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

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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.

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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 $ml \cdot kg^{-1} \cdot min^{-1}$) 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 ± 1.5 based on a 0–10 scale; area under the curve: 0.887), modified PeSI (mean bias: -0.5 ± 1.4 based on 0–10 scale; area under the curve: 0.886) and RPE (mean bias: -0.7 ± 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.

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1. Introduction

Efforts to quantify an individual's health risk during situations of exertional-heat stress have led to the development of >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 (≤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 ± 2.5 (range: 20.6–30.0) years; height: 178.4 ± 5.1 (166.4–186.3) cm; body mass: 79.4 ± 8.5 (64.8–94.1) kg; sum of eight-site skinfold thickness: 83.8 ± 29.5 (49.6–150.8) mm; body surface area [25]: 2.0 ± 0.1 (1.7–2.2) m^2; maximal aerobic capacity: 57.2 ± 4.4 (49.6–66.0) $ml \cdot kg^{-1} \cdot min^{-1}$; maximal HR: 194 ± 10 (179–207) $b \cdot min^{-1}$]. 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® 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™ 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 (0.70 kg; 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