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Perception or reality: Can thermal perceptions inform management of firefighters in the heat?

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ABSTRACT

Accurately assessing the physiological status of firefighters during work in the heat is critical to ensuring their safety. Evaluating core temperatures (T_c) in the field is problematic due to cost and limitations in technology and accuracy. As such, fire services rely on individual perceptions of wellbeing. The present study aimed to establish whether perceptual responses measured using the perceptual strain index (PeSI), calculated from rate of perceived exertion (RPE) and thermal sensation (TS), could reliably predict the physiological strain (PSI) encountered by experienced firefighters working in a hot environment. We conducted two firefighting simulations (set-pace and self-paced) in a purposefully built heat chamber (100 ± 5°C) comprised of two 20-min periods separated by a 10-min recovery outside the chamber. Physiological strain was measured via heart rate (HR) and gastrointestinal temperature (T_{gi}) and compared with PeSI at 5-min intervals. To evaluate the predictive ability of the PeSI for PSI, mean differences and the 95% limits of agreement (LOA) were established, along with correlation coefficients at each 5-min interval. Moderately significant correlations occurred in the second work bout of the self-paced trial only (10 min: $r = 0.335$, 15 min: $r = 0.498$, 20 min $r = 0.439$) with no other correlations observed at any other time during either trial or during the rest periods. Bland-Altman analysis revealed mean differences of −0.74 ± 2.70 (self-paced) and +0.04 ± 2.04 (set-paced) between PeSI and PSI with the 95% LOA being −4.77 to 3.28 (self-paced) and −4.01 to 2.01 (set-paced). The wide LOA and lack of correlations observed between perceptual and physiological strain in both self-paced and set-paced work trials indicate that PeSI is not sufficiently reliable as a sole measure of wellbeing for firefighters working in the heat. Hence, we recommend that fire services prioritise the development of reliable and effective monitoring tools for use in the field.

KEYWORDS
Heat stress; perceptual strain index; physiological strain index; safety

Introduction

Firefighters are regularly exposed to high levels of ambient and radiant heat while wearing specialized personal protective clothing (PPC) and self-contained breathing apparatus (SCBA). Wearing PPC and SCBA, while crucial to ensuring firefighter safety, adds to the thermal burden of the operating environment in two ways: by increasing physical load and consequent metabolic heat production, as well as limiting evaporative sweat loss to dissipate body heat. The resultant elevated core (T_c) and skin temperatures (T_{sk}) increase the risk of firefighters suffering premature fatigue and heat-related illness.[1,2] Furthermore, the strain resulting from elevated T_c may be contributing to the likelihood of a cardiac event, the leading cause of mortality and morbidity in urban firefighters.[3,4] Accurately evaluating the risk of fatigue resulting from elevated T_c would contribute to the management of firefighters at work. However, significant logistical issues exist to monitoring T_c in the field.

To mitigate the impact of elevated T_c on firefighter safety and operational readiness, a wide variety of cooling methods have been evaluated for use during, or at the conclusion of, emergency responses.[5] Despite research in the area, there is limited information to objectively determine when such cooling should be employed. An obvious goal is to adhere to the National Fire Protection Association (NFPA) 1584 and the ISO9886, that recommend T_c not exceed 38.5°C.[6,7] However, monitoring T_c during firefighting operations is rarely undertaken due to questionable accuracy of tympanic thermometry[8] and logistical and ethical issues associated with valid measurements from the rectum and oesophageal tract. Ingestible

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thermometers, that measure temperature from the gastrointestinal tract (T_{gi}), are considered a valid measure of T_c during ambulatory work,[9] and they possibly provide a practical solution to measuring T_c in the field. However, these thermometers represent a significant cost for fire services as well as technical limitations given that ingestion is required up to 6 hr prior to use[10] generally making their adoption as a prophylactic tool inappropriate. These limitations do not diminish the responsibility of fire services to ensure the safety and operational readiness of firefighters and, as a result, the development and provision of a monitoring protocol that is reliable and simple to use should be a priority.

