

## **Perceived exertion is as effective as the perceptual strain index in predicting physiological strain when wearing personal protective clothing**

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### **Competing interests**

The authors have no conflict of interests to declare.

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**Highlights**

- Individuals operating in chemical/biological protective garments are likely to experience high levels of physiological strain
- Non-invasive and practical methods of predicting physiological strain are needed.
- Thermal comfort does not improve the ability of the perceptual strain index to predict physiological strain
- Rating of perceived exertion provided an accurate prediction of physiological strain under these work conditions

## ABSTRACT

**Objective:** The perceptual strain index (PeSI) has been shown to overcome the limitations associated with the assessment of the physiological strain index (PSI), primarily the need to obtain a core body temperature measurement. The PeSI uses the subjective scales of thermal sensation and perceived exertion (RPE) to provide surrogate measures of core temperature and heart rate, respectively. Unfortunately, thermal sensation has shown large variability in providing an estimation of core body temperature. Therefore, the primary aim of this study was to determine if thermal comfort improved the ability of the PeSI to predict the PSI during exertional-heat stress. **Methods:** Eighteen healthy males (age: 23.5 years; body mass: 79.4 kg; maximal aerobic capacity: 57.2 ml·kg<sup>-1</sup>·min<sup>-1</sup>) wore four different chemical/biological protective garments while walking on treadmill at a low (<325 W) or moderate (326–499 W) metabolic workload in environmental conditions equivalent to wet bulb globe temperatures 21, 30 or 37 °C. Trials were terminated when heart rate exceeded 90% of maximum, when core body temperature reached 39 °C, at 120 min or due to volitional fatigue. Core body temperature, heart rate, thermal sensation, thermal comfort and RPE were recorded at 15 min intervals and at termination. Multiple statistical methods were used to determine the most accurate perceptual predictor. **Results:** Significant moderate relationships were observed between the PeSI ( $r = 0.74$ ;  $p < 0.001$ ), the modified PeSI ( $r = 0.73$ ;  $p < 0.001$ ) and unexpectedly RPE ( $r = 0.71$ ;  $p < 0.001$ ) with the PSI, respectively. The PeSI (mean bias:  $-0.8 \pm 1.5$  based on a 0–10 scale; area under the curve: 0.887), modified PeSI (mean bias:  $-0.5 \pm 1.4$  based on 0–10 scale; area under the curve: 0.886) and RPE (mean bias:  $-0.7 \pm 1.4$  based on a 0–10 scale; area under the curve: 0.883) displayed similar predictive performance when participants experienced high-to-very high levels of physiological strain. **Conclusions:** Modifying the PeSI did not improve the subjective prediction of physiological strain. However, RPE provided an equally accurate prediction of physiological strain, particularly when high-to-very high levels of strain were observed. Therefore, given its predictive performance and user-friendliness, the evidence suggests that RPE in isolation is a practical and cost-effective tool able to estimate physiological strain during exertional-heat stress under these work conditions.

**Key words:** *Subjective indices, psychophysiological measures, thermoregulation, thermal behaviour, perceived exertion*

## 1. Introduction

Efforts to quantify an individual's health risk during situations of exertional-heat stress have led to the development of more than 100 heat stress indices [1]. Despite this, deriving a heat stress index that is accurate yet universally applicable has proved challenging [2]. The physiological strain index (PSI) developed by Moran et al. [3] is arguably the most common index used to monitor and assess the effects of heat stress in industrial, military and research settings. The PSI assigns equal weight to normalised increases in core body temperature ( $T_C$ ) and heart rate (HR), reflecting the thermoregulatory and cardiovascular strain experienced by an individual [3]. The index sums strain as a single arbitrary value on a 0 (no strain) to 10 (very-high strain) scale [3]. Unfortunately, the application of the PSI in some circumstances has proved difficult, specifically when the acquisition of physiological measures (i.e.,  $T_C$  and HR) is not practical or possible. This may be due to interference from the ambient environment (e.g., inaccuracy of tympanic temperature in hot environments) [4, 5], inaccessible measurement sites (rectal, tympanic, oesophageal) [4], associated stigma or invasiveness of some measures (rectal, oesophageal) and/or the considerable expense of some technologies (ingestible pill).

Modelled on the PSI, the perceptual strain index (PeSI) has been shown to overcome these limitations, with the subjective scales of thermal sensation and rating of perceived exertion (RPE) providing surrogate measures of  $T_C$  and HR, respectively [6]. We have previously shown that the PeSI shares a moderate relationship ( $r = 0.77$ ;  $p < 0.001$ ) with the PSI when wearing heavy (~34 kg) personal protective clothing across a range of environments and metabolic workloads [7]. Several other studies have demonstrated the ability of the user-friendly PeSI to predict physiological strain across clothing types [6, 8-10], operational scenarios [8, 9, 11] and in the field [10, 12]. Further, the PeSI has shown the capacity to differentiate strain between activity [8] and fitness [6] levels. Fundamental to the PeSI is the ability of thermal sensation to provide an accurate subjective prediction of  $T_C$ . However, several investigations [7, 9, 13, 14] have observed relationships ranging from  $r = 0.28$  to  $0.72$  between these interrelated variables; weaker when compared to that shared by RPE and HR (ranging from  $r = 0.81$  to  $0.92$ ) [7, 9]. Further, Savage et al. [15] have shown thermal sensation to be a highly variable and overall a poor predictor of  $T_C$  when used during a simulated fire suppression activity across a range of temperatures and particularly when individuals experienced their highest  $T_C$ 's. Consequently, the variation in the ability of thermal sensation to predict  $T_C$  may explain the disparity observed between the PeSI and the PSI.

