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Physiological and perceptual strain of firefighters during graded exercise to exhaustion at 40 °C and 10 °C

Abstract

Purpose: *To study whether perceptual identification should be included as a measure to evaluate physiological stress.*
Methods*: Physiological variables; oxygen uptake (*V_{O2}*), ventilation, heart rate (HR), blood lactate concentration, rectal temperature (*T_{rec}*) and mean skin temperature (*T_{skin}*), perceptual variables; rate of perceived exertion (RPE), thermal sensation (TS) and time to exhaustion were measured at submaximal and maximal intensities during graded exercise on a treadmill to exhaustion in 12 firefighters wearing protective clothing and extra mass at 40 °C and 10 °C. The physiological strain index (PhSI) and perceptual strain index (PeSI) were calculated.*
Results: *Apart from* T_{rec}*, all the physiological and perceptual variables were higher at submaximal intensities of 40 °C. Time to exhaustion was 16% shorter and the corresponding* V_{O2} *was reduced by 7% in the heat. A high correlation (r=89) between the PhSI and PeSI was found in both temperatures. PeSI scores were equal to PhSI at both ambient temperatures, except at the two highest intensities in the heat, where PeSI was higher.*
Conclusions: *These findings support the use of perceptual identification to evaluate physiological stress. However, at very high intensities under hot conditions the perceptual strain was estimated higher than the physiological strain. More precise indexes are needed to include perceptual measures in safety standards.*

Keywords: firefighters; physiological strain index; perceptual strain index; ambient conditions; body temperature

1. INTRODUCTION

Extremely hot environmental conditions, high work intensity, heavy and impermeable protective clothing and equipment all together expose firefighters to significant levels of cardiovascular and thermoregulatory stress [1-7]. In addition to the high ambient temperature, the combination of high metabolic heat production and limited capacity for heat dissipation through the clothing imposes an extra heat stress [8]. Before unacceptable risk levels are reached, firefighters should be able to sense and grade physiological heat strain at different environmental temperatures and work intensities when exposed to it.

A simple physiological strain index (P*h*SI) has been developed by [9]. The index is found to be a valid model in estimating heat tolerance in healthy young men. Two physiological parameters, rectal temperature (T_{rec}) and heart rate (*HR*), are included in the index, which adequately depict the combined strain reflecting both thermoregulatory and cardiovascular systems. Also, a perceptual-based strain index (P*e*SI) has been developed by [10] that includes rate of perceived exertion (*RPE*) and thermal sensation (*TS*).

How the variables included in the strain indexes are affected by exercise in the heat has been studied earlier. T_{rec} rises independently of ambient temperature during moderate- and high-intensity exercise within a temperature range of 20 to -10 °C [11]. Furthermore, a rise in T_{rec} is proportional to the relative workload [12]. However, when the ambient temperature approaches skin temperature, which happens at approximately 35 to 40 °C, a reduced ability to dissipate generated heat occurs while wearing protective clothing [13, 14]. This is due to both the elevation in metabolic heat production and a decrease in evaporative efficiency. Skin temperatures are strongly influenced by the ambient conditions. Besides the increased blood flow that is needed to supply the working muscles with oxygen during exercise, blood flow to the skin increases during exercise, thus improving metabolic heat transfer from the core to the skin. This becomes even more pronounced when firefighters exercise in warmer environments dressed in protective clothing, when the additional blood flow poses an extra challenge for the circulatory system, often observed as raised *HR* and sweat loss [12, 15]. The *TS* corresponds well with the skin temperature [16] when the skin temperature changes, despite wearing protective clothing and exercising [17]. In addition, the *RPE* included in the P*e*SI equation is found to be higher in the heat than under cool conditions at submaximal exercise intensities

[3, 16, 18-22]. According to [23], *RPE* is affected by various physiological criteria measures that increase in the heat.

Correlation studies, which have compared variables included in the strain indexes, have found strong to moderate correlations [24-26]. The study by Gallagher et al. [25] compared variables included in the P*h*SI and the P*e*SI during a treadmill exercise, in which firefighters performed intermittent and continuous walking in a heated room at a temperature in the range of 33–40 °C. The study revealed strong correlations between *RPE* and *TS* (r = 0.82 – 0.94), and between *RPE* and *HR* (r = 0.86 – 0.92). [26] and [24] also found a strong correlation between *RPE* and *HR* (r = 0.75; r = 0.81, respectively) during exercise testing until exhaustion. However, correlation between core temperature and *TS* was moderate (r = 0.62) [24]. When comparing the two indexes, P*h*SI and P*e*SI, inconsistent data is found. Gallagher et al. [25] and Borg et al. [24] found a significant moderate correlation between P*h*SI and P*e*SI when firefighters were walking on a treadmill. However, Petruzzello et al. [27] did not find a significant correlation (r = 0.55) between these indexes in a similar setting.

To avoid heat-related injuries, a firefighter's warning system should include accurate perceptual outcome measurements. The scores of P*h*SI and P*e*SI are classified from 0 to 10, where zero represents 'no strain' and 10 means 'very high strain' [9]. Only a few studies have compared the scores of these two indexes in firefighters walking on a treadmill. Petruzzello et al. [27] and Hostler et al. [28] compared P*h*SI to P*e*SI under thermoneutral conditions. In the study by Petruzzello et al. [27], P*e*SI was consistently lower than P*h*SI. On the other hand, in the study by Hostler et al. [28] P*e*SI was higher than P*h*SI. Under hot conditions (40 °C), Tikuisis et al. [10] found that extremely fit participants reported P*e*SI to be lower than P*h*SI, while unfit participants found them to be equal. However, Gallagher et al. [25] found that P*e*SI in fit participants was higher after walking in 40 °C, and Borg et al. [24] also reported a higher PeSI when healthy firefighters walked in the heat. The inconsistent outcomes of these earlier studies suggest that more research is needed to identify the connection between physiological and perceptual strain in firefighters exercising, especially in hot environments. Protocols used in these earlier studies included both intermittent and/or continuous treadmill walks at submaximal intensities in a solitary environment [10, 25, 27]. Only the study by Borg et al. [24] used heavier weights, which is typical for firefighters in operations, in three different environments. However, the walking intensity in that study was submaximal and a minimum of physiological variables were measured. Appropriate tests in a controlled laboratory setting make it possible to incorporate relevant measures when experienced firefighters exercise. This makes it possible to study the relationship between P*h*SI and P*e*SI and the impact of protective clothing and added weights across a range of submaximal exercise intensities and at exhaustion in different environmental temperatures.

Safety standards do not include perceptual measures [29]. To develop a better warning system for the firefighter's health at work, a firefighter's warning system should thus include accurate perceptual outcome measurements. Therefore, perceptual and physiological outcomes ought to be studied at different environmental temperatures and work intensities.

To our knowledge, the impact of heat on the connection between P*h*SI and P*e*SI using a graded exercise to exhaustion has not previously been studied. The purpose of this study was firstly to investigate physiological and perceptual responses at 40 °C compared to 10 °C during graded exercise to exhaustion when wearing firefighting clothing and carrying an extra load simulating firefighting equipment, and then comparing the P*h*SI to P*e*SI under the two environmental conditions, separately. We hypothesised that there would be strong correlations between the P*h*SI and P*e*SI in cool as well as in hot environmental conditions and that P*e*SI could express the cardiovascular and thermal strain associated with graded exercise while wearing firefighting clothing and equipment.

