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Laboratory Assessment of Heat Strain in Female and Male Wildland Firefighters

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ABSTRACT

Wildland firefighters (WFF) face a set of specific work-related factors that directly affect their physical and cognitive abilities and compromise their health and safety. The working conditions include hard physical work and environmental conditions that combine high temperatures and high radiant heat. Such environments make using personal protective equipment (PPE) mandatory to protect them from risks. This fact restricts heat removal and adds extra weight, increasing thermal strain and the risk of heat-related illnesses on WFF. Since the number of females WFF has increased, it is necessary to study the repercussions of heat stress on this group. To date, it is not yet well-known whether sex-related differences in thermoregulation will be relevant when the individuals are wearing PPE and performing high physical effort in a hot environment. Therefore, we aimed to investigate the physiological response when performing moderate to high-intensity effort in a hot-dry environment while wearing PPE according to sex. Twenty WFF 10 females [23.9 ± 3.2 yr, 163.8 ± 3.4 cm and 62.7 ± 9.1 kg] and 10 males [31.9 ± 6.6 yr, 178.8 ± 5.8 cm and 73.9 ± 7.7 kg]) performed a 125 min treadmill test in a controlled ambient (30 °C and 30% relative humidity). The protocol consisted of two exercise stages where WFF performed different continuous and variable exercise bouts in order to mimic the effort performed during real deployments. Participants wore the full standard PPE during the test. Oxygen uptake (VO_2), heart rate (HR), core temperature (CT) and chest temperature (SkT) were monitored throughout the test. HR and CT were used to calculate the physiological strain index (PSI). Differences in body mass pre-post trials corrected for fluid intake were used to calculate sweat production (SwP), sweating rate (SwR), and evaporative efficiency (EE). Differences ($p < 0.05$) between females and males were found in $\%VO_{2max}$ (62.5 ± 7.4 vs 55.3 ± 5.), HR (155 ± 10 vs 134 ± 14 beats·min^{-1}), % of maximal HR (81.3 ± 3.5 vs 42.3 ± 6.5), CT (38.0 ± 10 vs 37.7 ± 0.33 °C), SkT (36.0 ± 0.6 vs 35.3 ± 0.6 °C) and PSI (4.1 ± 0.5 vs 3.5 ± 0.6). Even though SwR was higher ($p < 0.05$) for male participants (1001.5 ± 268.3 ml) compared to females (647.5 ± 145.9 ml), females had higher EE (32.9 ± 4.6 vs 16.7 ± 6.2 %). In conclusion, performing high-intensity exercise in hot-dry conditions while wearing PPE leads to a higher thermal and cardiovascular load for female WFF, making them more susceptible to heat illness. These results could be linked to lower aerobic fitness, sweating rate, and hormonal aspects that increased the thermal burden.

Keywords: Thermal stress, Cardiovascular effort, Physiological demands, Personal protective equipment, Sweat rate, Sweat efficiency, Physically demanding occupations, First responders

INTRODUCTION

Wildland fire suppression is an extremely demanding occupation related to the specific factor it poses (Cuddy et al., 2015). During wildfire suppression, wildland firefighters (WFF) face a series of specific conditions, such as the orography of the terrain (Brotherhood, 2008), smoke inhalation (Wegesser et al., 2009), handling of heavy hand tools (3-20 kg) (Rodríguez- Marroyo et al., 2012), use of personal protective clothing (PPE) (Carballo-Leyenda et al., 2018) and the long duration of the effort in hot environmental conditions (Carballo-Leyenda et al., 2021; Sol et al., 2018). Altogether, these factors lead to high physical demands (Rodríguez-Marroyo et al., 2012), accelerating the appearance of fatigue and increasing the risk of exertional heat illness as heat production often exceeds dissipation capacity (Cuddy et al., 2015). In this scenario, wearing personal protective equipment (PPE) is mandatory to preserve the security and health of workers. However, it has been shown that using PPE increases the production of metabolic heat and reduces the dissipation of body heat, mainly due to greater encapsulation by layers of clothing (Barr et al., 2009; Carballo-Leyenda et al., 2018). Consequently, the physiological response is further augmented and characterised by increased core and skin temperature, heart rate, sweat rate and subjective perceptions of effort and thermal sensation (Petruzzello et al., 2009).

