 4.6 and 5.3 kg condition, respectively). At the end of exercise, those values of VO_2 were 47%, 53%, 47%, 52% VO_{2max} for the 3.2, 3.9, 4.6 and 5.3 kg conditions, respectively. Heart rate (HR) during exercise did not show any difference among the four conditions (Fig. 3a) with the 77%, 80%, 77%, and 79% HR_{max} at the end of exercise for the four conditions, respectively. However, the increments in HR were significantly greater for the 5.3 kg condition than the other three conditions ($P < 0.05$, Fig. 3b). Systolic, diastolic and mean arterial pressure did not show any differences among the four conditions during all the phases.

Total body mass loss

Total body mass losses were not significant, 562 ± 169 g h^{-1}, 673 ± 143 g h^{-1}, 630 ± 150 g h^{-1} and 683 ± 189 g h^{-1} for the 3.2, 3.9, 4.6, and 5.3 kg conditions. No significant differences were found in evaporative sweat rates among the four conditions (216 ± 43 g h^{-1}, 239 ± 47 g h^{-1}, 229 ± 51 g h^{-1}, and 233 ± 50 g h^{-1} for the four conditions), but the evaporative sweat rate to the total body mass loss was significantly lower for the 5.3 kg condition than the 3.2 kg condition (40.2 ± 8.1%, 36.0 ± 5.4%, 36.6 ± 3.7%, and 34.9 ± 4.5% for the four conditions, respectively) ($P < 0.05$).

Subjective perceptions

There were no significant group differences in whole body thermal comfort, sweat sensation, and thirst sensation. However, subjects felt less warm and less uncomfortable on their feet at the end of exercise and in recovery for the 3.2 kg condition when compared to the other three conditions ($P < 0.05$, Figs. 4 and 5). Ratings of perceived exertion (RPE) at the end of the exercise was 14.0 ± 2.0, 14.4 ± 1.5, 14.7 ± 1.5, and 15.1 ± 2.1 for the four

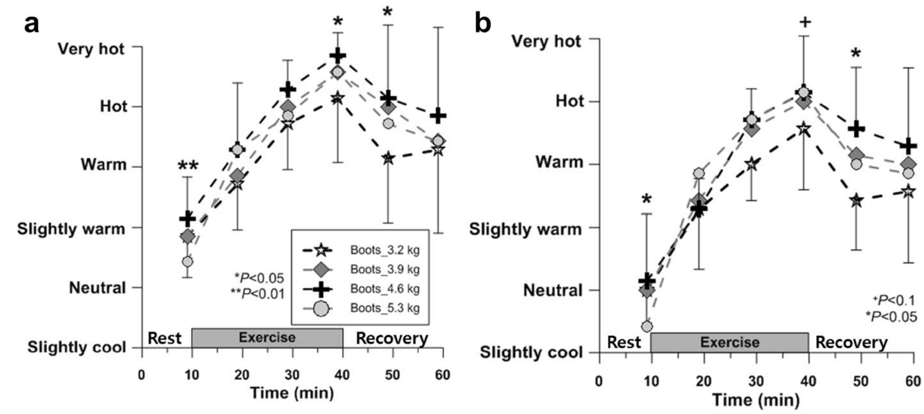

Fig. 4 Time courses of overall thermal sensation (**a**) and feet thermal sensation (**b**). *$P<0.05$, **$P<0.01$, and ***$P<0.001$

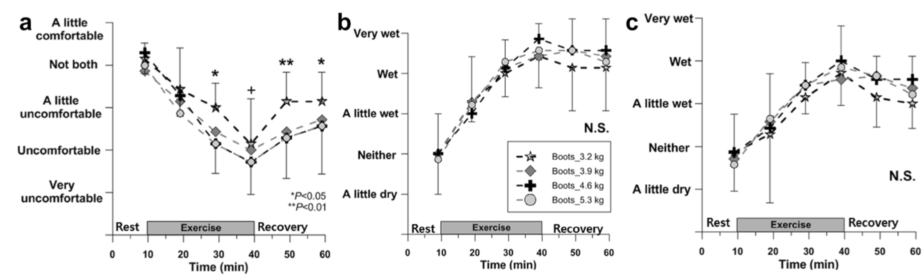

Fig. 5 Time courses of feet thermal comfort (**a**), overall sweat sensation (**b**) and feet sweat sensation (**c**). *$P<0.05$, **$P<0.01$, and ***$P<0.001$

conditions and RPE at the 5.3 kg condition was significantly higher than the 3.2 kg condition ($P<0.05$).

