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Heat tolerance during uncompensable heat stress in men and women wearing firefighter personal protective equipment

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ABSTRACT

Firefighters run a risk of heat strain during occupational tasks. The number of female firefighters has been increasing, but research relevant to this group is still scarce. We aimed to investigate whether there are any sex differences in heat tolerance or physiological responses during uncompensable heat stress while wearing firefighter personal protective equipment. Twelve female (28 ± 7 years, 66 ± 5 kg, 51.7 ± 4.7 mL kg^{-1} min^{-1}) and 12 male (27 ± 7 years, 83 ± 8 kg, 58.8 ± 7.5 mL kg^{-1} min^{-1}) participants performed walking (maximum of 60 min) at 6W·kg^{-1}, 40 °C, and 14% relative humidity. No differences were observed between groups in heat tolerance, rectal temperature, heart rate, percent body mass loss, thermal sensation, and rate of perceived exertion. Thus, when personnel are selected using gender-neutral physical employment standards, sex is not an independent factor influencing heat tolerance when wearing firefighter personal protective equipment during uncompensable heat stress.

1. Introduction

Firefighters run a risk of heat strain during occupational tasks. Heat strain occurs when humidity, air temperature, radiant heat, or inadequate air movement, combined with heavy work or clothing, raises the body temperature and reduces the person's physical reactivity and ability to reason clearly (Ramsey, 1995). Increasing core temperature can negatively affect cognitive performance (Faerevik and Reinertsen, 2003; Grether, 1973; Hancock, 1981), which can increase the risk of making mistakes, which can be critical in firefighting scenarios. Heat strain increases the risk of heat-related illnesses, such as heat exhaustion and heat stroke. Historically, firefighting has been a male-dominated occupation. However, in recent years, the number of female firefighters has steadily increased in several countries. For example, in the UK 6.4% of firefighters were women in 2019 compared to 3.6% in 2009, in Sweden 5.9% of firefighters were women in 2020 compared to 2.4% in 2010, and in Norway 3.6% of firefighters were women in 2020 compared to 2.3% in 2016, according to national authorities. Nevertheless, research relevant to female firefighters is scarce.

At a live fire scenario, firefighters must move around, lift, drag and carry heavy objects at high ambient temperatures, all while wearing heavy and stiff personal protective equipment (PPE). High ambient temperature and heat generated from the use of muscles during heavy physical work can generate heat strain, which is recognized by an increase in heart rate (HR) and core temperature as the body tries to dissipate heat (Cheung et al., 2000). In addition, the PPE worn by the firefighters for protection from the external environment has low water vapor permeability and high insulation, which reduce the capacity to dissipate heat by both evaporative and non-evaporative mechanisms, thus increasing the rate of heat storage for a given rate of heat production ($\dot{H}_{prod}$). Furthermore, the PPE also increases the metabolic $\dot{H}_{prod}$ for a given amount of work (Dorman and Havenith, 2009; Renberg et al., 2020; Taylor et al., 2012). The combination of high metabolic $\dot{H}_{prod}$, wearing PPE, and high ambient temperature leads to uncompensable heat stress (UHS) wherein the $\dot{H}_{prod}$ exceeds the heat loss potential, leaving the body in a state of continuous heat gain. While PPE serves to

Abbreviations: CHS, compensable heat stress; HOTT, occupational heat tolerance test; HTT, heat tolerance test; MR, metabolic rate; NLIA, Norwegian Labour Inspection Authority; SS, sensation of shivering and sweating; TC, thermal comfort; TS, thermal sensation; UHS, uncompensable heat stress.

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protect the wearer from serious personal injury and even death, recent data suggest that more firefighters die or are injured from heat stress due to inadequate metabolic heat dissipation than from environmental heat exposure in the line of duty (NFPA, 2017).

In situations with compensable heat stress (CHS), enough heat can be lost to the environment so that the body is not in a continuous state of heat gain. However, heavy physical work in CHS situations can lead to a rise in core temperature. Individuals are classified as heat tolerant if the changes in their rectal temperature (T_{re}) and HR tend to plateau, while in the intolerant subjects, there is a continuous rise in these parameters in the same environment with the same workload (Moran et al., 2004). A heat tolerance test (HTT) has been developed to identify individuals who may be heat intolerant during CHS and has been used in the Israel Defense Forces (Moran et al., 2007). Because the clothing worn in the HTT allows heat loss by evaporation of sweat, individuals with an attenuated sweat response are at a disadvantage. However, during work wearing PPE, the ability to lose heat by sweating is minimized. To assess heat tolerance for personnel wearing PPE in hot environments, Watkins et al. (2018a) developed an occupational heat tolerance test (HOTT) that has a shorter duration than the HTT and is performed while wearing PPE. In the HOTT, a fixed $\dot{H}_{prod}$ in $W{\cdot}kg^{-1}$ also better enables unbiased comparisons of changes in T_{re} between groups unmatched for body size during UHS (Ravanelli et al., 2017). One study has reported differences in heat tolerance using the HOTT between fire service instructors and controls, including four female participants (Watkins et al., 2019). However, to our knowledge, studies focusing on sex differences in heat tolerance using the HOTT have not been published.