In the absence of reliable, objective measures of body temperatures during emergency responses, fire services typically rely on informal perceptual assessment of firefighters based on their perceptions to determine readiness for operational re-entry. Tools used to complement physiological monitoring of athletes, such as the validated subjective scales, rating of perceived exertion (RPE),[11] and thermal sensation (TS)[12] could be used to more formally assess the perceived state of firefighters should they be sufficiently reliable. The RPE scale provides a means of assessing subjective intensity during exercise or work, acting as a surrogate of HR, whereas TS is the subjective integration of input from deep tissue and skin temperatures, and may be indicative of T_c. In order to standardize the interpretation of RPE and TS, a perceptual strain index (PeSI)[13] was developed and validated in endurance athletes as an analogue for the physiological strain index (PSI), a measure that combines T_c and HR in order to quantify heat stress.[14] Preliminary evidence suggests that the PeSI may be useful for monitoring firefighters, as a strong relationship has been identified with the PSI during exercise wearing PPC in laboratory studies.[15,16] Specifically, Borg et al.[15] reported that the PeSI generally correctly or conservatively estimated the PSI and that the measures were significantly correlated. The authors therefore concluded that the PeSI provides a good estimation of the PSI when wearing encapsulating PPC.

Previous studies, including the one conducted by Borg et al.[15] evaluating the validity of perceptual responses, have generally been conducted on participants with limited PPC familiarity undertaking set paced exercise in a laboratory. Pacing during emergency events can be dictated by operational needs and tempo, potentially negating the application of fixed paced research to operational settings. Furthermore, the PeSI is yet to be tested with experienced firefighters exposed to extreme temperatures at a self-determined pace. As a result, this study will present both a set-paced, and self-paced trial to evaluate PeSI in both conditions using experienced professional firefighters with a rest period between work bouts.

Since firefighters doff some of their PPC to cool during rest breaks, it is possible that the rapid T_{sk} decrease post exercise will result in a commensurate decrease of perceived strain[17] despite body temperatures remaining elevated.[18] This potential uncoupling of individual perceptions and actual body temperatures during rest periods may limit the applicability of the PeSI to firefighter settings. Thus, the present study used the physiological and perceptual responses of professional urban firefighters in a hot environment to compare the ability of the PeSI to predict the PSI. We hypothesized that during work periods the predictive ability of the PeSI for PSI would be similar to that reported for laboratory studies. However, the incorporation of a rest period, reflecting real world settings, would likely influence the PeSi/PSI relationship due to a rapid T_{sk} decline as they exit the hot environment and remove their PPC. These hypotheses were tested across two studies: a self-paced one and also a set-paced one using similar protocols. Results from this study will inform incident controllers of the potential use of perceptual responses as tools for the evaluation of individual risk of heat stress in firefighters during emergency work.

Methods

Participants

Two groups of professional male firefighters were recruited from an Australian fire service (Study 1, n = 39 and Study 2, n = 20) (Table 1). Height was measured to the nearest 0.1 cm using a wall-mounted stadiometer (Seca, Hamburg, Germany) and weight to the nearest 0.1 kg with electronic scales (Seca, Hamburg, Germany). Body composition was assessed by Dual Energy X-Ray Analysis (DXA) using a narrow fan beam (4.5°) (GE Healthcare, UK) following an overnight fast. Informed written consent was obtained from all participants based on protocols approved by the University of Canberra Human Ethics Research Committee.

Study design

For both studies, participants completed two 20-min simulated work tasks in a purpose built heat chamber set at 100 ± 5°C as previously described.[19] The heat in

Table 1. Demographics and morphometrics of participants (mean ± SD).