Physiological strain index (PSI)

Physiological strain indexes (PS-Is) at the end of exercise were 4.9 ± 0.5, 5.4 ± 0.6, 5.1 ± 0.7, and 5.4 ± 0.9 for the 3.2, 3.9, 4.6 and 5.3 kg conditions, and there was no difference among the four conditions. At the end of recovery, there was no significant difference among the four conditions (PSI: 3.2 ± 0.8, 3.5 ± 0.9, 3.3 ± 0.8, and 3.7 ± 1.0).

Discussion

Most previous studies reported the effects of the weight load (~ 3 kg) added on the feet on metabolic cost. The present study is original and practical in that it explored the overloaded impact on the feet (3 kg–5 kg) in terms of both physiological and psychological strain while wearing firefighting PPE. We could not find significant differences in most physiological variables between 4.5 and 7.5% of body mass (3.2 to 5.3 kg per pair), while there was a psychological impact of overloaded weight on the feet.

Least impact of overloaded weight on physiological burden

Care should be taken when interpreting the physiological and subjective strain because only the heart rate was significantly influenced by boot weight increases whereas other variables that we measured did not reflect the impact of weight increases. In other words, increments in heart rate during exercise were meaningful when deciding the impact of overloaded on the feet, but rectal temperature, oxygen consumption, total sweat rate or blood pressure did not reflect the load difference among the boot weight conditions. In fact, no significant influence of boot mass increase on thermoregulatory responses, especially, accumulated body heat storage (increase in core body temperature) could be expectable. For the psychological variables, there were significant differences in overall and feet thermal sensation and feet thermal comfort between the 3.2 to 5.3 kg conditions. In this case, the inconsistency of the results between physiological and psychological variables may partly be pertinent to the offsetting the burden of the PPE weight (15 kg in total) against the burden of boot weight increase (700 g each). For example, psychological burden from wearing the 15 kg PPE may make insignificant the physiological burden from increasing boot weights by 700 g. Huang et al. (2009) reported that there was no significant differences in cardiovascular responses between wearing rubber boots (2.9 kg) and leather boots (2.4 kg) when wearing firefighters' PPE (23% body mass). Turner et al. (2010) found that small and insignificant increases in HR and $\dot{V}O_2$ during simulated stair climbing for rubber firefighter boots (2.93 kg) compared leather firefighter boots (2.44 kg), which could be evidence that during very high intensity, short duration simulated stair climbing in full PPE and added SCBA, the effects of small differences in boot weight are further diminished.

Psychological strain might be earlier than physiological strain due to weight load on the feet

A novel and important finding of the present study was that psychological or subjective strain from increasing boot weight appeared earlier than the physiological strain, especially, in terms of heart rate. Subjects expressed significantly increased local thermal comfort on the feet and increased overall/local thermal sensation at the 5.5% body mass (3.9 kg per pair). It needs to be noted that subjects felt warmer and thermally uncomfortable for the 3.9 kg condition than for the 3.2 kg condition even though there was no difference in the physiological variables that we measured between 3.2 and 3.9 kg conditions. According to Kim et al. (2014), they could not find any significant benefit in thermal sensation and comfort when taking off fire protective boots of 2.1 kg during 30-min exercise. Taken together, it seems that psychological burden due to protective boots lighter than 3 kg for 30 min walking is negligible. The present results suggest that subjective strain does not always correspond to physiological burden in a timely manner and there may a threshold in weight increase that aggravates subjective feelings and evaluation. We suggest that subjective strain may be a valuable preliminary alarm for the physiological strain of firefighters wearing PPE. We found no particular mechanisms for the earlier triggering of subjective strain, but there are studies that have reported a temporal dissociation between psychological and physiological strains to an identical stress (For example, subjects feel psychological strain to a certain stress but there was no physiological changes). However, further studies with active firefighters, who have psychological strain in the line of duty, are required to validate the present finding.

Upper limit of boot weight

Korea Fire Institute (KFI) regulates that the mass of firefighter's protective boots should be below 2.8 kg for rubber boots and 3.0 kg for leather boots (KFI 2014), but US firefighters wear heavier boots (up to 4.4 kg) (Park et al. 2014). According to the 7th Size Korea (2015), Korean young males' and female's body weight are on average 71 kg and 56 kg, respectively, meaning 2.5 kg boots are approximately 3.5 and 4.5% body mass. From previous research showing 3% increase per kg in energy expenditure (Turner et al. 2010), we posited that boots alone would increase metabolic cost. In addition, because female firefighters are increasing in Korea, the mass limit of the boots should be recommended as the percentage of wearer's body mass, not as an absolute value. As a next step, our concern was to explore the impact of overloaded weight on the feet on physiological and psychological strain while walking and wearing firefighters' PPE. This approach is practical and beneficial for occupational safety experts and PPE manufacturers who integrate wearable technologies in protective boots. In practice, firefighters' boots become heavier due to fire water accumulating inside them, mud or snow accumulating on them as well as smart technological components embedded. Based on the present results, we suggest the upper limit for boots to be 5% body mass of a firefighter, which means 3 and 4 kg boots for 6 and 80 kg firefighters, respectively.