2. METHODS

2.1. Subjects

Twelve healthy, non-smoking, physically fit firefighters served as participants in this study (Table 1). Participants were given full information about the procedure and experiments before they gave their written consent to participate. All had 3–7 years of full-time experience in the fire brigade in Trondheim, Norway, and were familiar with firefighting work. The experiments were carried out in early winter, and the firefighters had no regular training in the heat, nor did they take saunas regularly. The study was performed according to the Helsinki declaration and was approved by the Regional Research Ethics Committee in Medicine.

Table 1 near here.

TABLE 1. Characteristics of the participants

Physical property (unit of measurement)	*M* ± *SD*	Range
Age (years)	39 ± 5	28–46
Height (m)	1.81 ± 0.03	1.77–1.86
Body mass (kg)	84 ± 5	77–93
BMI	25.6 ± 1.4	23–27
HR_{max} (bpm)	190 ± 2.7	174–208
V_{O2max} (L·min^{-1})	4.51 ± 0.26	4.06–4.91
V_{O2max} (ml·min^{-1}·kg^{-1})	53.7 ± 3.6	49.0–60.3

Notes. BMI = body mass index. V_{O2max} = maximal oxygen uptake. HR_{max} = maximal heart rate. The data are *M* ± *SD* and range of the participants. *n* = 12.

2.2. Overall design and approach to the problem

The participants performed three treadmill tests: a pretest for aerobic performance, and a main study of two graded exercises until exhaustion in a climate chamber set at either +40 or +10 °C. The pretest $VO_{2\ max}$ value was also used to determine the relative intensity of each stage of the graded exercise for each individual during the main study. The two trials that comprised the main study were carried out two to seven days apart, and in random order. Physiological data (V_{O2}, ventilation, *HR*, blood lactate concentration, T_{rec} and skin temperatures) and perceptual data (*RPE* and *TS*) were collected at each stage and at exhaustion. Time to exhaustion was also measured and taken as aerobic performance time. The participants were requested to avoid heavy physical exercise during the day before each test. Each subject carried out the tests at the same time of the day, and they fasted for ≈2 h before each test.

2.3. Pretests

The participants' V_{O2max} was established by treadmill running at 5% inclination. The participants were dressed in shorts, t-shirt and jogging shoes. The V_{O2max} was measured after a warm-up run on the treadmill. In order to achieve V_{O2max} within 5–6 min for each subject, the test started at 3 m s^{-1} (range = 2.5–3.3 m s^{-1}) and the treadmill speed was increased every minute in steps of 0.1–0.3 m s^{-1}, while V_{O2} and *HR* were recorded continuously. At the end of the run a sample of 5 μl blood was taken from a fingertip to measure the blood lactate concentration. The criterion that V_{O2max} had been reached was the absence of a further increase in V_{O2} in spite of a further increase in treadmill speed [30]. The V_{O2max} was taken as the median of the three highest recordings of 10 s each at the end of the V_{O2max} test.

2.4. Main study

The participants performed two graded walking tests until exhaustion on a treadmill in a climate chamber (Figure 1). The temperature of the climatic chamber was maintained at 40 or 10 °C (± 0.5 °C) with relative humidity of 50% and 20% (± 3%), respectively. During both tests the participants were equipped with personal protective clothing (long woollen trousers, cotton t-shirt, fire-protective trousers and jacket, helmet and gloves) and jogging shoes. The total thermal insulation of this ensemble, determined using a heated thermal manikin, was 0.527 m^2 K W^{-1} (3.40 clo). According to Standard No. EN 342:2004, a clo unit is an expression of the insulation capacity provided by either a single garment or a total clothing ensemble (1 clo unit = 0.55 m^2 K/W) [31].

Each firefighter carried an extra mass of 30 ± 0.5 kg during the tests to simulate essential equipment, taken as 7 kg for the firefighting garment and an additional 23 kg, distributed evenly close to and along the torso with 4 kg on the chest and 19 kg of weight discs in a backpack. The load and distribution were the same under both environmental conditions.

On arrival at the laboratory each subject's body mass was measured. Thermistors for T_{rec} and six skin temperatures (T_{skin}) were mounted, as well as a heart-rate monitor. In order to obtain baseline data, the subject rested in a sitting position for 20 min at an ambient temperature of 25 °C, dressed in protective clothing, except for the jacket. The baseline data of T_{rec}, T_{skin}, blood lactate concentration, and *HR* were recorded. At the end of the resting period the subject put on the jacket and the additional weight. The graded exercise began within 2 min after the subject entered the climate chamber.

A graded exercise to exhaust the subject in the course of 20–30 min was chosen in order to simulate the time used during smoke diving (Figure 1). The exercise intensity during the 9 min warm-up period (the first stage) was chosen to require a V_{O2} of 35% of the subject's V_{O2max} (treadmill inclination 2%). After a 1 min break to allow a blood sample to be taken, the exercise intensity was raised by 12% of the subject's V_{O2max} (corresponding to 4% increase in treadmill inclination), and the subject walked for another 4 min at this intensity before a further 1 min break for blood sampling. This procedure was repeated until subjective exhaustion. If the treadmill's maximum inclination of 15% was reached before the subject was exhausted, the treadmill speed was increased stepwise (+ 0.1 $m \cdot s^{-1}$) until exhaustion while the inclination was kept at 15%. A final blood sample was taken after the last exercise stage.

[Figure 1 about here]

The time to exhaustion was taken from the start of the treadmill walk until volitional exhaustion. The 1 min breaks for blood lactate sampling are thus included in the performance times. Since each 1 min break allowed some recovery, we required the subject to exercise for at least 2 min of the final exercise stage to allow that stage to be included in the performance time.

The criteria for termination of the experiment were a T_{rec} of 39 °C or subjective exhaustion. All participants terminated the test by the subjective exhaustion criterion.

2.5. Measurements and instruments

Data on *HR*, V_{O2}, ventilation, T_{rec} and T_{skin} were recorded continuously until exhaustion. Blood lactate concentration was measured at the end of each stage. Body weight was measured before and after the exercise. A rating of perceived exertion (*RPE*) [32, 33] and thermal sensation (*TS*) [34] were recorded at the start, during the last exercise minute of each step, and at the end of the test. Index scores of P*h*SI and P*e*SI were calculated at each stage and at exhaustion.

2.5.1 Physiological variables

V_{O2} and ventilation were measured by the Metamax II (Cortex Biophysics GmbH, Leipzig, Germany) portable metabolic analyser [35]. The instrument has built-in averaging in the hardware that delays the output vis-à-vis the true values by approximately 30 s [35]. The data are expressed as reported by the Metamax with the correction of 30 s for the built-in delay. *HR* was measured with a heart-rate recorder (Polar Electro OY, Kempele, Finland), and blood lactate concentration using a portable 1710 Lactate Pro™ analyser (Arkray Factory Inc, KDK Corporation, Shiga, Japan) [36]. T_{rec} was measured by a rectal thermistor (YSI 700, Yellow

Springs Instruments, Yellow Springs, OH, USA; ± 0.15 °C), which was introduced 10 cm into the rectum. Skin temperatures were measured by thermistors (YSI 400, Yellow Springs Instruments; ± 0.15 °C) taped to the skin at six locations. A weighted mean skin temperature (T_{skin}) was taken from the temperature measured on the forehead, chest, anterior and posterior thigh, posterior forearm and back, according to a modification of Hardy and DuBois [37]. Body weight was measured by a digital scale (Mettler Toledo GmbH, Albstadt, Germany) and weight loss was calculated from the difference in nude body mass before and after the exercise. Water intake was not allowed during the trials.