Thermal comfort may offer a more accurate alternative to thermal sensation when measuring an individual's perceptions of their surrounding environment [16, 17]. By definition, thermal sensation refers to the relative intensity of the temperature being sensed (e.g., warm), whereas thermal comfort is the expression of satisfaction with that temperature (e.g., comfortable) [16, 17]. Although linked, these thermal indices are inherently different, with a

particular rating of thermal comfort not strictly associated with a given level of thermal sensation and vice-versa [18, 19]. Changes in  $T_c$  have been reported to be the dominant driver of thermal comfort [20]; however, others [21, 22] have demonstrated that changes in skin temperature modulate ratings of thermal comfort. Accordingly, the sensation of thermal comfort, or rather discomfort is thought to provide the early drive for the initiation of a conscious action (e.g., the addition or removal of clothing) to maintain thermoregulatory homeostasis [23]. Consequently, thermal comfort may provide an equal, if not more accurate moment-to-moment relative indicator of perceived thermoregulatory strain and therefore improve the effectiveness of the PeSI.

Improving the ability of the PeSI to predict physiological strain would enhance the monitoring, management and safety of individuals operating in thermally stressful situations. For example, during hazardous material (HAZMAT) handling, where personnel are required to dress in light weight (<5 kg) chemical/biological protective garments, potentially with a self-contained breathing apparatus (SCBA; ~12 kg), while completing low-intensity physical tasks for prolonged periods of time. These garments impair avenues for heat loss creating a situation of uncompensable heat stress, particularly in hot environments and consequently inducing considerable thermoregulatory and cardiovascular strain [24].

Previously, we have demonstrated that the PeSI is capable of predicting the PSI during relatively short ( $\leq 60$  min) bouts of exercise when wearing heavy protective clothing (~34 kg) where the majority of participants were limited by cardiovascular strain [7]. Therefore, the primary aims of this study were to: (1) determine if thermal comfort improved the ability of the PeSI to predict the PSI when wearing HAZMAT protective clothing; and (2) examine whether the PeSI and a modified PeSI maintain their predictive accuracy during longer duration (up to 120 min) exercise bouts where participants are predominately limited by thermoregulatory strain. It was hypothesised that a modified PeSI would provide a more accurate prediction of the PSI compared to the PeSI.

## 2. Methods

### 2.1 Participants

Eighteen young and healthy males volunteered for this study [age:  $23.5 \pm 2.5$  (range: 20.6–30.0) years; height:  $178.4 \pm 5.1$  (166.4–186.3) cm; body mass:  $79.4 \pm 8.5$  (64.8–94.1) kg; sum of eight-site skinfold thickness:  $83.8 \pm 29.5$  (49.6–150.8) mm; body surface area [25]:  $2.0 \pm 0.1$  (1.7–2.2) m<sup>2</sup>; maximal aerobic capacity:  $57.2 \pm 4.4$  (49.6–66.0) ml·kg<sup>-1</sup>·min<sup>-1</sup>; maximal HR:  $194 \pm 10$  (179–207) b·min<sup>-1</sup>]. Prior to testing, participants provided written informed consent and completed a medical history questionnaire. All experimental procedures were

approved by the university human research ethics committee at the Queensland University of Technology.

## 2.2 Protective Garments

During trials, participants wore one of the following biological/chemical ensembles:

(1) The National Fire and Protection Association (NFPA) 1994 Class 3 Emergency Response Suit (ERS; Lion Apparel, Dayton, Ohio, USA) chemical/biological protective garment made from a three-layer protective fabric consisting of a selectively permeable barrier film laminated between outer and inner textiles. The ERS consists of a one-piece fully encapsulating hooded jump suit, including outer gloves and booties (1.35 kg) and a respirator and canister (0.70 kg; Promask with a pro 2000 PF10 filter; Scott Safety, Lancashire, England) with a combined ensemble weight of 2.05 kg.

(2) The NFPA 1994 Class 3 Chemical/Biological Protective Clothing System (CPCS; Lion Apparel, Dayton, Ohio, USA) consisting of a jacket, trousers, a hood, booties and inner and outer gloves (1.40 kg) worn underneath a Nomex<sup>®</sup> Flight Suit (0.85 kg; Lion Apparel, Dayton, Ohio, USA) and with a respirator and canister (0.70 kg; as above). This ensemble had a combined weight of 2.95 kg.

(3) The air-permeable, charcoal impregnated Saratoga<sup>™</sup> Hammer Suit (Tex-Shield, Washington, DC, USA), a two-piece garment consisting of a hooded coat and trousers, socks and gloves (3.45 kg) and a respirator and canister (0.70kg; as above). The ensemble had a combined weight of 4.15 kg.

(4) The NFPA 1994 Class 2 Improved Chemical Garment (ICG; Lion Apparel, Dayton, Ohio, USA), a one-piece fully encapsulating hooded jump suit with outer gloves (3.05 kg) and a SCBA (12.45 kg; Scott Contour 300, Scott Safety, Lancashire, England). The ICG was worn with a respirator and canister (0.70 kg; as above) during all trials to maintain respiratory resistance constant across all ensembles [26] and had a combined ensemble weight of 16.2 kg.

To elicit higher workloads, SCBA (not connected) and additional weight were used. During moderate workloads, the ERS and CPCS ensemble configurations were worn with a SCBA, plus an additional 8.25 kg weight (added over the SCBA). The combined weights of the ensembles during these trials were: 22.75 and 23.65, respectively.

Participants' under clothing for the ERS, ICG and Saratoga ensembles consisted of a t-shirt, shorts, socks, and underwear. Base layer clothing for the CPCS ensemble consisted of shorts, socks, and underwear. Athletic shoes with a soft rubber sole were also worn during each trial. These base clothing requirements were standardised in accordance with American Society for Testing and Materials (ASTM) F2668-07 [27].

### 2.3 Environmental Conditions and Metabolic Workloads

Participants completed up to 120 min of treadmill-walking in an environmental chamber with a  $4.7 \text{ km}\cdot\text{h}^{-1}$  simulated wind speed at wet bulb globe temperature's (WBGT) 21, 30, and 37 °C. These WBGT conditions were obtained by the following ambient temperatures and relative humidity's: (1) 24 °C, 50%; (2) 32 °C, 60%; and (3) 48 °C, 20%, respectively. During trials, ambient temperature and relative humidity were continuously monitored independent of the chamber (QuestTEMP 36, 3M, St. Paul, Minnesota, United States). Within an ensemble, the order of WBGT was randomly allocated using a random number generator.