Differences in thermoregulation between men and women have been investigated, with some controversy regarding sex as an independent factor influencing thermoregulation and if the difference is primarily due to different morphology (Notley et al., 2017, 2019; Yanovich et al., 2020). On average, women have a lower maximal oxygen consumption (VO_{2max}), a higher body fat percentage, and a larger surface area-to-mass ratio (A_D/m) when compared with men. Notley et al. (2017) showed that women take advantage of their larger A_D/m to dissipate heat to the environment when the ambient temperature is lower than the skin temperature. However, when exercising in a hot environment with an ambient temperature higher than the skin temperature, a larger A_D/m can be a disadvantage because it will allow for more heat gain from the environment. High aerobic fitness, expressed as VO_{2max}, has in several studies been related to an increased sweating function (Foster et al., 2020). However, Ravanelli et al. (2021) found that during UHS, the increased sweating function and smaller rise in core temperature for physically fit individuals were probably related to a mild heat adaptation by frequent and persistent increases in the core temperature during aerobic training, and not VO_{2max} per se. Sex appears to be an independent factor with regard to sweating capacity, with men having a higher sweating capacity for a given amount of $\dot{H}$prod. Gagnon and Kenny (2011) showed that men had a higher sweating capacity than women under CHS when matched by A_D/m and exercising at a fixed rate of $\dot{H}$prod. Moreover, these differences in sweating capacity under CHS only resulted in a lower heat dissipation for women when the subjects were performing work at high rates of $\dot{H}$prod, wherein heat needed to be dissipated in greater amounts (Gagnon and Kenny, 2012). However, as the metabolic rate increases, ambient temperature and relative humidity have less influence on the rate of heat storage when military PPE is worn (Mclellan and Havenith, 2016). Because the evaporation of sweat on the skin surface and its movement through the clothing layers take time, the relative humidity is of greater importance in the case of lower metabolic rates with longer durations (Mclellan et al., 1996). Thus, when wearing PPE and working at high metabolic rates, an increased sweating response will not necessarily improve heat loss and may instead increase the rate of dehydration (Cheung et al., 2000). Increased core temperature leads to a strain on the cardiovascular system, which is further exacerbated with dehydration (González-Alonso et al., 2008). Thus, under UHS conditions while wearing PPE, the lower sweating capacity of women might protect them from dehydration (Eijsvogels et al., 2013). When heat stressed, dehydration further reduce exercise capacity and performance, and increases heat storage (Armstrong et al., 2007), and has been associated with heat stroke (Carter et al., 2005).

It is not yet known whether any sex-related differences in thermoregulation will be relevant when the individuals are wearing PPE and working in a hot environment, such as that in the HOTT. To ensure good health and safety for all firefighters, a better understanding of the potential sex differences in the response to heat exposure relevant to firefighting tasks is needed. Therefore, we aimed to investigate whether there are any sex differences in heat tolerance or physiological responses when exposed to UHS while wearing firefighter PPE.

2. Materials and methods

2.1. Participants

Fourteen male and 13 female participants volunteered to take part in this study. Twelve male and 12 female participants were included (Table 1) after passing the Norwegian Labour Inspection Authority (NLIA) aerobic fitness test (see 2.3 Pretests). Two of the female participants were firefighters, the rest of the participants were recruited from local fitness centers. Norwegian firefighters must pass the NLIA test to be considered fit for duty. Consistent with the principles of the Declaration of Helsinki, the participants were informed about the test protocol and their right to withdraw from the study at any time before they provided their written informed consent. The study was approved by the Regional Committee for Medical and Health Research Ethics, Middle Norway.

Participants were instructed to arrive at the laboratory in a euhydrated state; avoid alcohol, heat exposure >25 °C, and exhaustive exercise for 24 h prior to testing; and avoid consuming coffee, tea, or chocolate for 2 h prior to testing, with adherence checked via a questionnaire. The questionnaire also contained questions related to their physical exercise profile, their use of sauna, the menstrual cycle phase (days since start of last menstruation, average cycle length), and hormonal contraception use. In terms of the participants' physical exercise profile, four of the female participants and three of the male participants trained 2–3 times per week, whereas eight of the female and nine of the male participants trained every day. Regarding the intensity of their training, most of the participants usually worked so hard that they were sweating and experiencing shortness of breath when exercising, with a few exercising to exhaustion. For all but one female participant, the typical duration of exercise lasted >30 min. None of the participants

Table 1
Participant characteristics.

Participant characteristics	Women (n = 12)		Men (n = 12)	
	Mean ± SD	Range	Mean ± SD	Range
Age (years)	28 ± 7	[20–38]	27 ± 7	[19–39]
Height (cm)	171 ± 5*	[161–178]	183 ± 5	[172–189]
Body mass (kg)	65.8 ± 4.7*	[57.9–73.9]	82.6 ± 8.2	[73.7–103.4]
Surface area (m^2)	1.76 ± 0.09*	[1.61–1.89]	2.04 ± 0.10	[1.92–2.28]
A_D/m ($m^2{\cdot}kg^{-1}{\cdot}100$)	2.68 ± 0.09*	[2.56–2.86]	2.48 ± 0.12	[2.21–2.63]
BF (%)	29 ± 5*	[17–35]	21 ± 3	[17–24]
HR_{max} (bpm)	189 ± 10	[170–207]	194 ± 8	[180–207]
VO_{2max} ($mL{\cdot}kg^{-1}$ min^{-1})	51.7 ± 4.7*	[47.2–58.6]	58.8 ± 7.5	[47.8–72.8]
VO_{2max} ($L{\cdot}min^{-1}$)	3.37 ± 0.27*	[3.11–4.04]	4.78 ± 0.40	[4.13–5.39]

A_D/m, surface area-to-mass ratio; BF, body fat; HR_{max}, maximal heart rate; SD, standard deviation; VO_{2max}, maximal oxygen consumption. Range is presented as minimum and maximum values. *Significant difference between sexes, p < .05.

used sauna regularly, and no participants had been exposed to heat (>25 °C) within 24 h before the test.

In the present study, external validity was deemed most important, as it has been noted that much of the existing literature on sex differences in response to exercise heat stress lacks external validity (Corbett et al., 2020). The study was designed to examine the heat tolerance of a group similar to female firefighters, achieved by including physically fit female participants who had passed the NLIA test. Thus, the menstrual orientation (e.g., natural menstruating, contraceptive user, oligomenorrheic) or cycle phase was recorded, but it was not used as an inclusion criterion. In addition, the participants were only tested once, decreasing the need to control for the menstrual cycle phase. Results from the questionnaire show that two female participants were taking oral contraceptives and eight had an intrauterine device. Six of the female participants who used an intrauterine device and one who used oral contraceptives reported either oligomenorrhea or amenorrhea. The remaining two female participants did not use any contraceptives and performed the test during their follicular menstrual phase.