Limitations and implications

One of limitations is the experimental setup of walking on the treadmill. In practice, there are several impediments for firefighters when walking such as mud, snow, water, grade, stairs or smoke (darkness). Pandolf et al. (1976) set the terrain factors as follows: 1.0 black top road, 1.1 dirt road, 1.2 light brush, 1.5 heavy brush, 1.8 swampy bog, and 2.1 loose sand. Such impediments may trigger the weight thresholds of the boots earlier. Second, the young male students who participated in the present study may have been unfamiliar walking in protective boots, aggravating and triggering earlier their psychological strain. Although the physical fitness of the young male subjects (48.8 ± 3.8 ml min^{-1} kg^{-1} in VO_{2max}) was acceptable to be firefighters, active firefighters might express different psychological opinions. Third, we did not measure strides or gait but the stride shorten as the boot weight increases. We kept the treadmill speed at the 5.5 km h^{-1} constantly and subjects did not run but walked fast. However, the walking strides may not be even for the four weight conditions. Fourth, we did not compare the boot conditions with the ordinary condition of wearing running shoes. For this reason, we did not provide any metabolic cost of wearing protective boots relative to the wearing ordinary shoes. Fifth, we recruited seven male subjects but the number might be not enough for the statistical significance, especially, for psychological variables. Also, female firefighters may express different psychological opinions on the upper limit of absolute values because their average foot size is smaller than male firefighters'. Sixth, we could not conduct our experiment in a single-blind study because the appearance of boots with mud clearly identified their own weight, but we might have reduced any possible psychological confounding if the experiments were done in being blinded to subjects. Lastly, we used the rubber boots not leather boots in the present study. Even the rubber boots are more common for Korean firefighters, different materials and designs could induce significant influences on the physiological and psychological burden. Huang et al. (2009) and Turner et al. (2010) reported no significant differences in cardiovascular responses between rubber and leather boots, but US firefighters reported that wearing rubber boots induced greater change in walking pattern along with greater discomfort, poor fit, low resistance against abrasion when compared to wearing leather boots (Park et al. 2014). In this light, comparisons of the rubber boots with leather boots are needed in further studies.

Conclusions

The present study was conducted to explore the impact of overload weight over the feet (3.2–5.3 kg; 4.5–7.5% body mass) on physiological and subjective strain while wearing firefighting protective boots and protective clothing. It is of particular moment that heavier boots increased wearers' psychological strain when walking while wearing full PPE, and that psychological strain were reached earlier than those for physiological strain. The present results indicate that the psychological limit of fire protective boot weight that aggravates the subjective burden was approximately 5% body mass [between 3.2 kg (4.5%BM) and 3.7 kg (5.5%BM)]. We finally suggest a 5% body mass upper limit for boot weight because the protective boots often become heavier due to external factors (fire water, mud, etc.) in the line of duty. We suggest that subjective strain of the feet may be a valuable preliminary alarm for the physiological strain of workers wearing heavy boots. Further, the 5% limit values could be effectively applied for manufacturers who develop new protective boots integrated with wearable technologies and for occupational safety experts who set the upper limit of boot weight.

Practitioner summary

The present results provide the weight range of fire protective boots for inducing physiological and subjective strain. This study provides a criterion for avoiding excessive physical strain on workers who wear heavy boots, including firefighters' boots.

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Authors' contributions

The contribution of authors are as follows: JY developed the idea of this study. SH, Y and JY planned the methods, directed the experiments, interpreted the results and prepared manuscript. SH and Y contributed to the data collection and analysis. All authors read and approved the final manuscript.

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Availability of data and materials

The datasets used and/or analyzed during the currentstudy are available from the corresponding author on reasonable request.

Competing interests

The authors declare that they have no competing interests.