To simulate a variety of metabolic workloads (light:  $<325 \text{ W}$  and moderate: 326 to 499 W) a combination of treadmill walking intensity (speed or grade) and additional weight was used where required [28]. For each of the respective workloads the following treadmill speed and gradients (based on the average participant body mass of 79.4 kg) were used: (1) light: Saratoga, ERS and CPCS each at  $4 \text{ km}\cdot\text{h}^{-1}$ , 1%; and (2) moderate: ERS and CPCS each at  $4.5 \text{ km}\cdot\text{h}^{-1}$ , 1% and ICG at  $4 \text{ km}\cdot\text{h}^{-1}$ , 1%. Participants completed only one trial per testing day, as multiple trials have the potential to induce some level of physiological or perceptual fatigue. A minimum of one week separated each testing day. Experimental trials were completed between November 2013 and February 2015, in Brisbane, Australia.

### 2.4 Pre Experimental and Experimental Procedure

The initial visit to the laboratory consisted of a maximal aerobic capacity assessment, the collection of anthropometric measures and a familiarisation with the protective clothing, perceptual scales and testing procedures. These procedures followed standardised laboratory protocols, which have been described elsewhere [7, 29]. In order to measure  $T_c$ , participants were instructed to swallow an ingestible telemetric pill at least 6 h prior to arriving at the laboratory. This allowed sufficient time for the sensor to pass from the stomach into the gastrointestinal tract [30].

Participants arrived at the laboratory in the morning (08:30–09:30) having avoided alcohol and strenuous exercise in the previous 24 h and caffeine in the previous 12 h and provided a mid-stream urine sample to confirm hydration status via a urine specific gravity (USG) measurement. A USG of  $<1.020$  was considered euhydrated [31]. Following this, the ingestible pill was located using a radio receiver (CorTemp, HQ Inc., Palmetto, FL, USA), participants were fitted with a HR strap and sensor (Polar Team<sup>2</sup>, Kempele, Finland) and four wireless temperature sensors (DS1922L-F50 iButtons, Maxim Intergrated, Sunnyvale, California, USA) set to record at 30 s intervals were secured using sports tape (Beiersdorf Elastoplast Sport, Australia) to the back of neck, inferior border of right scapula, dorsal left hand and proximal third of right tibia as previously described [7]. Mean skin temperature ( $\bar{T}_{sk}$ ) was calculated and mean body temperature were calculated as previously described [7].

Participants were subsequently seated for a period of 15 min to allow the collection of baseline physiological measures.

Participants then donned the assigned garment configuration and entered the environmental chamber. During trials, standard termination criteria were applied in accordance with the American Society for Testing and Materials guidelines F2688-07 [27]: (1)  $T_C$  reaching 39 °C; (2) 120 min of exercise; (3)  $HR \geq 90\%$  of maximum; or (4) due to fatigue or nausea. Following termination, the participant exited the environmental chamber, all protective clothing was removed and the participant was allowed to recover in an air-conditioned laboratory.

### 2.5 Physiological and Perceptual Outcome Measures

Throughout trials, participants' HR and  $T_C$  were continuously recorded and monitored in real-time, and skin temperature was logged for retrospective analysis. The subjective measures of thermal sensation, thermal comfort and RPE were assessed at 15 min intervals and immediately prior to the termination of a trial. Thermal sensation was assessed using a modified Gagge 8-point scale [14] with 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' and 13 'unbearably hot'. Thermal comfort was measured using Gagge's 9-point scale [14] with the following numerical-verbal anchors: 1 'comfortable', 1.5, 2 'slightly comfortable', 2.5, 3 'uncomfortable', 3.5, 4 'very uncomfortable', 4.5 and 5 'extremely uncomfortable'. RPE was obtained using the [32] Borg 15-point scale with 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' and 20. Standardised instructions of 'rate your perception of thermal sensation in the current environment' [14], 'how comfortable are you with the current environment' [14] and 'currently, how hard do you feel the work rate is' [32] were provided to participants.

### 2.6 Physiological and Perceptual Strain Indices

The PSI, PeSI and modified PeSI were calculated at discrete 15 min intervals and immediately prior to trial termination [6, 7]. The PSI employed (Equation 1) was initially proposed by Moran et al. [3] and subsequently adapted [6]. This index attributes equal weight to thermoregulatory and cardiovascular parameters and rates physiological strain on a 0–10 scale. The PSI is defined as:

**Equation 1.** The physiological strain index

$$PSI = 5 \cdot ((T_{CT} - \text{resting } T_C)/(39.5 - \text{resting } T_C)) + 5 \cdot ((HR_T - 60)/(HR_{max} - 60))$$

where *resting*  $T_C$  is the participant's lowest stable  $T_C$  recording obtained during the 15 min period of seated rest prior to donning the protective garment;  $HR_{max}$  is the individual's maximal attainable HR measured during the maximal aerobic capacity assessment; and  $T_{CT}$  and  $HR_T$  are the  $T_C$  and HR recordings at the time of interest. Finally, an arbitrary value of  $60 \text{ b}\cdot\text{min}^{-1}$  was assigned for resting HR [6].

This study used an adapted PeSI [6, 8] based on the mathematical construct of the PSI; where thermal sensation and RPE responses equally contribute to total perceived strain (Equation 2), similarly expressed on a 0 to 10 scale.

**Equation 2.** The perceptual strain index

$$\text{PeSI} = 5 \cdot ((\text{thermal sensation} - 7)/6) + 5 \cdot ((\text{RPE} - 6)/14)$$

where *thermal sensation* and *RPE* are the respective subjective recordings at a point during activity. By analogy, the modified PeSI (Equation 3) equally acknowledges the contribution of thermal comfort and RPE to an individual's perceptual state. Perceptual strain is calculated on a 0 to 10 scale, allowing the direct comparison with the PSI.

**Equation 3.** The modified perceptual strain index

$$\text{Modified PeSI} = 5 \cdot ((\text{thermal comfort} - 1)/4) + 5 \cdot ((\text{RPE} - 6)/14)$$

In the equation, *thermal comfort* and *RPE* are the respective recordings of each scale at a time of interest.