2.5.2. Perceptual variables

Each subject rated his perceived level of strain on the 10-point category rating scale of perceived exertion (*RPE*), where 0 = *no strain* and 10 = *total exhaustion* [32, 33]. For subjective evaluation of thermal sensation (*TS*) an 11-point scale from –5 to +5 was used, on which 0 = *neutral* and +5 = *intolerably hot* [34].

2.5.3. Physiological and perceptual strain indexes

The physiological strain index (P*h*SI) was calculated by the equation of Moran et al. [9]. The strength of this index lies in its ability to rate and compare strain between any combination of climate and clothing [9]. The P*h*SI is stated as in Equation (1):

$$PhSI = 5 \times (T_{rec,t} - T_{rec,0}) \times (39.5 - T_{rec,0})^{-1} + 5 \times (HR_t - HR_0) \times (HR_{max} - HR_0)^{-1}, \quad (1)$$

where P*h*SI = physiological strain index, T_{rec} = rectal temperature, *HR* = heart rate. The $T_{rec,t}$ and HR_t are simultaneous measurements made at time *t*, at the end of each increment. The index 0 denotes the value at baseline (Figure 1). In our study, the P*h*SI, which normally gives scores in the range 0–10, remained within the following range of values of P*h*SI: $T_{rec,0} \leq T_{rec,t} \leq 39.5$ °C and 55 bpm $\leq HR_t \leq HR_{max}$ for the individual; HR_{max} was here taken from the results of the pretests rather than using the proposed value of 180 bpm suggested by Moran et al [9].

The perceptual-based strain index (P*e*SI) was defined by the equation of Tikuisis et al. [10]. The P*e*SI is stated as in Equation (2):

$$PeSI = 5 \times (TS_t - TS_0) \times (5 - TS_0)^{-1} + 5 \times (RPE_t) \times 10^{-1} = TS_t + (RPE_t) \times 2^{-1}, (2)$$

where P*e*SI = perceptual strain index, *TS* = thermal sensation, *RPE* = rate of perceived exertion. The TS_t and RPE_t are simultaneous perceptual registrations made at the end of each increment in exercise intensity. TS_0 denotes 'neutral' thermal sensation. The perceptual strain index, which also normally gives scores in the range 0–10 was within the following range of values: $0 \leq TS \leq 5$ and $0 \leq RPE \leq 10$. The interpretation of the strain levels is: 0.0–2.9 = *no/little strain*, 3.0–4.9 = *low strain*, 5.0–6.9 = *moderate strain*, 7.0–8.9 = *high strain* and 9.0–10.0 = *very high strain* [9]. To increase sensitivity of *RPE* and *TS*, our participants were told to differentiate the sensation scores by rating the efforts in 0.5-point steps instead of 1-point steps.

2.6. Data analyses and statistics

Quantile-quantile (QQ) plots were used to test the assumption of normally distributed data. Analysis of variance with repeated measures (ANOVA) was used to compare the physiological and perceptual variables and the indexes P*h*SI and P*e*SI at baseline and the three first submaximal steps under the two environmental conditions. If the ANOVA reported a statistically significant effect, a two-tailed *t*-test for paired observations was used and the Bonferroni correction of *p* was applied for all multiple comparisons. Paired two-tailed *t*-tests was also used to identify differences in performance, physiological and perceptual variables between temperatures at exhaustion. The data is summarised as *M* and *SD* for anthropometric data and *M* and *SEM* for the physiological and perceptual data. SPSS version 15.0 was used for data analysis. The subjective rating scales were treated as continuous variables. Skin temperature data for one subject were lost. Data for statistical analyses were taken as the average value for the last minute of exercise at each stage. At exhaustion, V_{O2} was taken as the median of the three highest recordings of 10 s each. To find the relationship between the physiological and perceptual responses during graded exercise under hot and cool conditions, a Pearson's correlation coefficient between the participant's P*h*SI and P*e*SI scores across all submaximal intensities at each temperature was used.

3. RESULTS

Time to exhaustion was 29 min 43 s (*SEM* = 51 s) at 10 °C and 17% shorter in the heat (24 min 58 s; *SEM* = 41, *p* = 0.000).The participants reached exhaustion one stage earlier in the heat.

3.1. Physiological measures

V_{O2} did not differ at the end of the warm-up period (the first stage) between the two ambient conditions ($p = 0.160$). Thereafter, V_{O2} increased with exercise intensity at both temperatures, and was 8% higher at the submaximal exercise intensities in the warmer environment (Figure 2A). The participants became exhausted at a lower exercise intensity in the heat, and peak V_{O2} was 7% less in the hot environment than in the cool one (3.8 L·min^{-1} vs 3.5 L·min^{-1} ; p = 0.011; Figure 2a). Peak V_{O2} was 84% (*SEM* = 2) at 10 °C and 78% (*SEM* = 2) at 40 °C of the V_{O2max} established during the treadmill running pretest.

[Figure 2 about here]

Ventilation was 39.2 L·min^{-1} (*SEM* = 1.4) at the end of the warm-up period at 10 °C and 40.9 L·min^{-1} (*SEM* = 1.5; $p = 0.010$) in the heat. Thereafter, ventilation increased with exercise intensity at both temperatures and was 10, 15 and 19% higher in the heat at the second, third and fourth stage; 48.6 L·min^{-1} (*SEM* = 1.8) vs. 53.7 L·min^{-1} (*SEM* = 2.3), 64.2 L·min^{-1} (*SEM* = 2.4) vs. 73.8 L·min^{-1} (*SEM* = 3.0) and 87.3 L·min^{-1} (*SEM* = 3.2) vs. 103.8 L·min^{-1} (*SEM* = 4.0); respectively ($p < 0.001$). Ventilation at exhaustion was 8% less in the heat (122 L·min^{-1}; *SEM* = 5 vs 113 L·min^{-1} *SEM* = 2; $p = 0.035$.

Blood lactate concentration at baseline was 1.1 mmol·L^{-1} (*SEM* = 0.1). At the equivalent submaximal exercise intensities, the blood lactate concentration was higher in the heat than at 10 °C (Figure 2b). At exhaustion, the blood lactate concentration was lower in the heat.

HR at baseline did not differ between the two conditions, but after 5 min of the warm-up it was 10 bpm ($SEM = 2$) higher in the heat than at 10 °C ($p = 0.001$; Figure 2c). Thereafter HR rose linearly and in parallel during the submaximal exercise, and was thus 18 bpm ($SEM = 2$) higher at 40 °C than at 10 °C (12%). At exhaustion, HR was 10 bpm (10 °C) and 5 bpm (40 °C) lower than HR_{max} (Table 1).

Baseline T_{rec} was equal in both conditions (37.2 °C; $SEM = 0.1$), and rose by 0.9 °C ($SEM = 0.1$) to exhaustion in both conditions (Figure 3a). T_{skin} was 33.9 °C ($SEM = 0.3$) at baseline. During the warm-up period, T_{skin} did not change from the rest values in the cool conditions, while it rose by 2.2 °C ($SEM = 0.2$) in the heat (Figure 3b). Thereafter, T_{skin} rose by 1.7 °C to exhaustion under both conditions. At the end of the exercise T_{skin} was thus 2.6 °C ($SEM = 0.3$) higher in the heat than in the cool environment and T_{rec} and T_{skin} were thus 38.1 °C at exhaustion in the heat.

[Figure 3 about here]

Body mass decreased by 0.9% (725 g; $SEM = 72$) at 10 °C and 1.2% (1011 g; $SEM = 72$) at 40 °C ($p < 0.001$). As a result of the shorter exercise time but greater weight loss in the heat, the average rate of weight loss was 70% higher in the heat than at 10 °C (1393 $g \cdot h^{-1}$; $SEM = 113$ vs 2352 $g \cdot h^{-1}$; $SEM = 167$; $p < 0.001$).