The integration of women in the traditionally manly profession has raised the question of their physical and physiological capabilities to perform equally effectively as their male counterparts. Literature has shown that, on average, women have a lower maximal oxygen consumption (VO_{2max}), a higher body fat percentage, a larger body surface area-to-mass ratio and decreased sweat gland production in hot conditions, leading to decreased work capacity and higher rise in body temperature compared to men (Gagnon et al., 2009; Roberts et al., 2016). It has also been suggested that this effect may be exacerbated during the luteal phase of the menstrual cycle due to hormonal fluctuations affecting central thermoregulatory centres (Charkoudian and Stachenfeld, 2016). These physiological and morphological differences would pose women with a higher risk of heat-related injuries during exercise under heat stress while wearing PPE (Renberg et al., 2022).

In recent years, the rate of female participation in physically demanding occupations such as the military and firefighting has increased (Anderson et al., 2022; Perroni et al., 2021), even reaching the 10-15% of wildland fire crews in the United States (Sol et al., 2018). Despite this fact, there is still a lack of studies on the role of sex in physical condition, work capacity and thermoregulation in professional sectors. Therefore, we aimed to investigate the thermophysiological response when performing moderate to high-intensity effort in a hot-dry environment while wearing PPE according to sex.

METHODS

Participants

Twenty-two active and healthy wildland firefighters candidates, 10 men (mean ± standard deviation; 31.9 ± 6.6 yr, 178.8 ± 5.8 cm and

73.9 ± 7.7 kg) and 10 women (23.9 ± 3.2 yr, 163.8 ± 3.4 cm and 62.7 ± 9.1 kg) who voluntarily participated in this study. All of them passed a work capacity test prior to participating in the study. Written informed consent was obtained from the volunteers before beginning the study. The study protocol was developed by the guidelines of the Helsinki Conference for research in humans and was approved by the Ethics Committee of the University of León, Spain.

Experimental Design

Each subject undertook two trials in two testing sessions separated by at least 48 h. Participants were asked to refrain from strenuous exercise and not to consume alcohol, caffeine, and tobacco for 24 h. previous. A graded exercise test was performed during the first testing session to determine the subjects' maximal aerobic capacity (VO_{2max}) and to subsequently use these data to program the intensity of the second trial specifically to each subject's characteristics. During the second trial, the participants performed a 125 min submaximal test wearing the personal protective equipment (PPE) currently used by Spanish WFF, which includes thermal-resistant clothing (65% fire retardant viscose, 30% Nomex and 5% Kevlar, 1.5 kg, surface mass 270 g ± m^{-2}, intrinsic thermal resistance 0.019 m2 $K{\cdot}W^{-1}$ and evaporative resistance 3.79 $m^2{\cdot}Pa{\cdot}W^{-1}$) and other protective elements such as a helmet, neck shroud, gloves and low calf hiking boots.

Graded Exercise Test

All subjects performed a graded treadmill exercise test (h/p Cosmos Pulsar, h/p Cosmos sports and medical GMBH, Nussdorf-Traunstein, Germany). A 10-minute warm-up preceded each test at 60% of maximum heart rate (8-10 km h^{-1}) and 5 minutes of stretching. The test began at 4 $km{\cdot}h^{-1}$ and a 10% gradient. Each minute the speed increased by 0.5 $km{\cdot}h^{-1}$ until reaching 6.5 $km{\cdot}h^{-1}$, from which time the slope increased 1 % every minute until volitional exhaustion.

Submaximal Treadmill Test

The submaximal test was performed at the same time of day (between 09:00 and 13:00). Ambient temperature and relative humidity were controlled at 30°C and 30%, respectively simulating average conditions previously reported in wildland fire suppression (Rodríguez-Marroyo et al., 2012). The overall experimental protocol consisted of 2 different exercise phases walking to varying intensities with a 15 min passive recovery period in between. Exercise stage 1 comprises two 20 min work bouts (6 $km{\cdot}h^{-1}$ and 3% slope) interspersed by 10 min passive recovery. Exercise stage 2 consists of two work bouts of 25 min interspersed by 10 min passive recovery. The intensity of the exercise in each work bout was set to elicit 7 min at a moderate-intensity (i.e., between the ventilatory thresholds), 15 min at a low-intensity (i.e., below the ventilatory threshold) and 3 min at a high-intensity (i.e., above the respiratory compensation threshold). This exercise intensity distribution represents the mean effort distribution performed by WFF during wildland fire suppression of 1–3 h duration (Rodríguez-Marroyo et al., 2012).