## 2.7 Statistical Analysis

Data are presented as mean  $\pm$  standard deviation (range) unless otherwise stated. The normal distribution of data was appropriately confirmed using descriptive methods (skewness, outliers and distribution plots) and inferential statistics (Shapiro-Wilk Test). To assess the relationship between both perceptual indices (i.e., the PeSI and modified PeSI) and the PSI we followed a robust analytical design, similar to our previous work [7].

Firstly, the absolute agreement between (1) the PeSI and PSI, and (2) the modified PeSI and PSI was assessed by calculating the mean bias and limits of agreement (LoA) using a modified standard deviation [33] for each perceptual index across the entire scale (0–10) and during high-to-very high strain (7–10) as per Moran et al. [3].

Secondly, the predictive ability of both perceptual indices was evaluated across the entire physiological strain scale (PSI: 0–10) and with reference to three arbitrary categories of no/little (0–2.9), low-to-moderate (3–6.9) and high-to-very high (7–10) physiological strain as per Moran et al. [3].

Thirdly, the predictive power of the PeSI and modified PeSI was evaluated by deriving two receiver operating characteristic (ROC) curves [34] using a single arbitrary cut-off of high physiological strain ( $PSI = 7$ ).

Fourthly, Pearson's correlation coefficient was used to determine the relationship between each of: the PSI, PeSI, modified PeSI, PeSI-PSI, modified PeSI-PSI, thermal sensation, thermal comfort, RPE, HR,  $T_C$ ,  $\bar{T}_{SK}$ ,  $\bar{T}_{SK}$  to  $T_C$  gradient and mean body temperature with respect to these same variables.

Finally, where a moderate relationship was observed ( $r > 0.5$  or  $< -0.5$ ) between the PeSI and PSI, and modified PeSI and PSI, and each of the subjective indices of thermal sensation, thermal comfort and RPE and the PeSI, a mixed linear model (dependant variable: PSI; covariate: one of PeSI, modified PeSI, thermal sensation, thermal comfort or RPE; random factors: participant and time; fixed factors: environmental temperature, workload and garment) was used to determine statistical significance of the correlation. Participant was used as a random factor to account for the within-participant correlation likely present within the data (due to repeated measures), and time to account for the non-uniform duration of trials.

All statistical analyses were performed using Statistical Package for the Social Sciences version 23.0 (SPSS Inc., Chicago, IL) and statistical significance was set at  $p < 0.05$ .

### 3. Results

In total, 18 participants completed 110 trials producing 588 individual recordings of the PSI, the PeSI and the modified PeSI. Each participant completed an average of 6 (range: 2–12) heat stress trials. Participants presented to the laboratory in a euhydrated state for all trials (USG:  $1.011 \pm 0.006$ ) with baseline measures: HR:  $61 \pm 7$  b·min<sup>-1</sup>;  $T_C$ :  $37.05 \pm 0.26$  °C;  $\bar{T}_{SK}$ :  $33.43 \pm 0.71$  °C; thermal sensation:  $6.8 \pm 0.6$  (scale: 6–13); and thermal comfort:  $1.0 \pm 0.1$  (scale: 1–5).

The average tolerance time was  $78.0 \pm 34.1$  (range: 20.0–120.0) min with physiological and perceptual measures at termination as follows: HR:  $153 \pm 25$  (range: 90–187) b·min<sup>-1</sup>;  $T_C$ :  $38.67 \pm 0.54$  (range: 37.25–39.27) °C;  $\bar{T}_{SK}$ :  $37.59 \pm 1.71$  (range: 34.13–43.88) °C;  $\bar{T}_{SK}$  to  $T_C$  gradient:  $1.07 \pm 1.41$  (-4.83–3.78) °C; mean body temperature:  $38.45 \pm 0.71$  (range: 36.71–40.02) °C; thermal sensation:  $10.6 \pm 1.4$  (range: 7–13); thermal comfort:  $3.7 \pm 0.9$  (range: 1–5); RPE:  $14.9 \pm 2.7$  (range: 8–19); PSI:  $6.7 \pm 1.9$  (range: 2.0–8.6); PeSI:  $6.2 \pm 2.0$  (range: 0.7–9.6); modified PeSI:  $6.5 \pm 2.0$  (range: 0.7–9.6). Table 1 provides a breakdown of the termination criteria met for each individual trial.

The mean bias (modified 95% LoA) between the PeSI and PSI was:  $0.3 \pm 1.5$  (-2.6 to 3.2; Figure 1a) across the entire scale (0–10), and for the three arbitrary strain categories was:  $0.8 \pm 1.3$  (-1.8 to 3.4) for no/little;  $0.2 \pm 1.4$  (-2.5 to 2.9) for low-to-moderate; and  $-0.8 \pm 1.5$  (-

3.7 to 2.1) for high-to-very high. The mean bias (modified 95% LoA) between the modified PeSI and PSI was:  $0.5 \pm 1.6$  (-2.6 to 3.6; Figure 1b) across the entire scale (0–10), and for the three arbitrary strain categories was:  $1.0 \pm 1.5$  (-2.0 to 3.9) for no/little;  $0.4 \pm 1.5$  (-2.5 to 3.4) for low-to-moderate; and  $-0.5 \pm 1.4$  (-3.2 to 2.2) for high-to-very high.

The predictive ability results of the PeSI and modified PeSI are shown in Table 2. The areas under the ROC curves (Figure 2) were: 0.887 (95% CI: 0.855–0.919) for the PeSI and 0.886 (95% CI: 0.854–0.917) for the modified PeSI.