3.2. Perceptual measures

The RPE was 2.1 at the end of the warm-up at 10 °C and 2.8 in the heat. At all submaximal steps RPE was higher in the heat (Figure 2d). At the termination of exercise, RPE was the same under both environmental conditions.

TS was 0.9 ($SEM = 0.1$) at the end of the warm-up at 10 °C and 1.8 ($SEM = 0.2$) at 40 °C (Figure 3c). This difference of 0.9 was reported at all submaximal steps during the exercise. Despite the shorter duration in the heat the TS at exhaustion was higher.

3.3. Physiological and perceptual strain indexes

The P*h*SI and P*e*SI both scored approximately 1.0 higher at each submaximal stage of the incremental exercise in the heat than in the cool environment ($SEM = 0.2$; $p < 0.001$). At exhaustion the P*h*SI did not differ between the two temperatures (score = 6.9, *SEM* = 0.2), while the P*e*SI was 7.4 at 10 °C and 0.8 points higher in the heat ($p = 0.006$) (Figure 4).

The P*h*SI and P*e*SI scores were equal in both the hot and cool environments except for the last submaximal stage of the graded exercise in the heat, where P*e*SI was higher than P*h*SI (Figure 4). The correlation between the subject's P*h*SI and P*e*SI across all submaximal intensities was $r = 0.89$ in 40 °C and $r = 0.88$ in 10 °C ($p < 0.010$).

[Figure 4 about here]

4. DISCUSSION

This study presents firstly physiological and perceptual variables and strain indexes of firefighters during a graded exercise to exhaustion in a hot environment compared to a cool one. Further, the perceptual strain compared to the physiological strain in the two environments is presented. The primary findings from this research are: (1) Submaximal variables included in the physiological (*HR*) and perceptual (*TS*, *RPE*) strain indexes were higher in the heat, apart from T_{rec}, which did not differ; (2) A significant strong correlation between the P*h*SI and the P*e*SI was found in both environmental conditions; (3) The two index scores were equal in both the hot and the cool environment except at the highest submaximal intensity and at exhaustion in the heat where the P*e*SI was highest.

4.1. Physiological and perceptual differences between two environmental temperatures

The cost of temperature regulation affects maximal performance in the heat as shown by the 17% reduction in time to exhaustion and 7% reduction in peak V_{O2}. It is well known that aerobic endurance performance is impaired, measured as a shorter time to exhaustion, in warm environments [38], which is largely dictated by changes in V_{O2max} [38, 39]. At 40 °C, the ambient temperature is higher than the skin temperature, which means that body heat can only be lost through evaporation of sweat. According to Kenefick et al. [40], dehydration (< 2% body mass) impairs performance even more in combination with external heat stress. Our participants were not directly dehydrated with a loss of 0.8% and 1.2% of their body weight at

10 and 40 ºC, respectively. However, a considerably higher rate of sweat loss (70%) in the heat in the present investigation may have had an effect on the reduced performance as well as the physiological and perceptual variables measured in the heat. Despite the participants being exhausted at a lower intensity in the heat, P*h*SI did not differ between the two environmental conditions at exhaustion. *HR* approached maximum (95–98% HR_{max}) at exhaustion, suggesting that the two exercises were terminated because of physical fatigue, probably related to cardiovascular limitations [41]. This is in line with Rowel et al. [42], which provided evidence that cardiovascular strain may be the foremost factor mediating fatigue during aerobic exercise in uncompensated heat stress conditions. At the end of the two exercises in the current investigation, T_{rec} was the same and reached 38.1 °C, which shows an ability to dissipate generated heat even in hot conditions. Also Borg et al. [24] found the same equal rectal temperature between trials in a comparable study lasting on average 30 min at 21, 30 and 37 °C. Metabolic heat production could therefore be the only contributor to a rise in T_{rec} [16]. Given the observation of a similar rectal temperature during our graded exercises, only heart rate could influence differences in P*h*SI.

HR was 18 bpm (13%) higher in the heat during the graded submaximal exercise. The combination of heat and exercise had a significant impact on the cardiovascular system, as shown by an 8% higher V_{O2} during submaximal exercise in the heat than in the cool environment. However, previous research is inconsistent for the effect of ambient temperature on submaximal V_{O2} in subjects dressed in protective clothing [43-46]. The high skin temperatures measured in the heat in our study stimulate a continuum of thermoregulatory responses, such as increased ventilation, circulation and a higher metabolism in the working muscles [40]. This may have increased V_{O2} and *HR* rate further in the heat [47]. The control of respiration was closely matched to the body's oxygen requirements at low intensity. However, the disproportionate additional increase in ventilation relative to metabolic requirements was greater during the hot trial, and the higher blood lactate concentration measured in the heat may have affected ventilation earlier by respiratory compensation. The disproportionate additional increase in both ventilation and *RPE* during the graded exercise show that ventilation may have affected the *RPE* considerably in the last part of the hot trial. *HR* as an indicator of perceived exertion is not consistent [23] because other physiological variables have higher correlation with *RPE* in certain circumstances. Chen et al. [23] found that the highest correlation was between *RPE* and ventilation, which occurred at maximal intensity.

Further research should thus include all potential physiological variables that may have an effect on the perception of strain, especially during intensive work in hot environments.

Although our subjects' rectal temperatures did not differ between the two exercise conditions, they experienced a higher heat strain in the hot environment, which suggests that the skin temperature may be more important to the experienced heat strain. That view has also been proposed by Tatterson et al. [16]. *TS* reflects T_{skin} at all intensities [34, 48] and the significantly higher T_{skin} during the submaximal exercises in the heat in our study demonstrates how skin temperatures affect the sensation scores. At exhaustion the identical perceived effort measured by *RPE* in both trials suggests that the participants exercised as strenuously in the heat as at the lower temperature. *TS* sensation was therefore the only contributor to the 0.8 higher P*e*SI at exhaustion in the heat. However, the P*e*SI at exhaustion in both environmental conditions was in the 7–8 zone, which denotes 'high' to 'very high strain' [24]. On the other hand, the P*h*SI reached only 6.9 at exhaustion in both trials, which is 'moderate strain', according to Moran et al. [9].

4.2. Correlation between physiological and perceptual strain

The basis of our hypothesis was an investigation into the relationship between the physiological and perceptual responses during graded exercise under hot and cool conditions. It is impractical to obtain an accurate measure of body temperature during actual firefighting activities. Therefore, firefighters' ability to sense and grade physiological strain when dressed in protective clothing should improve the margin of their safety at work, even in extreme temperatures. In our study, P*h*SI and P*e*SI increased over time at 40 and 10 °C, and the relationship between these indexes showed that there was a strong correlation, even under hot conditions (r = 0.89).