Measurements

ECG monitoring (Medisoft MedCard, Medisoft Group, Sorinnes, Belgium) was continuously measured throughout the tests. Breath-by-breath gas analysis (Medisoft Ergocard, Medisoft Group, Sorinnes, Belgium) was measured in periods of 3 min at the beginning and the end of each exercise bout. Core temperature (CT) was recorded every minute using a gastrointestinal temperature pill (e-Celsius® Performance, Bodycap, Hérouville Saint-Clair, France), which was activated and swallowed by participants at least 8 h before starting the field test. (Larsen *et al.*, 2015). Chest skin temperature (SkT) was measured using an iButton (DS1922L-F50, Maxim Integrated, Sunnyvale, California, USA) attached on the left major pectoral using surgical tape (Fixomull, BSN Medical, Hamburg, Germany) (Cuddy *et al.*, 2015).

TC and heart rate were used to calculate the physiological strain index (PSI) throughout the trials, according to Tikuisis *et al.* (2002). Subjects in underwear and each clothing component were separately weighted (50K150, COBOS, Hospitalet de Llobregat, Barcelona, Spain) at the beginning and the end of each trial. With body mass differences, we calculate the total sweat production (SwP), sweat rate (SwR) and sweat retained in the clothes (Kofler *et al.*, 2015). Total sweat was corrected for the fluid intake. Finally, sweat evaporation efficiency (EE) was calculated as the ratio between sweat evaporation and total sweat (Kofler *et al.*, 2015).

Statistical Analysis

The results are expressed as mean ± standard deviation (SD). The assumption of normality was verified using the Shapiro-Wilk test. When a non-normal distribution was found, data were log-transformed for analysis. Significant differences between males and females in anthropometric and physiological data measured during the first testing session were analysed using an independent t-test. This same analysis was performed to compare the sweat measurements obtained according to the WFF sex. A two-way repeated measures ANOVA was used to establish the influence of time and sex on the variables studied in the laboratory test. Bonferroni's test was used to establish significant differences between means when a significant F value was found. Significance level was set at $p<0.05$. SPSS+ V.26.0 statistical software (Chicago, Illinois, USA) was used.

RESULTS

Female WFF were younger ($p < 0.05$), shorter ($p < 0.05$), lighter ($p < 0.05$) and had a smaller ($p < 0.05$) body surface area (1.68 ± 0.11 vs. 1.92 ± 0.12 m^2) than their male counterparts. However, no significant differences in the body mass index (23.1 ± 2.5 ($kg \cdot m^{-2}$) and body surface area-to-mass ratio (2.66 ± 0.16 $cm^2 \cdot kg^{-1}$) were found. In addition, the VO_{2max} was similar in both sexes (47.5 ± 7.7 vs. 55.00 ± 9.6 $ml \cdot kg^{-1} \cdot min^{-}1$).

Table 1. Physiological parameters measured during the submaximal test (mean ± SD).

	Female	Male
Percentage of maximal HR (%)	81.31 ± 3.50	72.32 ± 6.5*
Percentage of VO_{2max} (%)	62.49 ± 7.43	55.25 ± 5.10*
Core temperature (°C)	38.01 ± 0.22	37.70 ± 0.33*
Chest skin temperature (°C)	36.0 ± 0.6	35.3 ± 0.6*
Physiological Strain Index (AU)	4.1 ± 0.5	3.5± 0.6*

HR, heart rate; AU, arbitrary units. *, significant difference (p<0.05).

Females showed a significantly higher ($p < 0.05$) physiological (i.e., % HR_{max} and %VO_{2max}) and thermal (i.e., CT and SkT) strain than males during the submaximal test (Table 1). Consequently, the PSI was higher ($p < 0.05$) for females compared to male participants.

The physiological variables pattern throughout the submaximal test is shown in Figure 1. A greater ($p < 0.05$) physiological strain during the course of the test was observed in females. Significant differences ($p < 0.05$) were found between women and men in the baseline CT (37.3 ± 0.30 vs 37.0 ± 0.29) and at minutes 3, 10, 20, 90, 115 and 122 (Figure 2A). Similarly, the baseline SkT was significantly higher ($p < 0.05$) in women compared to that analysed in men (36.0 ± 0.6 vs. 35.3 ± 0.6 °C). In addition, differences ($p < 0.05$) in SkT were observed at minutes 3, 10, 20, 72, 80, 107, 115, and 122 (Figure 2B). Finally, significant differences ($p < 0.05$) between groups in the PSI values were found in minutes 3, 10, 20, 87 and 122 (Figure 2C).