For evaluation of hydration status, the participants provided a urine sample on arrival at the laboratory. Urine specific gravity (USG) was measured using a refractometer (ORF 1PM, KERN & SOHN GmbH, Balingen, Germany), and the participants were considered hydrated if USG ≤1.025 (Kenefick and Cheuvront, 2012). Four participants (three men and one woman) had USG between 1.026 and 1.031. They were asked to drink 0.5 L water before the start of the test.

2.2. Experimental design

A heat tolerance test was performed at 40 °C with 14% relative humidity (RH), based on the HOTT (Watkins et al., 2018a). The participants visited the laboratory on three occasions, twice for pretest sessions and once for the heat tolerance test. The pretest sessions were carried out between October 2020 and January 2021, and the main tests were performed in February and March 2021. The absolute mean change in body mass between the pretest and the main test was 1.1 ± 0.7 kg. The purpose of the pretest sessions was to identify the correct sizes of firefighter PPE, perform the NLIA test, identify the correct speed needed for the participants to be working at 6 W kg^{-1}, and perform a test for the evaluation of VO_{2max} (Fig. 1). The anthropometric measurements were also performed at the pretest sessions. The body height and weight were measured, and skinfolds were measured using a Harpenden skinfold calliper (John Bull British Indicators Ltd., Bedfordshire, UK) at four different sites: over the biceps brachii muscle, over the triceps brachii muscle, the subscapular skinfold, and the suprailiac skinfold. The proportion of body fat was calculated using the sum of these four skinfold measurements in line with previously used protocols (Durnin and Womersley, 1974).

2.3. Pretest

The NLIA aerobic fitness test comprised walking for 8 min on a treadmill at 5.6 km h^{-1} at room temperature (23 ± 2 °C and 29 ± 6% RH). During the first and second min, the treadmill inclination was 4% and 7%, respectively. For the remaining 6 min, the inclination was set at 12%. The participants were dressed as for the heat tolerance test (see section 2.4) without the helmet, and with the addition of a self-contained breathing apparatus (18 kg). Total weight carried was 23.1 ± 1.1 kg for the male and 22.6 ± 0.8 kg for the female participants. The test was passed if the participant completed the test without relying on the railing.

A workload test was performed to identify the correct speed needed for the participants to be working at 6 W kg^{-1} in the heat tolerance test. The participants were asked to walk on the treadmill at 4.5 km h^{-1}, 5.5 km h^{-1}, and 6.5 km h^{-1} each for 5 min at 1% inclination, with a 1-min interval between each walking session (28 ± 3 °C and 14 ± 5% RH). They were dressed as for the heat tolerance test (see section 2.4). Linear regression was used to calculate the individual walking speed needed for each participant to be working at 6 W kg^{-1}.

The test for the evaluation of VO_{2max} was performed at room temperature (23 ± 3 °C and 27 ± 8% RH), while the participants were wearing running shoes and the participants preferred sports clothing. A stepwise increment in exercise intensity was performed during running on the treadmill until exhaustion. The inclination was 5.3% and all participants started running at 7 km h^{-1}, with a 1 km h^{-1} increase every min until exhaustion. The main criterion for an attained VO_{2max} was no further increase in VO_2 despite a further increase in the rate of exercise. A respiratory exchange ratio (RER) > 1.0 was used as an additional criterion (Åstrand and Rodahl, 1986).

2.4. Heat tolerance test

Before the main test, the participants wore their personal socks and undergarments and were equipped with and dressed in shirts (Spirit, Devold, Langevåg, Norway) and pants (Spirit). They then rested while seated at room temperature (23.1 ± 0.9 °C, 23 ± 7% RH) for 20 min. Next, they were dressed in fire protective equipment (jacket [PBI MAX Parallon 600, Wenaas, Måndalen, Norway], trousers [PBI MAX Parallon 600], fire hood [Spirit], helmet [Magma, Bullard, Cynthiana, KY, USA], and gloves [Tex Grip 2.0, Wenaas, Måndalen, Norway]). The total weight of the PPE was 6.4 ± 0.1 kg for the female participants and 6.9 ± 0.2 kg for the male participants. They wore their own running shoes. The participants were provided an additional 10-min rest period while they were wearing the PPE before they entered the environmental chamber (39.7 ± 0.3 °C, 14 ± 1% RH). In this chamber, the participants walked continuously for a maximum of 60 min, working at the preset speed to achieve $\dot{H}_{prod}$ at 6 W kg^{-1} 60 min was considered a sufficient duration for all participants to reach relevant heat stress levels. As T_{re} at approximately 38.5 °C has been measured during repeated bouts of firefighting activities, that was deemed a relevant core temperature (Horn et al., 2013). The test was terminated before the 60-min duration if T_{re} reached 39.0 °C or at the will of the participant.

2.5. Measurements and calculations

T_{re} was measured continuously at a depth of 10 cm using a thermistor probe (YSI 400; Yellow Springs Instruments, Yellow Spring, OH, USA).

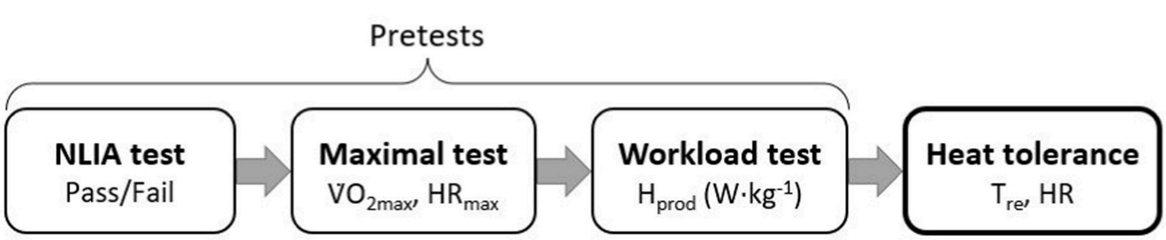

Fig. 1. Schematic of the test setup with primary variables. NLIA test; Norwegian Labor Inspection Authority test for aerobic fitness, VO_{2max}, maximal oxygen consumption; HR_{max}, maximal heart rate; H_{prod}, heat production; T_{re}, rectal temperature.