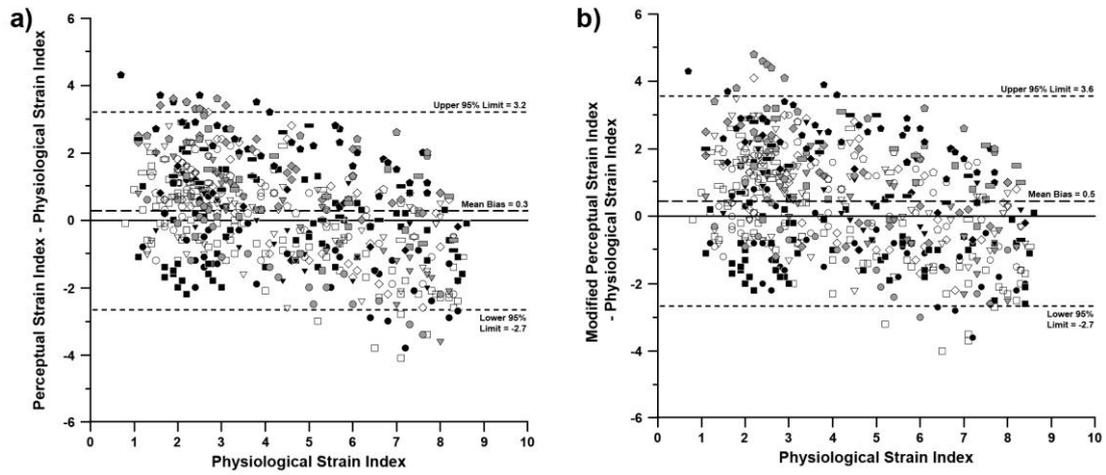
Finally, Pearson's revealed weak-to-moderate correlations (Table 3) between the difference in PeSI and PSI and the modified PeSI and the PSI and each of HR,  $T_c$ ,  $\bar{T}_{sk}$ ,  $\bar{T}_{sk}$  to  $T_c$  gradient and mean body temperature. The mixed linear model revealed the correlations between the PeSI and PSI ( $r = 0.74$ ;  $p < 0.001$ ; Figure 3a) and modified PeSI and PSI ( $r = 0.73$ ;  $p < 0.001$ ; Figure 3b) were both significant.

**Table 1.**

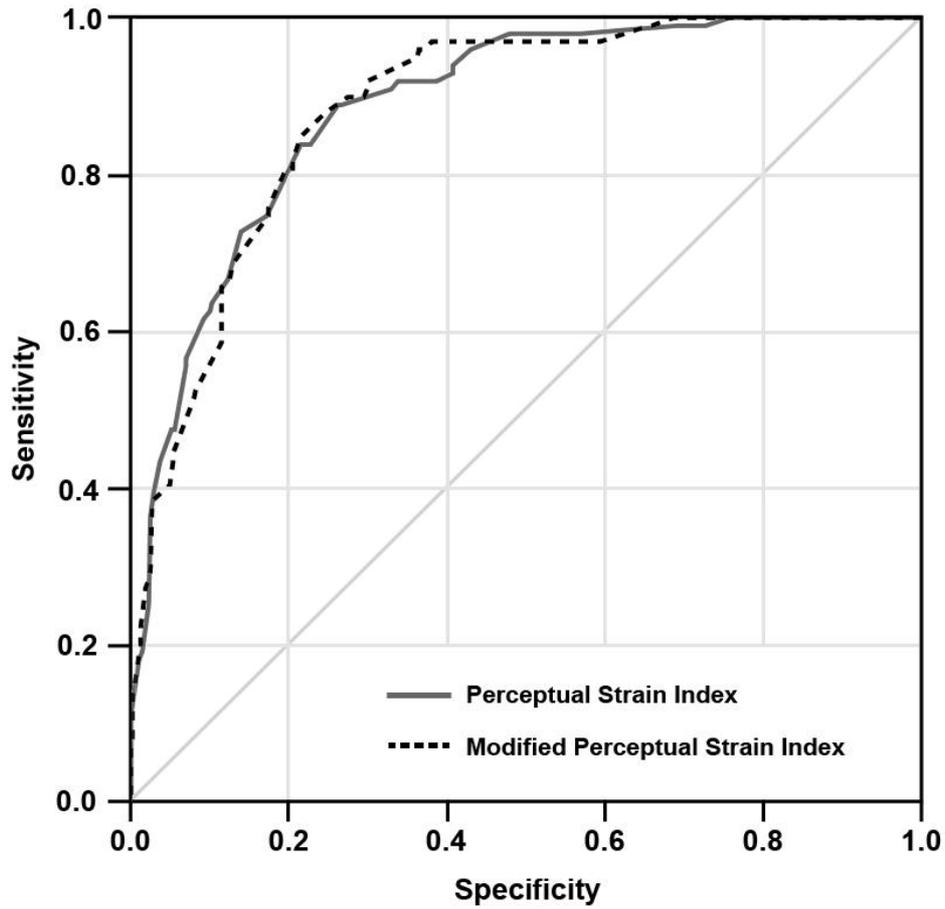
Trial termination matrix.

	21 °C WBGT			30 °C WBGT						37 °C WBGT		
<b>Ensemble</b>	ICG	ERS	CPCS	ICG	ERS	ERS	CPCS	CPCS	Saratoga	ICG	ERS	CPCS
<b>Workload</b>	Moderate	Light	Light	Moderate	Light	Moderate	Light	Moderate	Light	Moderate	Light	Light
Participant 1		Time	Time	T <sub>c</sub>	Time		T <sub>c</sub>		Time		T <sub>c</sub>	T <sub>c</sub>
Participant 2	T <sub>c</sub>					T <sub>c</sub>		T <sub>c</sub>		VF		
Participant 3	T <sub>c</sub>			T <sub>c</sub>	Time	T <sub>c</sub>		T <sub>c</sub>	T <sub>c</sub>	T <sub>c</sub>		
Participant 4	T <sub>c</sub>	Time	Time							HR	HR	T <sub>c</sub> /HR
Participant 5				T <sub>c</sub>	Time				T <sub>c</sub>			
Participant 6	T <sub>c</sub>	Time	Time	T <sub>c</sub>	Time	VF	VF	T <sub>c</sub>	T <sub>c</sub>	HR	T <sub>c</sub>	T <sub>c</sub>
Participant 7						T <sub>c</sub>		HR				
Participant 8			Time	T <sub>c</sub>	Time	T <sub>c</sub>	T <sub>c</sub>	T <sub>c</sub>	Time			VF
Participant 9	T <sub>c</sub>									T <sub>c</sub>		
Participant 10			VF				VF					T <sub>c</sub>
Participant 11		Time	Time	T <sub>c</sub>	Time	HR	T <sub>c</sub>	T <sub>c</sub>	Time		T <sub>c</sub>	T <sub>c</sub>
Participant 12		Time	Time								T <sub>c</sub>	T <sub>c</sub>
Participant 13	T <sub>c</sub>	Time	Time	T <sub>c</sub>	T <sub>c</sub>	T <sub>c</sub>	T <sub>c</sub> /HR	T <sub>c</sub>	T <sub>c</sub>	HR	T <sub>c</sub>	T <sub>c</sub>
Participant 14				T <sub>c</sub>	Time		VF		Time			
Participant 15	HR		Time			HR	T <sub>c</sub>	T <sub>c</sub>		HR		HR
Participant 16		Time	T <sub>c</sub>								HR	Time
Participant 17				HR	Time		VF		VF			
Participant 18	T <sub>c</sub>	Time	Time	T <sub>c</sub>	T <sub>c</sub>		T <sub>c</sub>		T <sub>c</sub>	HR	T <sub>c</sub>	T <sub>c</sub>