In line with our study, Gallagher et al. [25] found the same correlation (r = 0.89) between P*h*SI and P*e*SI over time (baseline, 20 min and 50 min) when they analyzed a combined data set of four different protocols under which firefighters walked on a treadmill at a temperature range of 33 to 40 °C for 50 min; two intermittent walks and two continuous walks. However, a field study by Dehghan et al. [49] found only a moderate correlation between P*h*SI and P*e*SI (r = 0.56) during firefighting work. Differently to other studies, Dehghan et al. [49] calculated P*h*SI from questionnaires, although their participants were exposed to heat, as in our study. In addition, Borg et al. [24] observed a moderate correlation (r = 0.77) between P*h*SI and P*e*SI during submaximal walks in different environmental conditions (20, 30 and 37 °C). On the other hand, Petruzzello et al. [27] found no significant correlation between P*h*SI and P*e*SI (r = 0.55) during a 15 min moderate treadmill walk in a thermoneutral laboratory when wearing protective clothing and a self-contained breathing apparatus. The inconsistent relationship between P*h*SI and P*e*SI in the current study and the above-mentioned studies may be due to different laboratory settings and sensation scales used. In our study the *RPE* 0–10 scale was used. To increase the accuracy in sensation our participants used a 20-point scale (0.5 points at each stage) when rating the effort (see methods). Other studies used an *RPE* 6–20 scale [24, 27] or *RPE* 0–10 scale [10, 25], however, sensitivity modification was not reported in these studies.

4.3. Is perceptual strain index a good estimate of physiological strain?

To the best of the authors' knowledge, this is the first study to compare the scores of the participant's P*h*SI and P*e*SI during submaximal and maximal intensities in cool and hot environmental conditions to find out whether firefighters were able to correctly estimate the P*h*SI. The physiological and perceptual scores did not differ in the two ambient conditions except at higher intensities in the heat, indicating that both indexes mostly changed in a very similar manner. However, the higher P*e*SI compared to P*h*SI in the last part of the hot trial shows that the perceptual index used may overestimate the physiological effort. One has to take into account how exercise in the heat affects the *RPE* and *TS* and a higher accuracy of perceptual indexes should therefore be developed and tested.

There are conflicting results as to the level and interpretation of the relationship between physiological and perceptual responses during exercise in the heat [10, 24, 25, 27, 28]. In line with our data, Petruzzello et al. [27] showed that P*h*SI and P*e*SI increased significantly over time and they concluded that even relatively brief bouts of exercise while career firefighters are wearing heavy impermeable clothing or in a simulated firefighting activity in the heat led to moderate to high levels of heat strain as assessed by P*h*SI and P*e*SI. However, in that study the P*e*SI was 1.6 units lower than the corresponding P*h*SI at the end of the 15 min treadmill exercise. Tikuisis et al. [10] also reported a P*e*SI score that was lower than P*h*SI for the trained participants. In that study, the participants walked slowly on a treadmill for 60 min dressed in semi-permeable protective clothing. Unlike in our study, the participants in these two studies used a nomex hood [27] or respirator [10] and the face was therefore less exposed to the heat because whereby thermal receptors in the face were covered. This may have affected the higher sensation scores in the current investigation and we are aware that we cannot ignore this limitation.

In line with our study, Gallagher et al. [25] also found P*e*SI one unit higher than P*h*SI after 20 min of four interrelated investigations of treadmill walking in a heated room while wearing thermal protective clothing. However, at exhaustion the two indexes were similar. Hostler et al. [28] also compared P*h*SI to P*e*SI when firefighters walked on a treadmill until exhaustion in 20 °C. Again, P*e*SI was approximately one unit higher than P*h*SI after 23 min of walking, and 2 units higher at exhaustion. It is worth mentioning that their participants were less aerobically fit (V_{O2max} = 43.7 ml·min·kg) than ours, as evidenced by a 23% lower V_{O2max}. Different fitness levels were suggested to affect the *RPE* and *TS* incorporated in the P*e*SI equation. On the other hand, Tikuisis et al. [10] found that less fit participants (V_{O2max} = 43.6 ml·min^{-1}·kg^{-1}) rated their physiological strain correctly. Moreover, in the study by Borg et al. [24] the mean bias between the P*h*SI and P*e*SI across the entire scale (zero to 10) was 0.8 higher for P*e*SI when fit and healthy participants walked on a treadmill in three environmental temperatures (21, 30 and 37 °C) at three different intensities (2.5, 4 and 5.5 km/t at 1% grade). In total, 66% of the P*e*SI responses correctly estimated the P*h*SI and 29% overestimated the P*h*SI. However, and in contrast to our study, at high to very high P*e*SI levels, P*e*SI was either correctly estimated (47%) or mostly underestimated (53%). In our study, 10 participants overestimated and two estimated correctly/underestimated the physiological effort at the highest submaximal step and at exhaustion. From a safety point of view, an overestimation of physiological effort should be preferred compared to underestimation, to avoid health risks during firefighting and smoke diving activities in the heat.

Current knowledge is inconsistent with respect to how participants are able to correctly estimate the physiological strain to the same thermal stimuli and exercise intensity. Differences between the current study and those of Borg et al. [24], Gallagher et al. [25], Hostler et al. [28], Petruzzello et al. [27] and Tikuisis et al. [10] may be methodological. The other studies had short-duration (< 15 min) or long-duration (> 20 min) continuous or intermittent exercise, while our long-duration exercise was graded until exhaustion in two different heat stress settings. Only the study by Borg et al. [24] used garment and equipment weight comparable to our study in different environmental temperatures, which is more comparable to the burden a firefighter carries on duty. However, in that study there was a constant submaximal workload until exhaustion during the tests and additional physiological measurements were not taken (V_{O2}, ventilation, weight loss, blood lactate measurements) to explain the physiological burden to a greater extent, especially at higher intensities.

As one means of improving safety strategies for firefighters, a graded exercise as used in the current investigation could make a useful contribution to the firefighter's ability to estimate physiological stress. However, in the current investigation the environmental temperature was only 40 °C, whereas firefighters often work in more extremes of temperatures. Under such conditions, a rise in core body temperature beyond safe limits can occur. Further research is therefore needed to determine how a broader cross-section of firefighters (gender, age, fitness level and anthropometry) might be able to subjectively convert the physiological strain more accurately in a wider range of environmental and work extremes in a laboratory as well as in field settings. In the future perceptual strain should be incorporated in international standards for the assessment of the risk of thermal strain on clothed workers in hot environments.

5. CONCLUSIONS

This study shows that heat increased the physiological and perceptual strain on firefighters performing exercise at increasing intensities to exhaustion wearing protective clothing and equipment. A strong correlation between the P*h*SI and the P*e*SI at both environmental conditions (40 °C and 10 °C) was found. Our participants were able to estimate the physiological strain as being at similar levels at both environmental temperatures until the end of the two tests. At very high intensities under hot conditions, the P*e*SI was higher than the P*h*SI, which provides a safety zone for the firefighter's physiological stress. These findings support the use of perceptual identification to evaluate cardiovascular and thermal strain.

Figure 1. Schematic presentation of the test protocol at 40 and 10 °C.

Figure 2. V_{O2}, blood lactate concentration, *HR* and *RPE* during an incremental exercise walking test on the treadmill at 10 and 40 °C until exhaustion.

Figure 3. T_{rec}, T_{skin} and *TS* during an incremental exercise walking test on the treadmill at 10 and 40 °C until exhaustion.

Figure 4. P*h*SI and P*e*SI during an incremental exercise walking test on the treadmill at 10 and 40 °C until exhaustion.