The rate of change in T_{re} (°C·h^{-1}) was calculated from the time taken to reach $\Delta T_{re} = 1.5$ °C. Skin temperatures were measured continuously using four YSI 400 skin thermistors positioned on the chest, anterior side of the upper arm, anterior thigh, and posterior calf. Mean skin temperature (T_{sk}) was calculated as suggested by Ramanathan (1964) (Equation (1)).

$$T_{skin}\ (^{\circ}C) = 0.3\left(T_{chest} + T_{upper\ arm}\right) + 0.2\left(T_{upper\ leg} + T_{lower\ leg}\right) \quad (1)$$

Nude body mass was recorded pre- and post-trial (ID1, Mettler-Toledo GmbH, Albstadt, Germany). Whole body sweat rate was calculated as change in body mass from pre-to post-trial divided by trial duration.

HR was continuously recorded using a heart rate monitor (Polar S810™ Electro OY, Kempele, Finland; ± 2 beats·min^{-1}). HR values at every min were averaged, and the HR for every 10-min duration is reported.

Gas exchange variables (Oxycon Pro®, Jaeger GmbH, Hoechberg, Germany) were recorded continuously and analyzed every 20 s during the heat tolerance test using the "mixing chamber" approach. Oxygen consumption (VO_2) and the respiratory exchange ratio (RER) were used for calculations of metabolic energy expenditure (MR) (Equation (2)). $\dot{H}_{prod}$ was calculated as the difference between MR and the external work rate (W) and expressed relative to body mass (Equation (3)). External work rate was calculated as suggested by Gordon et al. (1983). Here, body mass was defined as the sum of the body mass of the participant and the mass of the PPE.

$$MR\ (W) = \dot{V}O_2 \frac{\left(\frac{RER - 0.7}{0.3} e_c\right) + \left(\frac{1 - RER}{0.3}\right) e_f}{60} \times 1000 \quad (2)$$

$$\dot{H}_{prod}\ \left(W \cdot kg^{-1}\right) = \frac{(\dot{M} - W)}{Body\ mass} \quad (3)$$

Where e_c and e_f are the caloric equivalents per L of oxygen for the oxidation of carbohydrates (21.13 kJ) and fat (19.62 kJ), respectively.

T_{re} and HR were used to calculate the strain index (PSI) using the modified version of a previously used equation (Moran et al., 1998) by replacing the suggested 180 bpm with the maximal HR (HR_{max}) from the pretest (Equation (4)).

$$PSI = 5 \times \frac{\left(T_{re_t} - T_{re_0}\right)}{\left(39.5 - T_{re_0}\right)} + 5 \times \frac{\left(HR_t - HR_0\right)}{\left(HR_{max} - HR_0\right)} \quad (4)$$

Where t denotes simultaneous measurements taken every 5 min during the heat tolerance test, and the index 0 denotes the value at baseline.

2.6. Perceptual responses

Perceptual responses were assessed at the end of the resting period both without and with PPE, and then every 10 min during the exercise. Rate of perceived exertion (RPE) was assessed using the following numerical verbal anchors: 6, 7 "very, very light"; 8, 9 "very light"; 10, 11 "fairly light"; 12, 13 "somewhat hard"; 14, 15 "hard"; 16, 17 "very hard"; 18, 19 "very, very hard"; 20 (Borg, 1982). Perceived thermal sensation (TS) was assessed using a modified version of Gagge et al.'s (1967) rating of TS, using the following numerical verbal anchors: 5 "cool"; 6 "slightly cool"; 7 "neutral"; 8 "slightly warm"; 9 "warm"; 10 "hot"; 11 "very hot"; 12 "extremely hot"; 13 "unbearably hot." The sensation of shivering and sweating (SS) was assessed using the following numerical verbal anchors: 1 "heavy shivering"; 2 "moderate shivering"; 3 "some shivering"; 4 "neither shivering nor sweating"; 5 "some sweating"; 6 "moderate sweating"; 7 "heavy sweating" (Ha et al., 1996). Participants were also queried regarding thermal comfort (TC) using the following numerical verbal anchors: 1 "comfortable"; 2 "slightly comfortable"; 3 "uncomfortable"; 4 "very uncomfortable" (Gagge et al., 1967).

2.7. Statistical analysis

For statistical analyses, we used IBM SPSS Statistics version 25.0 (IBM Corp., USA). A two-way mixed method analysis of variance was used to investigate the interaction and main effect of sex (female, male) and time (0, 10, 20, 30, 40 min) for the physiological responses. For these tests, only the first five time points ($n = 24$) out of seven time points were analyzed, because some participants reached the termination criteria before the two last time points ($n = 21$ and $n = 10$ *respectively*). Greenhouse–Geisser corrections were used if the data violated the assumption of sphericity in the Mauchly's test of sphericity. Effect sizes from the analysis of variance were reported as partial eta squared (η_p^2). Differences in physical characteristics, workload during walking, and sweat responses between male and female participants were assessed using an independent samples *t*-test. Residuals were assessed for normality both visually and using the Shapiro–Wilk test. Friedman's test was used for analyzing the effects on nonparametric data (TS, RPE, sweating sensation, and TC) for each sex, and the Wilcoxon signed-rank test with Bonferroni corrections was used for paired samples between the two sexes. Bivariate analysis was conducted between time to reach $T_{re} = 38.5$ °C and $\Delta T_{re} = 1.5$ °C and possible related factors, such as baseline T_{re}, %BF, VO_{2max}, and A_D/m. Nonparametric data are presented as the median and range, and all other data as mean ± standard deviation. Differences were considered significant if $p < .05$. T_{skin} data for one female participant and gas exchange data for one male and one female participant in the heat tolerance test could not be used due to technical problems, for all other statistical tests $n = 24$.

3. Results

Fig. 2 shows the individual T_{re} values with the corresponding tolerance classification as recommended by Watkins et al. (2018a). The recommendation is to interpret the results along a continuum, rather than classifying people as ether heat tolerant or heat intolerant. An easily interpreted colour coded system with green, yellow, and red indicating more to less heat tolerant is proposed. Five participants were found to be in the "green zone" with $T_{re} < 38.0$ °C, 15 in the "yellow zone" with T_{re} 38.0 °C–38.5 °C, and four in the "red zone" with $T_{re} >$ 38.5 °C. No statistical difference (mean difference 0.1 (95% CI, −0.2 to 0.1) °C, $p = .627$) in T_{re} at 40 min was observed between female (38.2 ± 0.3 °C) and male (38.3 ± 0.3 °C) participants.