Total sweat (1570 ± 364 vs. 2546 ± 695 g) and sweat rate (648 ± 146 vs. 1002 ± 268 $g \cdot h^{-1}$) were significantly lower ($p < 0.05$) in women. However, the sweat evaporation efficiency (32.9 ± 4.6 vs. 16.7 ± 6.2%) was significantly higher in women ($p < 0.05$).

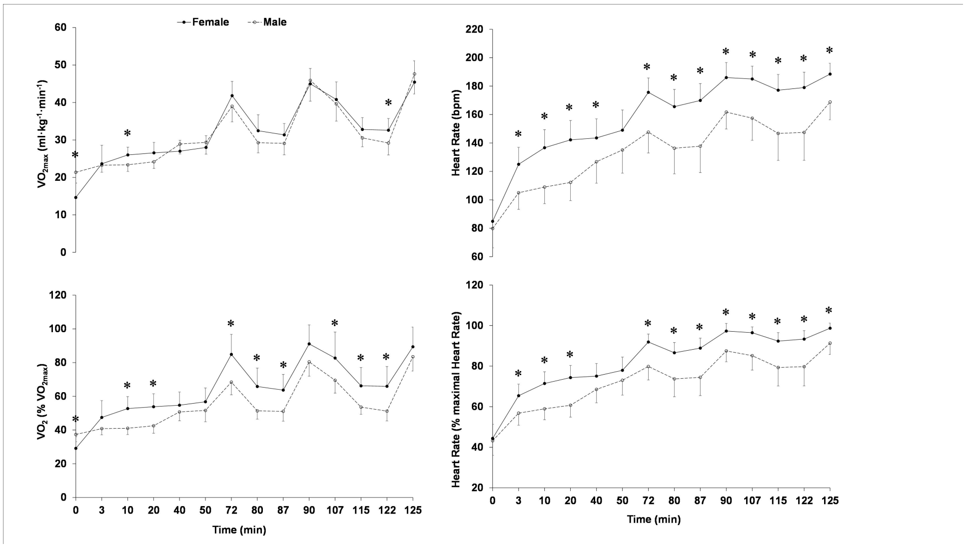

Figure 1: Comparative responses of oxygen uptake (A) and heart rate (HR) (B) during the laboratory test (mean ± SD). *, significant difference ($p < 0.05$).

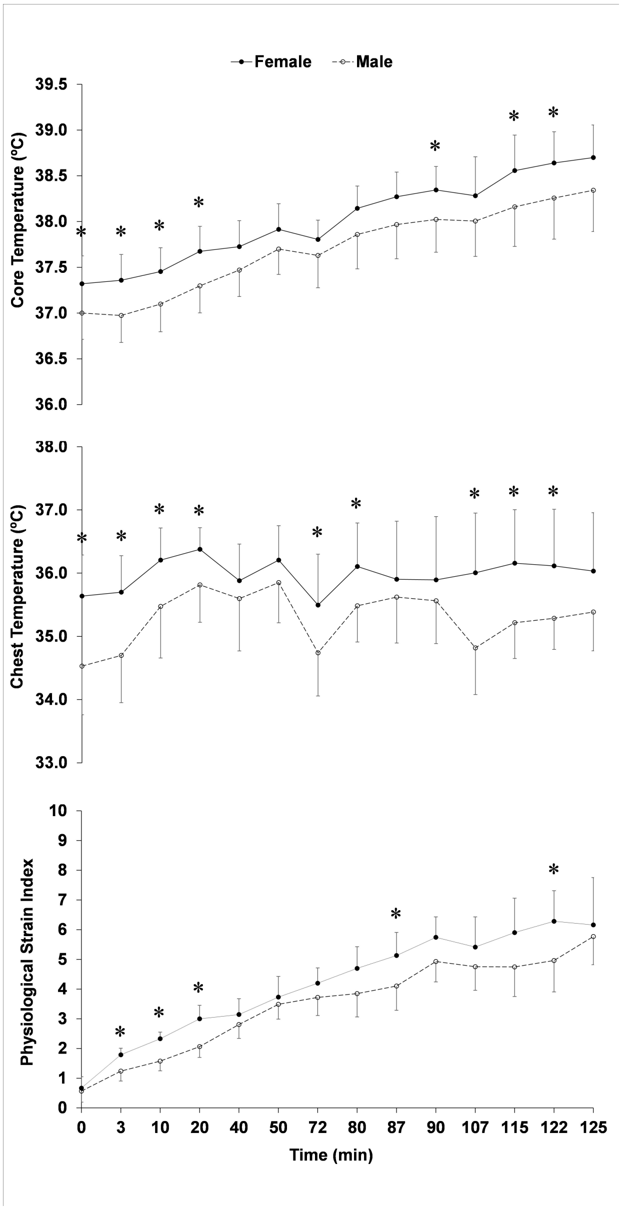

Figure 2: Gastrointestinal (A), chest skin temperature (B) and physiological strain index (C) pattern recorded during the submaximal test (mean ± SD). *, significant difference (p<0.05).