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References

Barr, D., Gregson, W., & Reilly, T. (2010). The thermal ergonomics of firefighting reviewed. *Applied Ergonomics, 41*, 161–172.
Bilzon, J. I., Scarpello, F. G., Smith, C. V., Ravenhill, N. A., & Rayson, M. P. (2001). Characterization of the metabolic demands of simulated shipboard Royal Navy fire-fighting tasks. *Ergonomics, 44*, 766–780.
Caltlin, M. J., & Dressendorfer, R. H. (1979). The effect of shoe weight on the energy cost of running. *Medicine and Science in Sports, 11*, 80.
Datta, S. R., & Ramanathan, N. L. (1971). Ergonomic comparison of seven modes of carrying loads on the horizontal plane. *Ergonomics, 14*, 269–278.
Davis, P. O., & Santa-Maria, D. L. (1975). Quantifying the human energy costs: A laboratory experiment. *Medical Fire Research Bulletin, 4*, 1.
Dorman, L. E., & Havenith, G. (2009). The effects of protective clothing on energy consumption during different activities. *European Journal of Applied Physiology, 105*(3), 463–470.
Dreger, R. W., Jones, R. L., & Petersen, S. R. (2006). Effects of the self-contained breathing apparatus and fire protective clothing on maximal oxygen uptake. *Ergonomics, 49*(10), 911–920.
Duggan, A. (1988). Energy cost of stepping in protective clothing ensembles. *Ergonomics, 31*(1), 3–11.
Fogarty, A. L., Armstrong, K. A., Gordon, C. J., Groeller, H., Woods, B. F., Stocks, J. M., et al. (2004). Cardiovascular and thermal consequences of protective clothing: A comparison of clothed and unclothed states. *Ergonomics, 47*(10), 1073–1086.
Frederick, E. C., Howley, E. T., & Powers, S. K. (1980). Lower O_2 cost while running in an air cushion type shoes. *Medicine and Science in Sports and Exercise, 12*, 81–82.
Givoni, B., & Goldman, R. F. (1971). Predicting metabolic energy cost. *Journal of Applied Physiology, 30*(3), 429–433.
Gledhill, N., & Jamnik, V. K. (1992). Characterization of the physical demands of firefighting. *Canadian Journal of Sport Sciences, 17*(3), 207–213.
Graveling, R., Hanson, M. (2000). Design of UK firefighter clothing. In Kuklane K, Holmer I (Eds), *Proceedings of Nokobetef 6 and 1st European Conference on Protective Clothing*. pp 277–280
Holmer, I., & Gavhed, D. (2007). Classification of metabolic and respiratory demands in firefighting activity with extreme workloads. *Applied Ergonomics, 38*, 45–52.
Holmer, I., Kuklane, K., & Gao, C. (2006). Test of firefighter's turnout gear in hot and humid air exposure. *International Journal of Occupational Safety and Ergonomics, 12*(3), 297–305.
Huang, C. J., Garten, R. S., Wade, C., Webb, H. E., & Acevedo, E. O. (2009). Physiological responses to simulated stair climbing in professional firefighters wearing rubber and leather boots. *European Journal of Applied Physiology, 107*(2), 163–168.
KFI (2014). *Performance criteria for firefighter's protective boots*. Korea Fire Institute (KFI).
Jones, B., & Knapik, J. (1986). The energy cost of women walking and running in shoes and boots. *Ergonomics, 29*(3), 439–443.
Jones, B., Toner, M., Daniels, W., & Knapik, J. (1984). The energy cost and heart rate response of trained and untrained subjects walking and running in shoes and boots. *Ergonomics, 27*(8), 895–902.
Kim, S., Jang, Y. J., Baek, Y. J., & Lee, J. Y. (2014). Influences of partial components in firefighters' personal protective equipment on subjective perception. *Fashion and Textiles, 1*, 1.
Knapik, J. J., Reynolds, K. L., & Harman, E. (2004). Soldier load carriage: Historical, physiological, biomechanical, and medical aspects. *Military Medicine, 169*, 45–56.
Lee, J. Y., Bakri, I., Kim, J. H., Son, S. Y., & Tochihara, Y. (2013). The impact of firefighter personal protective equipment and treadmill protocol on maximal oxygen uptake. *Journal of Occupational and Environmental Hygiene, 10*(7), 397–407.
Lee, J. Y., Choi, J. W., & Kim, H. (2008). Determination of body surface area and formulas to estimate body surface area using the Alginate method. *Journal of Physiological Anthropology, 27*(2), 71–82.
Legg, S. J., & Mahanty, A. (1986). Energy cost of backpacking in heavy boots. *Ergonomics, 29*, 433–438.
Lemon, P. W. R., & Hermiston, R. T. (1977). The human energy cost of firefighting. *Journal of Occupational Medicine, 19*, 558–562.
Louhevaara, V. A. (1984). Physiological effects associated with the use of respiratory protective devices. A review. *Scandinavian Journal of Work, Environment and Health, 10*, 275–281.
Louhevaara, V., Ilmarinen, R., Griefahn, B., Kunemund, C., & Makinen, H. (1995). Maximal physical work performance with European standard based fire-protective clothing system and equipment in relation to individual characteristics. *European Journal of Applied Physiology and Occupational Physiology, 71*, 223–229.
Martin, P. (1985). Mechanical and physiological responses to lower extremity loading during running. *Medicine and Science in Sports and Exercise, 17*(4), 427–433.
Miller and Stamford, 1987 Miller, J., Stamford, B., (1987). Intensity and energy cost of weighted walking vs. running for men and women. *Journal of Applied Physiology, 62*(4), 1497–1501.