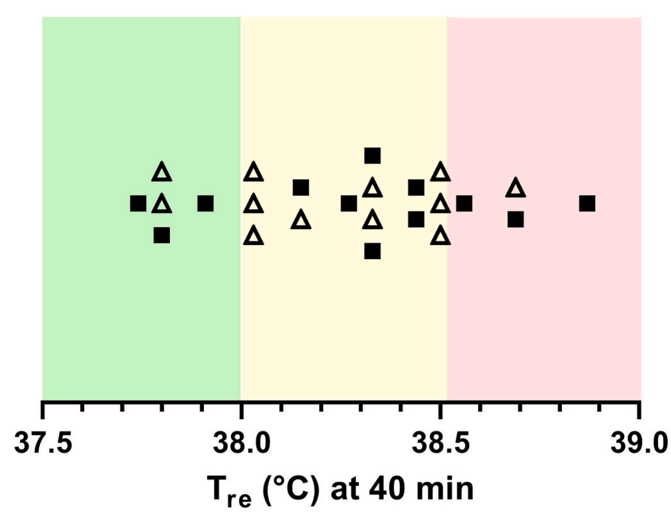

Fig. 2. Rectal temperatures (T_{re}) at 40 min of heat exposure. The color of the continuum is used as suggested by Watkins et al. (2018a). Unfilled triangles represent female participants and filled squares represent male participants. $n = 24$ (12 women and 12 men). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

There was a main effect of time on T_{re} ($F(1.2, 26.2) = 515.03$, $p < .001$, $\eta_p^2 = .96$) and ΔT_{re} ($F(1.2, 26.2) = 515.03$, $p < .001$, $\eta_p^2 = .96$), but no main effect of sex on T_{re} ($F(1, 22) = 0.75$, $p = .396$, $\eta_p^2 = .13$) or ΔT_{re} ($F(1, 22) = 0.75$, $p = .396$, $\eta_p^2 = .13$) was observed, and no interaction effect between time and sex was observed for T_{re} ($F(1.2, 26.2) = 0.87$, $p = .379$, $\eta_p^2 = .04$) and ΔT_{re} ($F(1.2, 26.2) = 0.87$, $p = .379$, $\eta_p^2 = .04$) (Fig. 3). The baseline T_{re} was 37.0 ± 0.4 °C for the female and 37.0 ± 0.2 °C for the male participants, with no significant difference between the groups (mean difference 0.05 (95% CI, −0.3 to 0.2) °C, $p = .696$). T_{re} for all participants reached 38.5 °C during the 60-min exposure. The average time taken to reach T_{re} = 38.5 °C was 46 ± 7 min and 45 ± 8 min for female and male participants, respectively. T_{re} of eight male and six female participants reached 39.0 °C between 44 min and 60 min of exposure and the tests were then terminated. None of the participants chose to end the experiment before reaching the termination criteria, either a T_{re} of 39.0 °C or exposure of 60 min. The time taken to reach a 1.5 °C increase in T_{re} was 49.9 ± 5.6 min and 44.5 ± 7.1 min for female and male participants, respectively, with no significant difference between the two groups (mean difference 5.39 (95% CI, −10.80 to 0.02) min, $p = .051$). Bivariate analyses of the data of all participants revealed a negative correlation between T_{re} at 40-min exposure and T_{re} at baseline ($r = 0.604$, $p = .002$). Moreover, the time taken to reach ΔT_{re} = 1.5 °C was not affected by the baseline T_{re} ($r = -0.033$, $p = .877$) (Fig. 4). %BF, VO_{2max}, and AD/m were not correlated with the time taken to reach T_{re} = 38.5 °C or ΔT_{re} = 1.5 °C ($p > .05$).

There was a main effect of time for both HR ($F(2.0, 44.2) = 509.3$, $p < .001$, $\eta_p^2 = .96$) and $\%HR_{max}$ ($F(2.1, 46.4) = 541.6$, $p < .001$, $\eta_p^2 = .96$)., but no main effect of sex for HR ($F(1, 22) = 0.02$, $p = .904$, $\eta_p^2 < 0.01$) or $\%HR_{max}$ ($F(1, 22) = 0.4$, $p = .552$, $\eta_p^2 = .02$) was observed, and no interaction effect between time and sex was observed for HR ($F(2.0, 44.2) = 0.9$, $p = .417$, $\eta_p^2 = .04$) or $\%HR_{max}$ ($F(2.1, 46.4) = 0.5$, $p = .650$, $\eta_p^2 = .02$) (Fig. 5). The increase from the resting HR to HR at 40 min of exposure was 50 ± 7 bpm for female and 55 ± 10 bpm for male participants.

It was found that whole body sweat rate in the male participants (1.4 ± 0.5 L h^{-1}) was significantly higher than for the female participants (1.0 ± 0.2 L h^{-1}) with a difference of 0.4 (95% CI, 0.09 to 0.70) L·h^{-1} ($p = .018$). However, no significant difference was observed in %BM loss between female (1.4 ± 0.3%) and male (1.5 ± 0.5%) participants (mean difference 0.1 (95% CI, −0.2 to 0.4) %, $p = .480$).PSI increased over time ($F(1.4, 30.6) = 774.1$, $p < .001$, $\eta_p^2 = .97$) from 1.3 ± 0.4 and 1.2 ± 0.4 at the start of exposure to 5.9 ± 0.7 and 6.1 ± 0.8 at 40 min of exposure for female and male participants, respectively, with no main difference between the groups ($F(1, 22) = 0.01$, $p = .913$, $\eta_p^2 < 0.01$) and no interaction effect between time and sex ($F(1.4, 30.6) = 0.4$, $p = .581$, $\eta_p^2 = .02$). Baseline T_{skin} was 34.0 ± 0.5 °C for both sexes and increased over time ($F(2.3, 47.5) = 534.3$, $p < .001$, $\eta_p^2 = .96$) to 37.8 ± 0.5 °C for female and 37.5 ± 0.4 °C for male participants, with no significant main effect between the groups ($F(1, 21) = 0.4$, $p = .837$, $\eta_p^2 < 0.01$).