**CPCS** = Chemical/biological protective clothing system; **ERS** = Emergency response suit; **HR** = Trial terminated due to heart rate exceeding 90% of maximum; **ICG** = Improved chemical garment; **Light** = Metabolic workload less than 325 watts; **Moderate** = Metabolic workload between 326 and 499 watts; **T<sub>c</sub>** = Trial terminated due to core body temperature reaching 39 °C; **T<sub>c</sub>/HR** = Trial terminated due to the simultaneous attainment of core body temperature and heart rate criteria; **Time** = Trial terminated due to reaching 120 min exercise time; **VF** = Trial terminated due to volitional fatigue; **WBGT** = Wet bulb globe temperature



**Figure 1.** Bland and Altman plots for (a) the perceptual strain index and (b) the modified perceptual strain index (with thermal comfort), with respect to the physiological strain index across the entire 0 to 10 scale. Solid line indicates the mean bias; dashed lines represent the modified 95% limits of agreement. Each participant is represented by a unique symbol-shade combination.



**Figure 2.** The receiver operating characteristic curves for the perceptual strain index (PeSI) and modified PeSI with reference to the arbitrary cut-off of high physiological strain (7 on the 0–10 scale). The areas under these curves are 0.887 (95% CI: 0.855–0.919) and 0.886 (95% CI: 0.854–0.917). Perfect predictions will have an area of 1.0; random predictions 0.5.

**Table 2.**

The predictive ability of the perceptual strain index and modified perceptual strain index using the three arbitrary categories of no/little, low-to-moderate and high-to-very high physiological strain, and across the entire 0–10 physiological strain index scale.

	PSI 0–2.9 No/little strain		PSI 3–6.9 Low-to-moderate strain		PSI 7–10 High-to-very high strain		PSI 0-10 Entire scale	
Number classified (via the PSI)	225		264		99		588	
Index	PeSI	Modified PeSI	PeSI	Modified PeSI	PeSI	Modified PeSI	PeSI	Modified PeSI
Correctly estimated	96 (42.7%)	94 (41.8%)	212 (80.3%)	190 (72.0%)	47 (47.5%)	58 (58.6%)	335 (60.4%)	342 (58.2%)
Overestimated	129 (57.3%)	131 (58.2%)	26 (9.8%)	51 (19.3%)	Not computable		155 (26.4%)	182 (31.0%)
Underestimated	Not computable		26 (9.8%)	23 (8.7%)	52 (52.5%)	41 (41.4%)	78 (13.3%)	64 (10.9%)

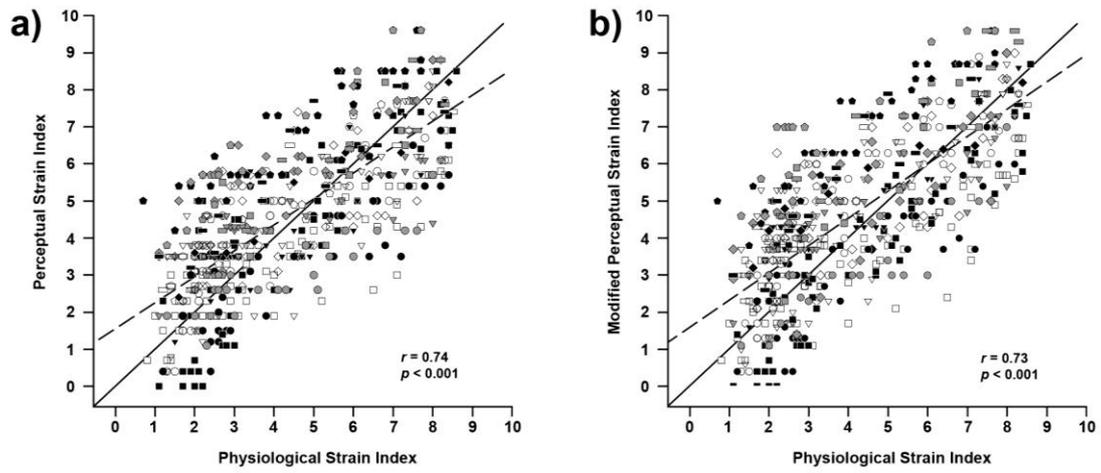
PeSI = Perceptual strain index; PSI = Physiological strain index

**Table 3.**

Summary of Pearson's regression correlations and their significance.