DISCUSSION

The main objective of this study was to evaluate the thermophysiological differences between men and women during a long-duration submaximal test in a thermally stressful environment (30°C and 30% relative humidity) while wearing a PPE. The key findings of this study include: i) the thermally stressful conditions led women to perform a higher exercise intensity; ii) women started the test with a higher baseline temperature, however, both sexes experienced similar rate of increase; iii) women obtained a higher evaporative efficiency despite their lower sweat rate.

The exercise intensity performed by women in terms of $\%VO_{2max}$ was ~7% greater than that performed by men. This circumstance possibly resulted from her worse physical fitness and could have meant that they accumulated more fatigue as the test progressed. This observation is supported by Yanovich et al. (2008), who found that women exercised at 19.4 $\%VO_{2max}$ higher than men when they compared the physiological response between military men and women during a fitness program. Murphy et al. (2001) obtained a higher $\%VO_{2max}$ for the group of women when comparing the physiological response while wearing chemical protective clothing. Roberts et al. (2016) pointed out that in real wildland fire suppression deployments, all crew members wear the same PPE, use the same equipment and have to meet the same performance objectives, so women maintain a higher work intensity. Results in the literature and those from our study support the idea that women's lower physical fitness drives them to work at a higher percentage of their maximum aerobic capacity, accelerating the onset of fatigue (Epstein et al., 2013).

Women's heightened intensity of effort resulted in a higher HR. The increased cardiovascular load would be the result of the greater demand imposed by an increase in CT combined with continuous exercise in the heat that drives the increase in blood flow to the periphery to avoid the increase in body temperature (Anderson et al., 2022; Notley et al., 2019). Despite this, a similar increase in CT as SkT throughout the test was observed for female and male participants, highlighting that the combined demands imposed by exercise, environment and clothing lead to an uncompensable heat strain in both sexes. Interestingly, women started the test with a higher CT (~0.3 °C) and SkT (~0.7 °C) than men and these differences were maintained throughout the trials. This observation made us think that the test did not cause greater thermal strain in women but that the biological differences between men and women would explain the observed results. It has been described that women's menstrual cycle can increase their CT by up to 0.5°C (Yanovich et al., 2020). Specifically, the influence of reproductive hormones would be behind this circumstance (Charkoudian and Stachenfeld, 2016). Seven women were in the luteal phase of their menstrual cycle when they performed the test, which could explain the ~0.3°C difference between the women and men CT since the beginning of the test. Although it has been suggested that the higher area-to-mass ratio of women compared to men could favor their heat loss and increase their performance (Notley et al., 2017), this circumstance was not observed in this study since the area-to-mass ratio was similar between both sexes.

Another relevant result obtained from our study was that even though the women reached a greater exercise intensity, CT and SkT, they obtained a lower total sweat loss and lower sweat rate (38.3 and 35.4%, respectively). These results align with previous studies that have analysed the effect of sex on sweat response by controlling the metabolic heat production in adults, suggesting that females have decreased sweating capacity during exercise with high metabolic heat loads (Gagnon and Kenny, 2012a). Noteworthy despite the higher sweating rates in men, a higher evaporative efficiency was found in the group of women. These results do not agree with those described in the literature, where higher absolute rates of evaporative heat loss have been seen in men (Gagnon et al., 2008). This observation could be due to the design and size of the protective clothing used by the females could have favoured sweat evaporation. The protective clothing used by the Spanish WFF is designed to consider the male framework, so its fit is improper for women due to their smaller body size. Using loose clothing when subjects exercise could facilitate the dry heat exchange by enhancing the ventilation of the microclimate between clothing and the body (pumping effect) (Havenith, 2002; Nunneley, 1989), making the thermoregulation less dependent on sweat production.

CONCLUSION

Performing high-intensity exercise in hot-dry conditions while wearing a personal protective equipment leads to a higher thermal and cardiovascular load for females. These results could be linked to lower aerobic fitness, sweating rate, and hormonal aspects that increased the thermal burden in women. Further studies comparing the thermoregulatory response between men and women wearing PPE are required to further substantiate these results.

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