The perceptual responses of SS, TS, and TC increased from rest to 40 min of exposure for all participants, and RPE increased from the start to 40 min of exposure for all participants. The perceptual responses at 40 min of exposure were similar between the female and male participants for RPE, TS, and TC (Table 2). SS at 40 min of exposure was different between groups, with the median response being "heavy sweating" for the female participants and "moderate sweating" for the male participants.

The participant characteristics of height, body mass, surface area, A_D/m, %BF, and VO_{2max} were different between the groups (Table 1). Age and HR_{max} were not significantly different between the groups. No significant differences in relative workload or walking speed were observed between the groups (Table 3).

4. Discussion

This study aimed to investigate whether there are any sex differences in heat tolerance or physiological responses during exposure to UHS while wearing firefighter PPE. To maintain ecological validity, the selection of participants was based on the current gender-neutral Norwegian physical employment standards for firefighters. Thus, all included participants completed the NLIA aerobic fitness test. In addition, the age and physical exercise profile was not significantly different between sexes. Our findings show that heat tolerance as defined by Watkins et al. (2018a) did not differ between the groups. However, large individual differences within both groups were observed for both heat tolerance and the rate of increase in T_{re}. Increases in T_{re}, T_{skin}, and HR were observed throughout the exposure for all participants, without group differences between women and men. Thus, the combination of high metabolic $\dot{H}_{prod}$, wearing PPE, and high ambient temperatures led to UHS where $\dot{H}_{prod}$ exceeded the heat loss, leaving the body in a state of continuous heat gain. No difference in $\dot{H}_{prod}$ was noted between the groups, and the aim of keeping approximately 6 W h^{-1} throughout the exposure was met.

For the heat tolerance classification set as T_{re} at 40 min of exposure, no differences were observed between the two groups. We performed the HOTT as described by Watkins et al. (2018a). Since our environmental chamber had an upper temperature limit of 40 °C, we used an ambient temperature of 40 °C and not 50 °C as used in the original HOTT. Because the effects of ambient temperature and relative humidity on tolerance time (time required to reach an endpoint criterion during heat exposure) when wearing PPE are marginal at work intensities >450–500 W (Cheung et al., 2000; Mclellan and Havenith, 2016) as in our study, we concluded that the classification of heat tolerance could be used as suggested by Watkins et al. (2018a). No previous study could be found comparing heat tolerance between men and women using the HOTT. For heat tolerance during CHS assessed using the HTT, limited evidence suggests that a higher proportion of women are heat intolerant (Druyan et al., 2012; Kazman et al., 2015; Lisman et al., 2014). However, this should be interpreted with caution considering the small sample size for women in these studies, their varying occupations, and

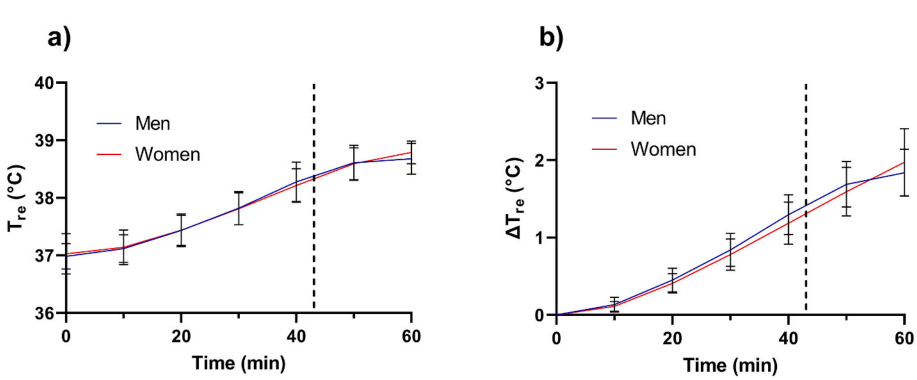

Fig. 3. (a) Rectal temperature (T_{re}) and (b) change in rectal temperature (ΔT_{re}) for female (red) and male (blue) participants. Values are mean ± standard deviation. Analysis of variance was performed using the five points to the left of the dashed lines, where n = 24 (12 women and 12 men). At 50 min, n = 21 (11 women and 10 men) and at 60 min, n = 10 (6 women and 4 men). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

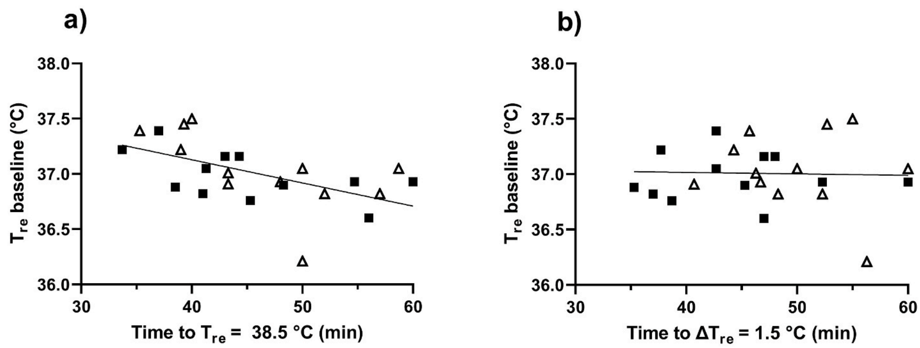

Fig. 4. Time taken to reach (a) rectal temperature (T_{re}) = 38.5 °C and (b) change in T_{re} (ΔT_{re}) = 1.5 °C plotted against baseline T_{re}. Trendlines are presented for all data points. Unfilled triangles represent female participants and filled squares represent male participants. n = 24 (12 women and 12 men).