	Study 1 (n = 39)	Study 2 (n = 20)
Age (years)	36.4 ± 8.4	39.2 ± 9.5
Height (metres)	1.79 ± 0.10	1.80 ± 0.07
Weight (kg)	83.8 ± 7.8	86.3 ± 8.7
Body Fat (%)	19.6 ± 6.0	20.3 ± 7.2
Body Surface area (m^{-2})	2.09 ± 0.14	2.02 ± 0.14

the chamber was provided by gas burners located on the ceiling, which also produced significant radiant heat. This temperature was chosen to represent the minimum thermal limit of a hazardous firefighting environment.[20] Participants wore structural firefighting PPC (Stewart and Heaton, Belmont, WA) and an SCBA (Scott Contour 300, Scott Safety Australia, Sydney NSW) weighing ∼22 kg. Work periods were separated by a 10-mine passive recovery outside the chamber (Study 1: 19.3 ± 2.7°C, Study 2: 13.5 ± 2.4°C) where participants removed their jackets, gloves and helmet, changed their SCBA cylinders and consumed 600 mL of water from sealed bottles stored at room temperature. Humidity was not recorded during testing, although average humidity for the area during similar times of the year has historically been between 71% at 0900 and 42% at 1500.[21] Participants exited the chamber briefly (<20 sec) at 10, 15, and 20 min for assessment of T_{gi}, TS, and RPE.

In Study 1, participants negotiated a multi-room facility filled with smoke and in darkness, to locate a cache of foam drums (∼20 kg) and return them individually to the starting location. Participants worked in pairs as per the fire service's standard operating procedures and conducted their search using pre-established techniques, which involved periods of crawling and climbing. Participants self-paced their efforts during the simulated search and rescue task.

In Study 2, participants negotiated the same multi-room facility carrying a foam drum (∼20 kg). However, unlike Study 1, there was no smoke and light was provided by torches issued by the fire service, worn on the chest of participants. Participants completed a standardised work protocol involving one circuit (∼14 m) of the hot facility every 30 sec.

Materials

Gastrointestinal temperatures (T_{gi}) for both studies were assessed at 5-min intervals following an initial 10-min period using an ingestible thermometer and radio receiver (HQ Inc, Palmetto, FL). The thermometer was swallowed at least 6 hr prior to testing to minimise the possible confounding influence of food or fluid.[1] Participants were excluded from T_{gi} analysis when baseline temperatures were ≤35.5°C or decreased by 2°C in any 5-min period to reduce the potential for dietary confounders to influence the results. Baseline T_{gi} was assessed with participants fully dressed and immediately prior to entry to the heat chamber.

The heart rate (HR) of participants were continuously monitored using a Suunto Memory belt (Suunto, Vaanta, Finland) and reported in beats per minute (bpm). Baseline HR was assessed at a single time point, immediately prior to entry to the heat cell with participants fully dressed and "on air."

Calculation of strain indices

Borg's rating of perceived exertion (RPE) was measured using a 14-point scale of 6 (very, very light) to 20 (very, very hard).[11] Participants were asked, "how hard are you working?" and responded by pointing to a number on a chart presented to them by researchers. Similarly, thermal sensation was measured using a 16-point scale of 0.0 (unbearably cold) to 8.0 (unbearably hot).[12] Participants were asked, "how do you feel?" and similarly responded by pointing to a number on a chart. The PSI was modified to include measurements exceeding the thresholds proposed by Moran et al.,[22] (T_{gi} >39.5 and HR >180 bpm) based on the equation:

$$PSI = 5\left(T_{git} - T_{gi0}\right) \times \left(T_{gimax} - T_{gi0}\right) + 5\left(HR_t - HR_0\right) \times \left(HR_{max} - HR_0\right),$$

whereT_{gi0} and HR_0 are the baseline T_{gi} and HR, respectively, and T_{git} and HR_t represent the T_{gi} and HR at a particular time point.

The modified perceptual strain index (PeSI) was calculated based on Tikusisis'[13] 0–10 scale. To calculate, RPE and TS were transformed at each time point using the equation:

$$PeSI = 5\left(\frac{(TS-4)}{4}\right) + 5\left(\frac{(RPE-6)}{14}\right).$$

Statistical analysis

Statistical analyses were performed in SPSS v.24 (SPSS, Inc., Chicago, IL). Results are presented as Mean ± SD. A repeated measure analysis of variance (ANOVA) was conducted to determine differences between time points for T_{gi} and HR. Post hoc tests were conducted using a Bonferroni adjustment with the alpha level set at $p \leq 0.05$ with 95% confidence intervals (CI) also reported.