Variable	Physiological strain index	Perceptual strain index	Modified perceptual strain index	Perceptual strain index - physiological strain index	Modified perceptual strain index - physiological strain index	Thermal sensation	Thermal comfort	Rating of perceived exertion	Heart rate	Core temperature	Mean skin temperature	Mean skin to core temperature gradient	Mean body temperature
Physiological strain index	-												
Perceptual strain index	0.74*	-											
Modified perceptual strain index	0.73*	0.95*	-										
Perceptual strain index - physiological strain index	-0.42*	0.29*	0.25*	-									
Modified perceptual strain index - physiological strain index	-0.36*	0.30*	0.38*	0.91*	-								
Thermal sensation	0.69*	0.95*	0.87*	0.30*	0.26*	-							
Thermal comfort	0.66*	0.87*	0.96*	0.22*	0.41*	0.85*	-						
Rating of perceived exertion	0.72*	0.94*	0.93*	0.25*	0.31*	0.79*	0.79*	-					
Heart rate	0.91*	0.73*	0.72*	-0.31*	-0.24*	0.66*	0.64*	0.74*	-				
Core temperature	0.95*	0.69*	0.68*	-0.43*	-0.36*	0.65*	0.63*	0.65*	0.82*	-			
Mean skin temperature	0.61*	0.58*	0.54*	-0.07	-0.07	0.59*	0.51*	0.51*	0.62*	0.50*	-		
Mean skin to core temperature gradient	-0.19*	-0.30*	-0.26*	-0.15*	-0.11	-0.33*	-0.25*	-0.23*	-0.27*	-0.04	-0.89*	-	
Mean body temperature	0.55*	0.43*	0.41*	-0.20*	-0.18*	0.39*	0.36*	0.41*	0.53*	0.54*	0.77*	-0.38*	-

\* p &lt; 0.001



**Figure 3.** Linear regression analysis of (a) the perceptual strain index and the physiological strain index; and (b) the modified perceptual strain index and the physiological strain index across the entire 0 to 10 scale. Solid line represents the line of identity; dashed line indicates the trend line; each participant is represented by a unique symbol-shade combination.

#### 4. Discussion

This is the first study to explore the ability of a modified PeSI incorporating thermal comfort and RPE to predict physiological strain during exertional-heat stress. The primary outcomes to emerge from this research are: (1) a modified PeSI does not improve the prediction of physiological strain compared to the PeSI proposed by Tikuisis et al. [6], confirmed by multiple statistical methods; and (2) unexpectedly, when used alone, the RPE is as good a predictor of the PSI, particularly when greater than high levels of physiological strain are expected. By design, this study has extended the application of the PeSI, demonstrating its ability as an accurate predictor of the PSI across a range of chemical/biological ensemble configurations of various weight (range: 2.05–23.65 kg), irrespective of metabolic workload or environmental temperature. However, these findings also suggest that the RPE scale is an appropriate tool for the subjective prediction of physiological strain during situations of prolonged exertional-heat stress.

Multiple statistical methods were used to determine if thermal comfort could serve as an alternative to thermal sensation in the calculation of the PeSI and subsequently improve its ability to predict the PSI. Pearson's correlation revealed the relationship between thermal comfort and core temperature ( $r = 0.63$ ) was no better than thermal sensation and core temperature ( $r = 0.65$ ). Not surprisingly, the PeSI and modified PeSI both shared a significant moderate relationship ( $r = 0.74$ ;  $p < 0.001$  and  $r = 0.73$ ;  $p < 0.001$ , respectively) with the PSI. This moderate relationship is consistent with previous research examining the relationship between the PeSI and PSI when wearing fire [8] or ordnance disposal [7] protective ensemble configurations. The predictive performance of the PeSI and modified PeSI were similar when discriminating between no/little, low-to-moderate and high-to-very high levels of physiological strain [3], with each index able to correctly or conservatively (over) estimate the PSI >86% of the time. This predictive performance is slightly worse compared to our previous work [7], where the PeSI was able to accurately estimate the PSI 94.7% of the time in a heavier ensemble (~34 kg) and shorter exercise duration ( $\leq 60$  min) when using the same arbitrary cut offs of low (PSI = 3) and high (PSI = 7) strain. Collectively, these results lead us to reject our initial hypothesis and suggest that the modified PeSI did not improve the ability to predict physiological strain via subjective scales.

High levels of physiological strain are associated with a reduction in work capacity, cognitive impairment and an increased risk of heat-related injury or illness [35, 36]. Therefore, the accurate prediction of the PSI is of greatest importance when individuals experience high-to-very high levels of physiological strain [3]. In the current investigation, the PeSI correctly estimated the PSI 47.5% of the time when strain was considered high-to-very high. In comparison, the modified PeSI performed slightly better, correctly estimating the PSI 58.6% of the time. Absolute agreement between the PeSI and the PSI (mean bias:  $-0.8 \pm 1.5$ ) and the

modified PeSI and PSI (mean bias:  $-0.5 \pm 1.4$ ) also indicated an improved performance when physiological strain was considered high-to-very high. However, the ROC curves (Figure 2) suggest the PeSI was an equally adept predictor of strain when differentiating between high or greater ( $PSI \geq 7$ ) levels of physiological strain.

Previously, Tikuisis and co-authors [6] demonstrated that trained individuals ( $\dot{V}O_{2MAX} = 59 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) underreported the PSI compared to untrained individuals ( $43.6 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ). Given the similarities of maximal aerobic capacity of participants in the current study ( $57.2 \text{ ml}\cdot\text{kg}^{-1}\cdot\text{min}^{-1}$ ) to the 'trained' group recruited by Tikuisis et al. [6], the underestimation of the PSI by both the PeSI and modified PeSI, particularly during high-to-very high levels of physiological strain is to be expected. The underestimation of the PSI observed in the current study and by Tikuisis et al. [6] and others [7] suggest that caution should be taken when interpreting perceptual strain responses from trained individuals, especially when high-to-very high levels of physiological strain are expected. However, it is likely that trained individuals with a high aerobic capacity would be more tolerant to heat stress and the apparent underreporting of the PSI may simply reflect a greater tolerance limit. Until further research is provided and based on the current findings, perceptual measures should not serve as a replacement for all current monitoring tools in the work place. Rather, perceptual measures should be viewed as a simple and cost-effective additional tool that could be used in conjunction with more practically feasible measures (e.g., HR) in order to optimise personnel safety.