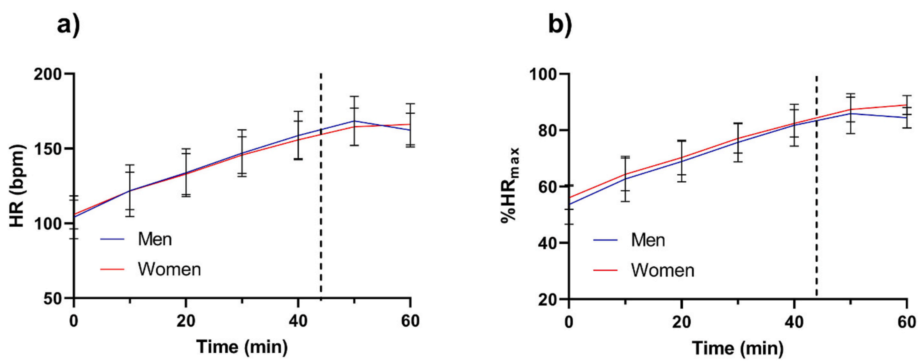

Fig. 5. Mean heart rate (HR) and percent of maximal HR ($\%HR_{max}$) for female (red) and male (blue) participants. Values are mean ± standard deviation. Analysis of variance was performed using the five points to the left of the dashed lines, where n = 24 (12 women and 12 men). At 50 min, n = 21 (11 women and 10 men) and at 60 min, n = 10 (6 women and 4 men). (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Table 2
Perceptual responses at 40 min of heat exposure.

	Women		Men	
	Median	Range	Median	Range
RPE	13	[11–16]	14.5	[12–20]
SS	7*	[6–7]	6	[6–7]
TS	11	[10–13]	11	[10–12]
TC	2.5	[2–4]	3	[2–4]

RPE, rate of perceived exertion; SS, shivering/sweating sensation; TC, thermal comfort; TS, thermal sensation. Values are median and range [min–max]. n = 24 (12 women and 12 men). * Significantly different between sexes, $p < .05$.

Table 3
Mean (±SD) workload during walking with mean difference, 95% confidence intervals (CI) and p value for the comparison between the sexes.

Variable	Women	Men	Mean diff. (95% CI)	*P* value	*n*
$\dot{H}_{prod}$ ($W \cdot kg^{-1}$)	5.8 ± 0.3	6.0 ± 0.5	0.2 (−0.2 to 0.6)	.272	22
VO_2 ($mL \cdot kg^{-1} min^{-1}$)	19.5 ± 1.0	19.7 ± 1.7	0.2 (−1.1 to 1.5)	.743	22
$\%VO_{2max}$	37.7 ± 3.6	33.5 ± 5.9	4.2 (−8.5 to 0.2)	.058	22
MR (W)	430 ± 33	551 ± 85	121 (64–178)	**<.001**	22
Walking speed ($km \cdot h^{-1}$)	5.8 ± 0.2	5.9 ± 0.3	0.1 (−0.1 to 0.3)	.469	24

$\dot{H}_{prod}$, heat production; MR, metabolic rate; VO_2, oxygen consumption; VO_{2max}, maximal oxygen consumption.
n = 22: 11 women and 11 men. Significant difference between sexes is highlighted using bold font.

their history of heat-related illness (Alele et al., 2020). Because the ambient temperature is 40 °C in the HTT and the participants wear shorts and T-shirts, the heat loss potential depends on the evaporation of sweat. Local and whole-body sweating during CHS has been found to be generally higher in men than women due to morphological differences, and not sex per se (Notley et al., 2017). Findings regarding heat tolerance obtained from CHS situations may not be directly transferable to UHS situations, especially when wearing PPE (Cheung et al., 2000), as in our study. When wearing PPE in a hot and dry environment, the microenvironment within the clothing layers becomes hot and wet, which restricts evaporative heat loss. An increased sweating function may therefore not necessarily be an advantage when wearing PPE in hot conditions, reducing the difference in heat tolerance between the sexes compared with that observed during CHS.

No differences in heat tolerance, T_{re}, T_{skin}, or HR were found between the groups in this study. By contrast, a study comparing the thermoregulatory responses of men and women wearing PPE while intermittently walking at 4 km h^{-1} at 40 °C reported shorter tolerance times for the women and higher T_{re}, T_{skin}, and HR for the women throughout the trial (Mclellan, 1998). These authors concluded that the women were at a thermoregulatory disadvantage compared with the men. Moreover, the women in that study had a lower VO_{2max} and higher %BF than the men. A sex difference in VO_{2max} and %BF was also noted in the present study; however, the included individuals for both sexes were physically fitter than those included in McLellan's study (1998), as noted by their higher VO_{2max} values (VO_{2max} 43.2 ± 6.6 vs 51.7 ± 4.7 and 49.0 ± 4.8 vs 58.8 ± 7.5 mL kg^{-1} min^{-1} for women and men respectively). When Mclellan (1998) grouped the participants according to their final T_{re}, and not by sex, the group with the lower VO_{2max} and higher %BF had the lowest tolerance time. Thus, it was concluded that differences in body composition and aerobic fitness have a significant influence on heat tolerance while wearing PPE during light intermittent exercise in hot environments. However, this seems not to be the case during higher-intensity work for physically fit women and men. The difference between exercise intensity in the study by McLellan (8 mL min^{-1} kg^{-1}) and that in our study (20 mL min^{-1} kg^{-1}) might explain the sex differences in his study and not in ours, because a high exercise intensity can preclude significant differences in heat tolerance (Cheung et al., 2000). However, in a firefighting situation, it is more likely that the exercise intensity is high, as demonstrated by a mean %HRmax of 85.4 ± 5.2 during a simulated firefighting exercise in extreme temperatures (Windisch et al., 2017). Also, the duration is limited by breathing cylinder time of approximately 20 min during work, thus providing ecological validity to the findings of the present study.