A number of different statistical analyses were conducted to establish the relationship between the PSI and the PeSI. In the first instance, a Spearman's correlation was conducted for the PeSI responses compared with PSI results to establish associations at each time point. Correlations were reported as being small (0.10), moderate (0.30), or large (0.50).[23] Second, the mean difference (MD) and the limits of agreement (LOA) were calculated across the 0–10 scales. To account for the repeat measures for each participant, the limits of agreement were calculated using a modified standard deviation (SD) according to Bland and Altman:[24]

$$Modified\ SD = \sqrt{\frac{\left(\sum m_i\right)^2 - \sum m_i{}^2}{(n-1)\sum m_i}}.$$

In the equation, m_i is the number of observations on a participant and n is the number of participants. The limits of agreement were then calculated as MD ± 1.96* modified SD.[24] From this, a 95% confidence interval (CI) was derived between the two measures. If the CI is narrower than a pre-determined cut-off, then the two measures are said to be interchangeable. The cut-off is determined based on what is being measured; for this article, a difference of less than 2 was considered an acceptable limit of agreement.

Results

A timeline of the PeSI and PSI responses during both self-paced and the standardized work protocol are presented in Figure 1. In Study 1, moderate correlations (Table 2) between the PeSI and PSI were observed in the second search and rescue period. No other significant correlations were observed during the testing period. In Study 2, no significant correlations (Table 2) were observed between the modified PeSI and PSI at any time point during the testing period.

The Bland Altman analysis (Figure 2) of modified PeSI and the PSI resulted in a mean difference in Study 1 *of* −0.74 ± 2.70 and the modified 95% LOA ranged from −4.77 to 3.28. In Study 2, there was a mean difference of +0.04 ± 2.04 and the modified 95% LOA ranged from −4.01 to 2.01.

Discussion

Despite the PeSI being validated as an analogue of the PSI in endurance athletes, the key finding of this study was that PeSI shows poor agreement with PSI during both self-paced and set-paced firefighting tasks in the heat, with the 95% LOA well outside the pre-determined cut-off of two units. This study is unique in that, to our knowledge, it represents the first examination of the PeSI in both a self-paced and also a set-pace simulation involving a rest period between work cycles, using experienced firefighters, to mimic actual fire scenes. Despite moderate correlations observed between the PSI and the PeSI in the later stages of the self-paced study (Study 1), the relationship appears limited during the earlier stages of an emergency incident, and also during rest periods where firefighters remove clothing as they rest and rehydrate (Figure 1). Furthermore, possibly due to lower levels of thermal strain in the set-pace study (Study 2), no significant correlation was established at any time point. As a result, we cannot recommend that the PeSI be used as a surrogate of physiological monitoring during emergency responses in the heat.

Similar T_{gi} values to the current study have been achieved during treadmill walking while wearing firefighting PPE[16] and also a fully encapsulated explosive ordinance disposal ensemble,[15] both in laboratory-based experiments. However, unlike our study where participants were all experienced professionals, participants in both Gallagher et al.[16] and Borg et al.[15] were not. Professional firefighters are ideal research participants for evaluating the validity of field-based measures, as they possess greater experience wearing PPC and working in the heat. Thus, their perception of RPE and TS likely