This study has provided the largest investigation of the relationship between the PeSI and PSI (588 data pairs; Figure 3) in a controlled laboratory. Moreover, the current study extends our previous work by demonstrating the PeSI is an accurate predictor of physiological strain when wearing a range of protective ensemble configurations for up to 120 min of physical activity. An important feature of this research is thermoregulatory strain being the major cause of trial termination compared to other criteria (e.g., exercise time, HR). This suggests individuals experienced considerable thermal strain and were not limited by the prescribed metabolic workload as with our previous work [7]. Therefore, the PeSI has now demonstrated its ability as a suitable predictor of physiological strain, irrespective of whether individuals are limited primarily by either cardiovascular or thermoregulatory strain when operating in explosive ordnance disposal or HAZMAT protective ensembles.

On the basis of the current findings a PeSI which uses both thermal sensation and comfort as a surrogate measure of thermoregulatory strain, in addition to RPE, may improve the subjective estimation of the PSI. Accordingly, thermal sensation and comfort were modelled to predict  $T_c$  and were subsequently weighted to contribute to half of a combined PeSI. Mixed model analysis revealed a PeSI using a weighted combination of thermal sensation and thermal comfort shared a moderate relationship ( $r = 0.74$ ,  $p < 0.001$ ) with the PeSI. However, the combined PeSI was a poorer predictor of the PSI during high-to-very high levels

of physiological strain [mean bias:  $-1.3 \pm 1.4$ ; AUC: 0.891 (95% CI: 0.860–0.922); correctly estimated the PSI 38.4% of the time]. Given the complexity of the combined PeSI and its poorer predictive performance during high-to-very high levels of strain, its future utility may be deemed inappropriate.

Logically, a simpler perceptual index with similar predictive performance compared to the currently used PeSI would be of benefit. This study explored whether the Borg 6–20 RPE scale (perceived strain =  $10 \cdot ((RPE - 6)/14)$ ) could be used to estimate the PSI. Unexpectedly, the RPE shared a moderated relationship ( $r = 0.71$ ;  $p < 0.001$ ) with the PSI and displayed similar predictive performance to the PeSI when physiological strain was considered high or greater [mean bias:  $-0.7 \pm 1.4$ ; AUC: 0.883 (95% CI: 0.851–0.916); correctly estimated the PSI 58.6% of the time]. These findings led to further exploration of our previous data set [7], so to evaluate the ability of the RPE to predict physiological strain in a heavier ensemble (~34 kg) over a shorter duration ( $\leq 60$  min) where trials were primarily terminated due to excessive cardiovascular strain. Employing the same analytic methods, RPE was again shown to have a moderate relationship ( $r = 0.76$ ;  $p < 0.001$ ) with the PSI, almost identical to that reported for the PeSI [7]. Moreover, when strain was considered high or greater ( $PSI \geq 7$ ), the RPE displayed similar or improved accuracy [mean bias:  $0.0 \pm 0.9$ ; AUC: 0.814 (95% CI: 0.726–0.902); correctly estimated the PSI 80% of the time] compared to the PeSI [mean bias:  $-0.2 \pm 1.0$ ; AUC: 0.841 (95% CI: 0.757–0.926); correctly estimated the PSI 46.7% of the time]. These findings further highlight the suitability of subjective measures, particularly RPE, along with physiological monitoring to be used during the monitoring and management of individuals operating under conditions of heat stress [37].

The similar predictive performance of the RPE as a measure of perceived strain is interesting. RPE is known to be an important feature of exercise; however, precisely what the RPE reflects and underlying neurophysiological mechanisms are poorly understood [38, 39]. Inputs from multiple bodily systems (e.g., the cardiovascular system) stressed during exercise are thought to contribute, in addition to other factors such as sensations of pain from locomotive muscles [40] and exercise duration [38]. Regardless, the above analyses suggest that RPE alone can serve as an accurate indicator of physiological strain during exertional-heat stress across a range of environments and metabolic workloads in chemical/biological and explosive ordnance disposal protective ensemble configurations. Given the simplicity of the RPE, the authors of the current study advocate its use to predict physiological strain, particularly when high-to-very high levels of strain are expected.

This study is not without limitations. The views of this study rest on the assumption that thermal perceptions can be expressed simply by global thermal sensation and comfort measures. Clearly this is too simple, particularly when regional differences in temperature sensation and thermal comfort have been demonstrated [16]. It is conceivable that skin

wettedness, absent from this study, was not homogenous across all ensemble configurations and therefore may have influenced the perceptual ratings of thermal comfort and sensation [41]. Sensitivity differences in thermal sensation and comfort also exist between the sexes [42] and across ethnicities. Consequently, it is unknown whether the results of the current study could be translated to females and to different ethnic populations. The maximum PSI value recorded in the current study was 8.6; therefore, it is unclear if data falling within the PSI 8.7 to 10 range, where individuals are at greatest risk of suffering a heat-related illness follow a similar trend as the current data set. This study used a  $T_C$  termination criteria set at 39 °C, likely much lower than the highest possible  $T_C$  able to be both attained and tolerated by the demographic of participants who completed this investigation [66]. Finally, it should be acknowledged that the primary dependant variable in this study, the PSI, artificially places a safe and ethical limit on the maximal achievable core temperature and as such, has not been criterion validated. Future work should consider the impact of intense training, heat acclimation, repeated exercise bouts on the same day, fatigue, muscle damage, circadian rhythm and sleep deprivation on the accuracy of subjective indices used to predict physiological strain.

## **5. Conclusion**

Many military, occupational and industrial situations require individuals to complete physically demanding tasks in thermally stressful environments often when wearing protective clothing. Accordingly, the ability to accurately predict and easily monitor physiological strain in these situations is an important feature of personnel safety. This is the first study to explore the ability of a modified PeSI incorporating thermal comfort and RPE to predict physiological strain during exertional-heat stress. The modified PeSI did not improve the prediction of physiological strain when completing treadmill-walking across a range of metabolic workloads and environments when wearing an assortment of lightweight HAZMAT protective ensemble configurations with and without a SCBA. Unexpectedly, RPE provided an equally accurate estimation of physiological strain, particularly when high-to-very high levels of strain were observed. Therefore, given its predictive performance and user-friendliness, the evidence suggests that RPE is a practical and cost-effective tool when estimating physiological strain during exertional-heat stress under these work conditions.

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