The $\dot{H}_{prod}$ in this study was fixed at approximately 6 W kg^{-1} as recommended for heat tolerance testing during UHS (Ravanelli et al., 2017; Watkins et al., 2018a) because it allows for unbiased comparisons of changes in T_{re} between groups with different body sizes, which is typically the case between men and women. Therefore, it could be stated that the similar T_{re} and HR values between the groups were expected because of the study design. However, large individual differences were observed in heat tolerance (Fig. 2) as well as the time taken to reach T_{re} = 38.5 °C and ΔT_{re} = 1.5 °C (Fig. 4). Moreover, a strong correlation between baseline T_{re} and time taken to reach T_{re} = 38.5 °C indicates that the absolute T_{re} after a set time in an exposure is affected by baseline T_{re}, but baseline T_{re} does not affect the rate of heat accumulation. Both baseline and absolute T_{re} may be of importance in a real-world setting. However, absolute T_{re} has a high clinical value in prediction and treatment of exertional heat illnesses (Casa et al., 2012, 2015), whereas methods to reduce baseline T_{re} before a firefighting mission might be valuable as preventive measures to maintain the T_{re} below pathological levels (Watkins et al., 2018b). In women, when the concentration of reproductive hormones changes during the menstrual cycle or with the use of hormonal contraceptives, the resting core temperature changes, accompanied by alterations in the thermoregulatory mechanisms (Charkoudian and Stachenfeld, 2014). In this study, no significant difference in T_{re} at the start of the test between the sexes were measured. Further, it has been argued that female reproductive hormones have insignificant effects on the thermoregulatory system and exercise performance under hot conditions (Lei et al., 2017; Notley et al., 2018), although more research is needed to conclusively support this finding.

It has been shown that much of the differences in thermoregulatory responses to exercise heat stress in men and women are due to fitness rather than sex per se, and a recent review has suggested that some of these differences may be offset by using appropriate gender-neutral physical employment standards (Corbett et al., 2020). The selection of participants for the present study was based on the current physical standards for employment for firefighters in Norway (Heimburg et al., 2013; NLIA, 2021). The inclusion was based on the aerobic fitness test, and not the muscle strength tests, because aerobic fitness has been shown to have an impact on thermoregulatory responses during heat stress and was therefore considered most important. This test has an oxygen demand of approximately 32 mL kg^{-1} total mass carried·min^{-1}, which equals approximately 41 mL kg^{-1} body mass·min^{-1} (Heimburg et al., 2013). All participants in the present study had a VO_{2max} > 47 mL kg^{-1} min^{-1}, and the mean levels for both groups were well above the average for Norwegian men (48.6 ± 9.6 mL kg^{-1} min^{-1}) and women (40.3 ± 7.1 mL kg^{-1} min^{-1}) in their 20s (Edvardsen et al., 2013). Nevertheless, the female participants had a lower VO_{2max} than male participants in the present study, which in theory should put them at a disadvantage. However, all the female participants were fit and performed physical exercise training on a regular basis, which helps optimize heat dissipation processes. This supports the notion that it is the aerobic exercise training and not the VO_{2max} per se that improves heat dissipation in uncompensable environments (Ravanelli et al., 2021).

Heat acclimatization also improves tolerance for activity during heat stress by increasing the maximum local and whole body sweat rates, reducing the core temperature at baseline and during exercise, and reducing the cardiorespiratory strain (Périard et al., 2015). No participants were heat acclimatized by frequent exposure to hot environmental conditions when performing the main tests because none reported regular use of saunas and the mean outdoor temperature in February and March 2021 in Trondheim, Norway was −4.6 °C and 1.7 °C, respectively. However, partial heat acclimation is likely to have occurred in our participants because they all reported performing aerobic fitness training several times a week. Ravanelli et al. (2021) provides evidence for the concept of partial heat acclimation from repeated thermal stress acquired during training sessions that improves sweating and core temperature responses during UHS. This partial heat acclimation status likely applies to many firefighters as well, as they must perform exercise training to meet the physical employment standards as well as job demands. Aerobic fitness (classified using a combination of VO_{2max} and frequency of aerobic training) also improves tolerance to increased core temperature, which means that endurance-trained individuals will tolerate a higher T_{re} at exhaustion (Mclellan and Havenith, 2016). Because the core temperature of firefighters is not monitored during their occupational tasks, the heightened tolerance to increased core temperature in aerobically fit individuals might then increase the time to exhaustion during heat exposure and would also better enable them to perform their tasks while wearing PPE. However, even though our participants on average had a high VO_{2max} and performed frequent aerobic exercise, large individual differences in heat tolerance and physiological response to the test were observed. This might indicate that in addition to the aerobic fitness test, a separate heat tolerance test could be used to identify the firefighters ability to tolerate heat strain associated with wearing PPE in hot environments relevant for their employment, as also suggested by others (Mclellan and Havenith, 2016; Watkins et al., 2018a). Then, interventions to improve the heat tolerance could be targeted the ones with the greatest need and give important information that could be used to adjust work routines (e.g., cooling strategies, hydration, job rotation) to improve the safety of the firefighters.

Some limitations of this study should be considered when interpreting these results. The mean age of participants of this study were lower than what is reported for studies including firefighters (Barr et al., 2010). However, heat tolerance seems to be minimally compromised by age in healthy and fit individuals (Kenney and Munce, 2003), which firefighters needs to be in order to pass the health and fitness employment standards. Further, when fighting fires, full PPE with boots and self-contained breathing apparatus is worn, increasing the physical workload (Taylor et al., 2012). Covering the face with the full-face masks limits the evaporation of sweat from the face. It also closes the gap around the neck of the jacket, limiting the air movement through vents and cuffs of the clothing (pumping effect) further reducing the evaporation of sweat from the body. Additionally, in real scenarios, ambient temperatures can easily exceed the 40 °C used in this study, increasing the heat load. Thus, further research is warranted to assess the association between heat tolerance results from a HOTT and heat tolerance during firefighter activities in extreme temperatures.

5. Conclusions

The present study shows that when personnel are selected using gender-neutral physical employment standards for firefighters, men and women have a similar heat tolerance and physiological responses during UHS where both non-evaporative and evaporative means of heat dissipation are impaired. However, large individual differences in heat tolerance were noted. Occupational heat tolerance tests could be used to identify individual tolerance levels. Individual or work interventions could then be established to ensure that the firefighters tolerate the heat strain associated with their work, regardless of their sex.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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