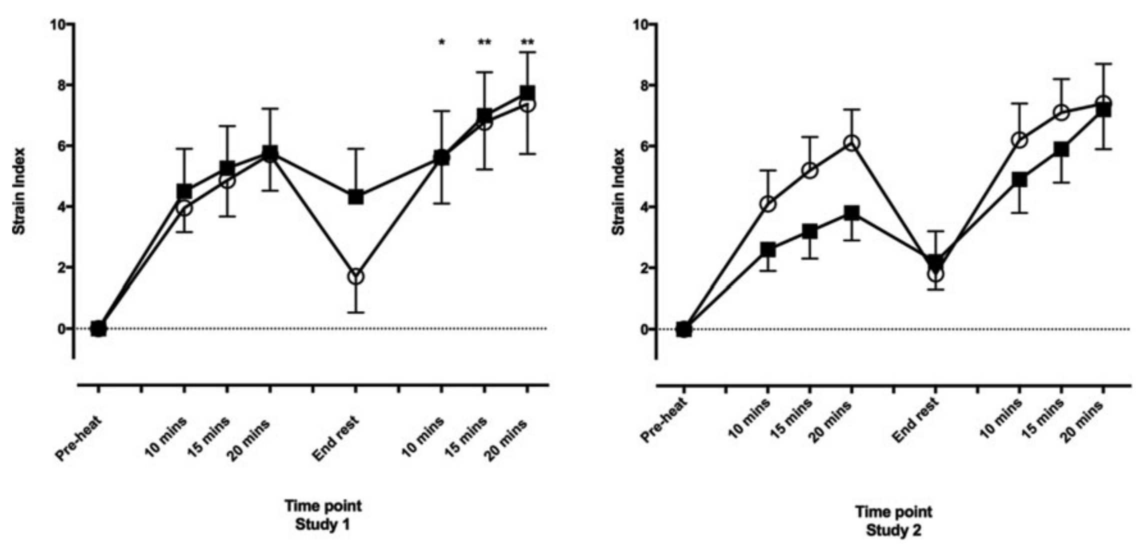

Figure 1. Perceptual Strain Index (PeSI) and the physiological strain index (PSI) at 5-min intervals following an initial 10-min search. * represents a significant correlation between PeSI and PSI at $p < 0.05$ and **represents a significant correlation between PeSI and PSI at $p < 0.01$ (mean ± SD).

Table 2. Spearman's rho correlation of the modified PeSI and PSI across testing periods for Study 1 and Study 2.

	1st Work Period				2nd Work Period		
Time point	10 min	15 min	20 min	Post - rest	10 min	15 min	End of testing
Study 1	0.280 $p = 0.088$	0.257 $p = 0.114$	0.148 $p = 0.367$	0.145 $p = 0.378$	0.335[a] $p = 0.037$	0.498[b] $p = 0.001$	0.459[b] $p = 0.004$
Study 2	0.235 $p = 0.319$	0.145 $p = 0.543$	0.058 $p = 0.807$	0.108 $p = 0.652$	0.335 $p = 0.125$	0.418 $p = 0.066$	0.062 $p = 0.796$

Note. Significant correlations are marked with [a]for $p < 0.05$ and [b]for $p < 0.01$.

varies to that of non-firefighters,[17] confounding the relationship between PeSI and PSI previously observed in untrained subjects. Furthermore, the ambient temperatures in both studies were substantially lower than in our study (≤48°C compared with ~100°C) and do not mimic what can be encountered during structural fires.[20] Lastly, the present investigation included two work bouts separated by a rest period, representing work and rest procedures adopted in most firefighting jurisdictions, as opposed to one work bout. Hence, the experimental procedures of the present study represent greatest validity for application to the fire ground compared with previous research studies.

The presence of high ambient temperatures and radiant heat in our study likely means that T_{sk} would be higher and more reflective of real-world firefighting conditions[20] than those presented by Gallagher et al.[16] and Borg et al.[15] Furthermore, Borg et al.[15] provided air movement which may have facilitated a lower T_{sk} to T_c gradient, thereby altering the perceptual responses of participants. Skin temperatures have previously been associated with perceived effort[25] and thermal sensation,[26] and therefore any differences between previous studies and ours may be attributed to higher T_{sk}.