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Figure legends

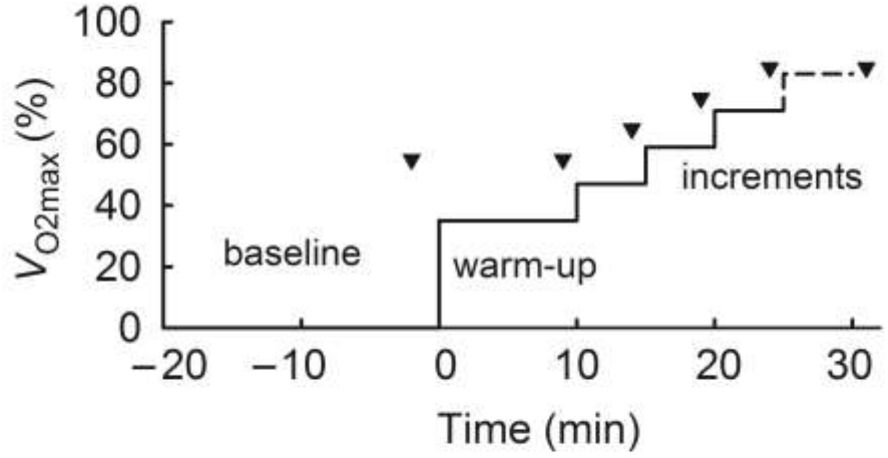
Figure 1. Schematic presentation of the test protocol at 40 and 10 °C. *Notes.* Baseline data were measured at 25 °C under resting conditions. The *y* axis represents exercise intensities. The dotted line indicates exhaustion, which occurred at different exercise intensities for each individual. The warm-up and each consecutive stage were followed by 1-minute breaks. The arrowheads (▼) denote blood lactate measurements during the 1-minute breaks. % V_{O2max} = % of maximal oxygen uptake.

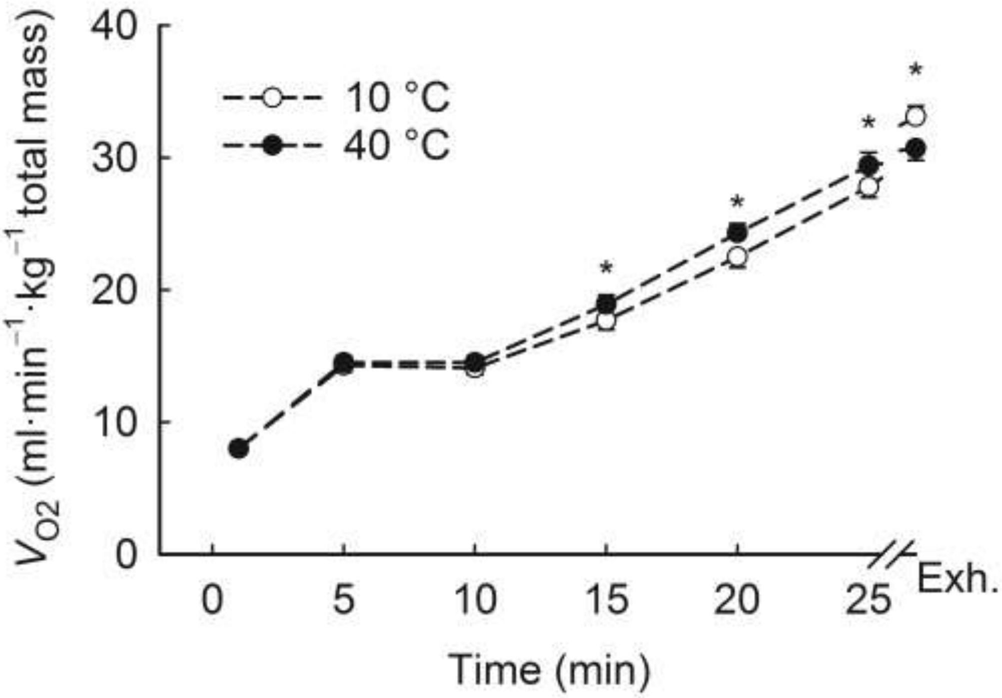
Figure 2. V_{O2}, blood lactate concentration, *HR* and *RPE* during an incremental exercise walking test on the treadmill at 10 and 40 °C until exhaustion. *Notes.* (a) V_{O2}. (b) blood lactate concentration. (c) *HR*. (d) *RPE*. The participants carried a total mass of 30 kg (protective clothing plus extra mass). The exercise intensity at 10, 15, 20 and 25 min ranged from 35 to 75% of their V_{O2max}. Error bars indicates that the participants continued walking with increasing intensity until exhaustion, which occurred at different exercise intensities for each individual. Values are *M* ± *SEM*, n = 12 for all exercise intensities except for 25 min at 40 °C (n = 10). * $p < 0.05$ for 10 vs. 40 °C. Exh. = exhaustion, V_{O2} = oxygen uptake, V_{O2max} = maximal oxygen uptake, *HR* = heart rate, *RPE* = ratings of perceived exertion.

Figure 3. T_{rec}, T_{skin} and *TS* during an incremental exercise walking test on the treadmill at 10 and 40 °C until exhaustion. (a) T_{rec}, (b)T_{skin} and (c) *TS*. The participants carried a total mass of 30 kg (protective clothing plus extra mass). The exercise intensity at 10, 15, 20 and 25 min ranged from 35 to 75% of their V_{O2max}. . Error bars indicates that the participants continued walking with increasing intensity until exhaustion, which occurred at different exercise intensities for each individual. Values are *M* ± *SEM*, n = 12 for all exercise intensities, except for 25 min at 40 °C (n = 10) * $p < 0.05$ for 10 vs. 40 °C. Exh. = exhaustion, V_{O2max} = maximal oxygen uptake, T_{rec} = rectal temperature, T_{skin} = mean skin temperature, *TS* = thermal sensation.

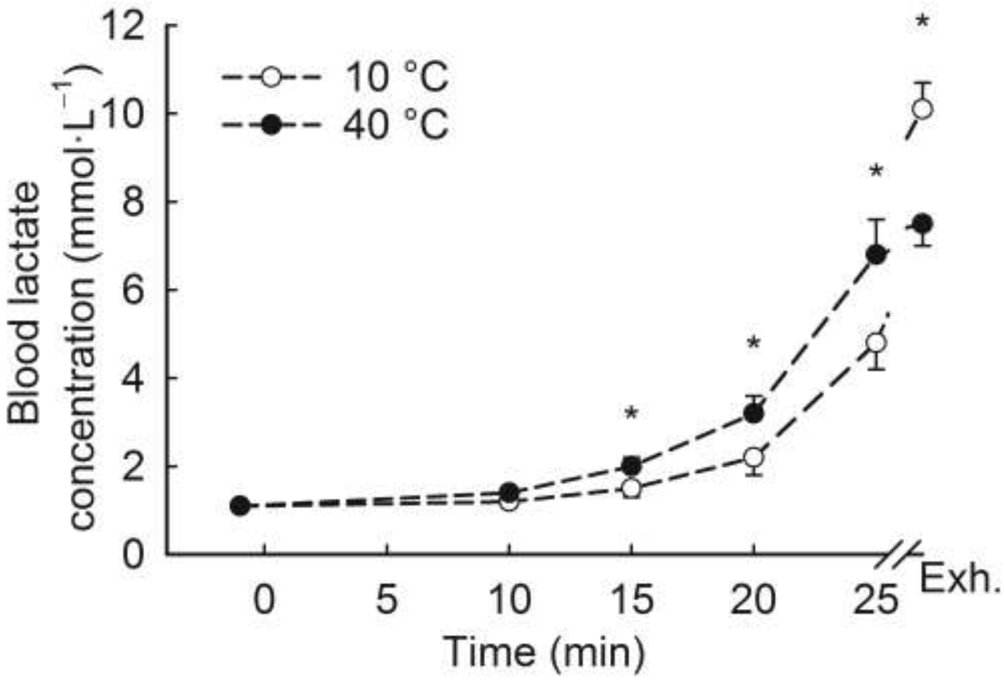
Figure 4. P*h*SI and P*e*SI during an incremental exercise walking test on the treadmill at 10 and 40 °C until exhaustion. The participants carried a total mass of 30 kg (protective clothing plus extra mass). The exercise intensity at 10, 15, 20 and