Myers, M. J., & Steudel, K. (1985). Effect of limb mass and its distribution on the energetic cost of running. *Journal of Experimental Biology, 116*, 363–373.
Neeves, R., Barlow, D. A., Richards, J. G., Provost-Craig, M., Castagno P. (1989). Physiological and biomechanical changes in firefighters due to boot design modifications. *Proceedings of the Tenth Annual Redmond Foundation Symposium on the Occupational Health and Hazards of the Fire Service*. p.42.
O'Connell, E. R., Thomas, P. C., Cady, L. D., & Karwasky, R. J. (1986). Energy costs of simulated stair climbing as a job-related task in fire fighting. *Journal of Occupational Medicine, 28*, 282–284.
Pandolf, K. B., Haisman, M. F., & Goldman, R. F. (1976). Metabolic energy expenditure and terrain coefficients for walking on snow. *Ergonomics, 19*(6), 683–690.
Pandolf, K. B., Givoni, B., & Goldman, R. F. (1977). Predicting energy expenditure with loads while standing or walking very slowly. *Journal of Applied Physiology, 43*, 577–581.
Park, H., Park, J., Kin, S.-H., & Boorady, L. (2014). Assessment of firefighters' needs for personal protective equipment. *Fashion and Textiles, 1*, 8.
Patton, J. F., Bidwell, T. E., Murphy, M. M., Mello, R. P., & Harp, M. E. (1995). Energy cost of wearing chemical protective clothing during progressive treadmill walking. *Aviation, Space, and Environmental Medicine, 66*, 238–242.
Raven, P. B., Davis, T. O., Shafer, C. L., & Linnebur, A. C. (1977). Maximal stress test performance while wearing a self-contained breathing apparatus. *Journal of Occupational Medicine, 1919*, 802–806.
Rintamaki, H. (2005). Protective clothing and performance in cold environments. In: *The 3rd International Conference on Human Environment System*, Tokyo, Japan, Sep 12–15.
Size Korea. (2015). https://sizekorea.kats.go.kr/.
Skoldstrom, B. (1987). Physiological responses of fire fighters to workload and thermal stress. *Ergonomics, 30*(11), 1589–1597.
Soule, R. G., & Goldman, R. F. (1969). Energy cost of loads carried on the head, hands, or feet. *Journal of Applied Physiology, 27*, 687–690.
Strydom, N., Graan, C., Morrison, J., Viljoen, J., & Heyns, A. (1968). The influence of boot weight on the energy expenditure of men walking on a treadmill and climbing steps. *Internationale Zeitschrift für Angewandte Physiologie Einschließlich Arbeitsphysiologie, 25*(3), 191–197.
Taylor, N. A. S., Lewis, M. C., Notley, S. R., & Peoples, G. E. (2012). A fractionation of the physiological burden of the personal protective equipment worn by firefighters. *European Journal of Applied Physiology, 112*(8), 2913–2921.
Teitlebaum, A., & Goldman, R. F. (1972). Increased energy cost with multiple clothing layers. *Journal of Applied Physiology, 32*(6), 743–744.
Turner, N. L., Chiou, S., Zwiener, J., Weaver, D., & Spahr, J. (2010). Physiological effects of boot weight and design on men and women firefighters. *Journal of Occupational and Environmental Hygiene, 7*, 477–482.
von Heimburg, E. D., Rasmussen, R. A. K., & Medbø, J. I. (2006). Physiological responses of firefighters and performance predictors during a simulated rescue of hospital patients. *Ergonomics, 49*(2), 111–126.
Williams-Bell, F. M., Villar, R., Sharratt, M. T., & Hughson, R. L. (2009). Physiological demands of the firefighter candidate physical ability test. *Medicine and Science in Sports and Exercise, 41*(3), 653–662.

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