The present study indicates that while demonstrating some potential for assessing the wellbeing of firefighters in the self-paced study during later work phases, in the absence of formal physiological monitoring protocols, incident controllers are unlikely to be able to accurately assess the wellbeing of firefighters based upon their perceptions of wellness during rest phases. Our previous work saw T_{sk} decrease rapidly when PPC was doffed during a rest period and the results of both studies presented indicate that during rest periods, perceptions of wellbeing are likely linked to reduced T_{sk} as firefighters remove their PPC, despite T_c continuing to rise.[17,19] This is an important distinction, as rest phases provide an ideal opportunity to assess and rehabilitate firefighters for subsequent work phases. Thus, if fire services persist in using perception based monitoring alone, it must occur immediately upon exiting or during fire suppression tasks when the PeSI is more closely correlated with the PSI and less affected by changes in T_{sk} arising from changing exposure to a cooler environment.

While the PeSI has some merit as a heat stress risk screening tool when firefighters are at elevated levels of thermal strain, the poor agreement between PeSI and PSI during both self-paced and controlled firefighting simulations prevent the endorsement of PeSI for use with firefighters during emergency responses. As accurate physiological assessment on the fire ground remains largely elusive, fire services should prioritise the development of accurate, cost-effective, and easily deployable tools to

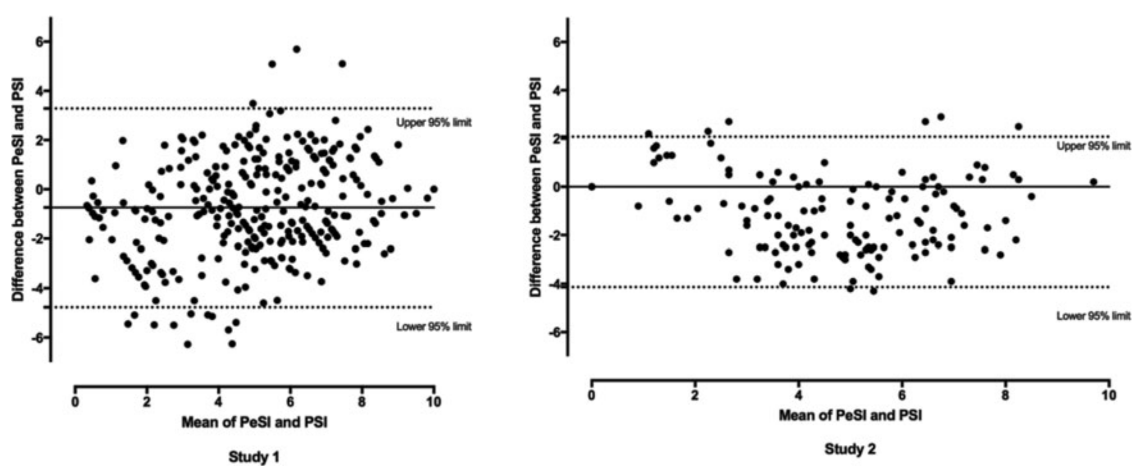

Figure 2. Bland and Altman plot of the modified perceptual strain index (PeSI) and the physiological strain index (PSI) across all time points for Study 1 and Study 2. Solid line represents the mean difference, dashed lines represent the upper and lower 95% limits of agreement.

measure the physiological strain of firefighters engaged in work tasks in the heat.

Conclusion

Due to only moderate correlations at best, we cannot recommend that the PeSI replace the need for proper medical supervision of firefighters during long duration emergency events. However, given that at this point we cannot accurately and easily assess T_c on the fire ground, we acknowledge that the PeSI may play a part of an overall monitoring package for use during the later stages of protracted emergency events in the heat. Caution must be used by incident controllers as part of an overall risk assessment when deciding on the appropriateness of re-entry to fire scenes based on individual perceptions of wellness particularly following a rest period where removing PPC may confound the responses given by firefighters.

Recommendations

Fire services must prioritize the development of practical and easily implemented formal monitoring tools to accurately evaluate the wellbeing of firefighters prior to re-entry to fire scenes.

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