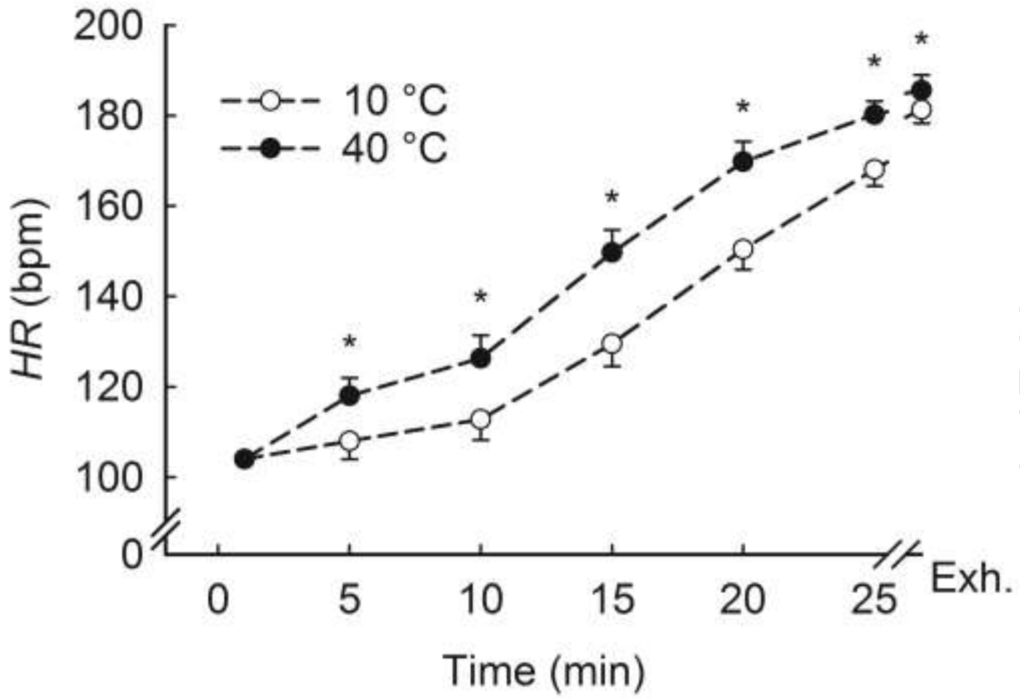
25 min ranged from 35 to 75% of their V_{O2max}. . Error bars indicates that the participants continued walking with increasing intensity until exhaustion, which occurred at different exercise intensities for each individual.Values are *M* ± *SEM*, *n* = 12 for all exercise intensities except for 25 min at 40 °C (*n* = 10). * $p < 0.05$ for P*h*SI vs P*e*SI at 40 °C. Exh. = exhaustion, V_{O2max} = maximal oxygen uptake, P*h*SI = physiological strain index, P*e*SI = perceptual strain index.


100
80
60
40
20
0
V_{O2max} (%)
baseline
warm-up
increments
−20
−10
0
10
20
30
Time (min)

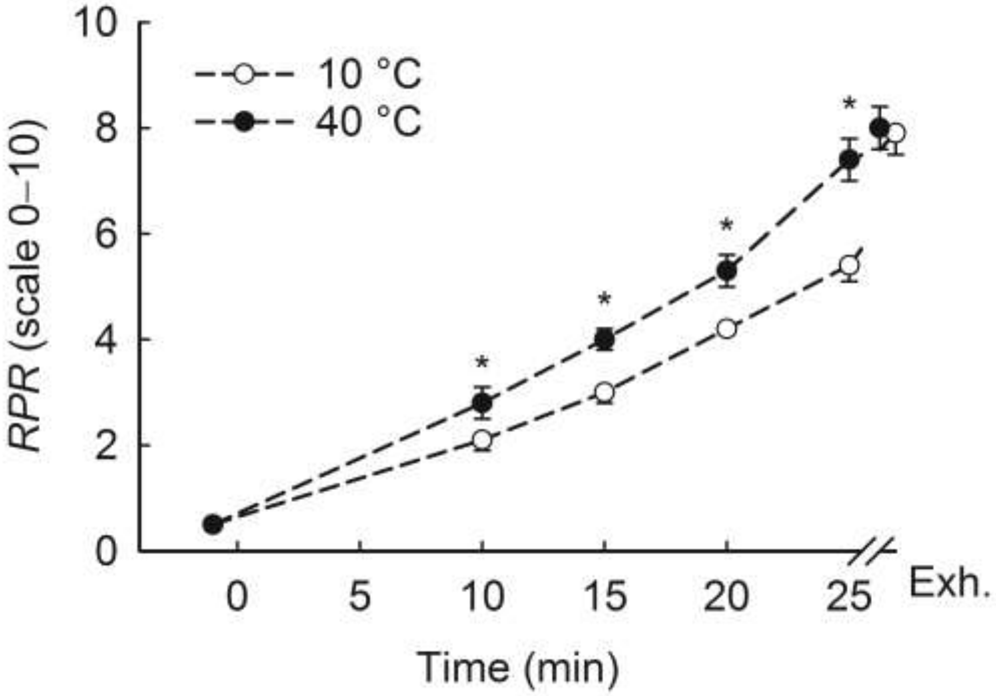


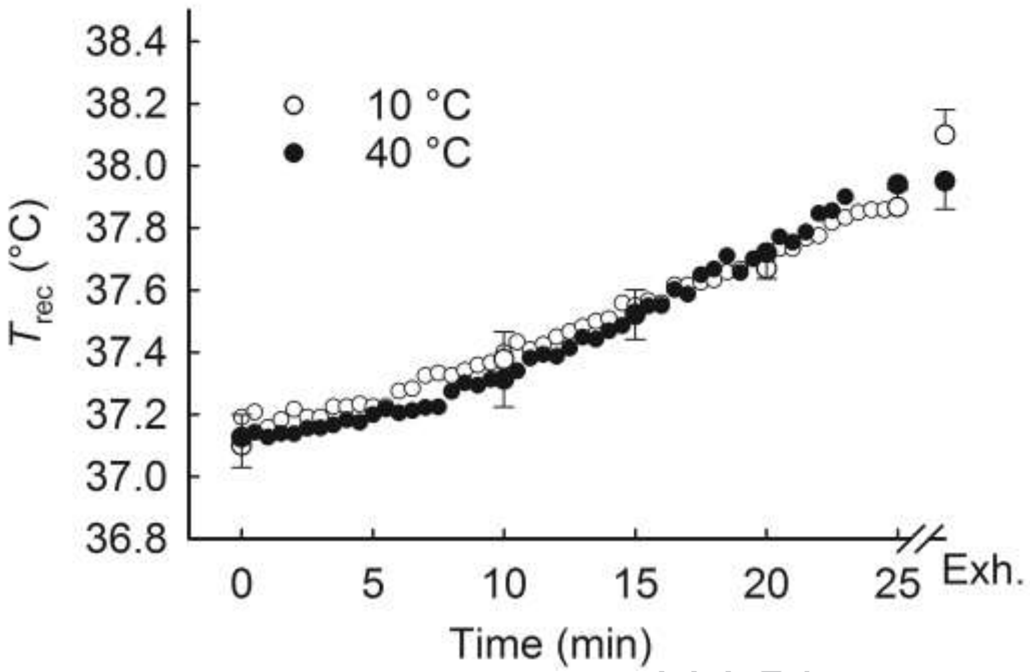
40
30
20
10
0
V_{O2} (ml·min^{-1}·kg^{-1} total mass)
10 °C
40 °C
*
0
5
10
15
20
25
Exh.
Time (min)

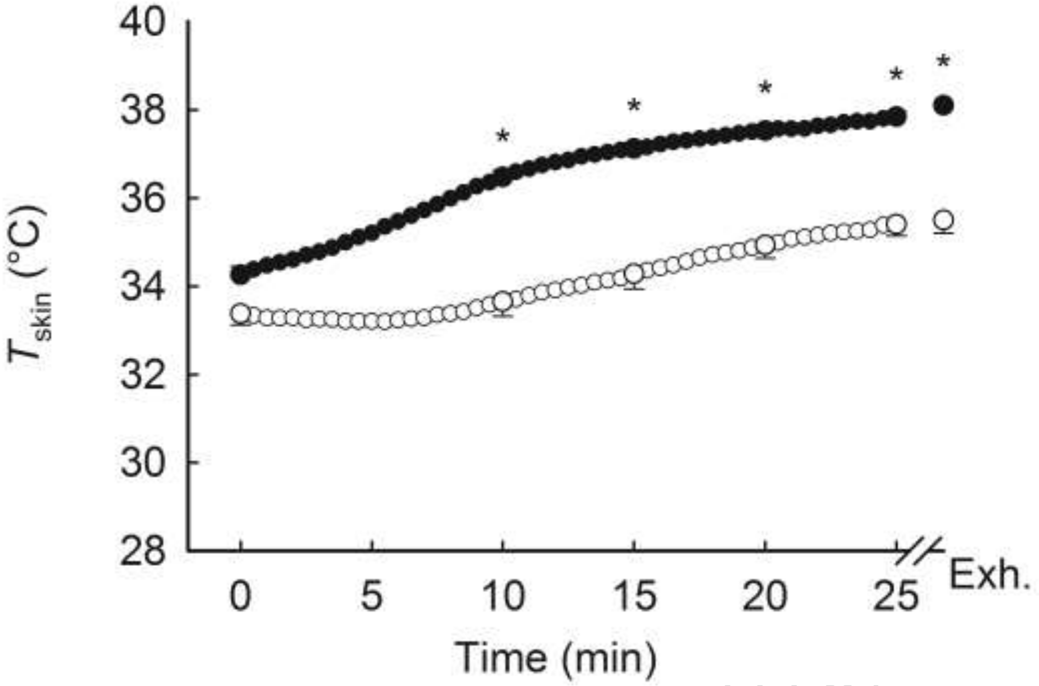

Blood lactate
concentration (mmol·L⁻¹)
12
10
8
6
4
2
0
10 °C
40 °C
*
*
*
*
*
0
5
10
15
20
25
Exh.
Time (min)



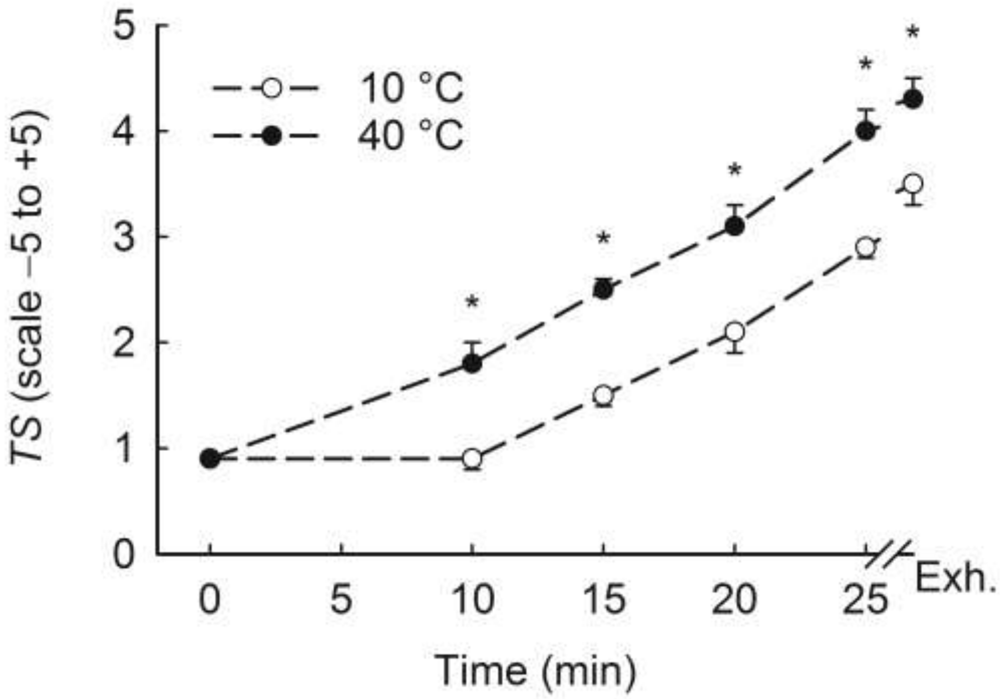
10 °C
40 °C
HR (bpm)
200
180
160
140
120
100
0
*
0
5
10
15
20
25
Exh.
Time (min)


10 °C
40 °C
RPR (scale 0–10)
Time (min)
Exh.
0
2
4
6
8
10
0
5
10
15
20
25
*
*
*
*

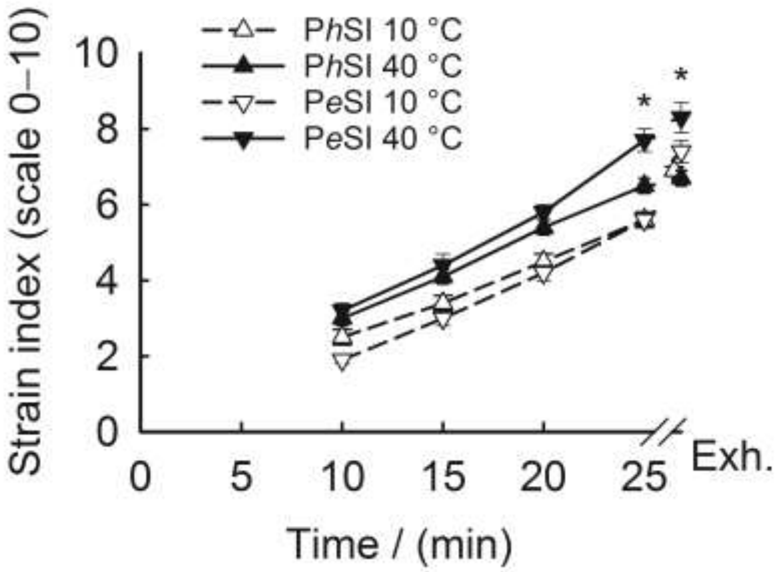

38.4
38.2
38.0
37.8
37.6
37.4
37.2
37.0
36.8
T_{rec} (°C)
10 °C
40 °C
0
5
10
15
20
25
Exh.
Time (min)



40
38
36
34
32
30
28
T_{skin} (°C)
0
5
10
15
20
25
Exh.
Time (min)



5
4
3
2
1
0
TS (scale −5 to +5)
10 °C
40 °C
*
0
5
10
15
20
25
Exh.
Time (min)


PhSI 10 °C
PhSI 40 °C
PeSI 10 °C
PeSI 40 °C
Strain index (scale 0–10)
10
8
6
4
2
0
*
*
0
5
10
15
20
25
Exh.
Time / (min)