Can perceptual indices estimate physiological strain across a range of environments and metabolic workloads when wearing explosive ordnance disposal and chemical protective clothing?

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Competing interests:
The authors have no conflict of interests to declare.

Funding:
This project is financially supported by the Australian Government, managed by the National Security Science & Technology Centre within the Defence Science & Technology Organisation, and the US Government through the Technical Support Working Group within the Combating Terrorism Technical Support Office. This support does not represent an endorsement of the contents or conclusions of the project. The funders had no role in study design, data collection and analysis, decision to publish, or preparation of the manuscript.

Highlights:

- Explosive ordnance disposal predisposes technicians to physiological strain.
- The current measurement of physiological strain is expensive and often impractical.
- The perceptual strain index is able to accurately estimate physiological strain.

ABSTRACT

Objective: Explosive ordnance disposal (EOD) often requires technicians to wear multiple protective garments in challenging environmental conditions. The accumulative effect of increased metabolic cost coupled with decreased heat dissipation associated with these garments predisposes technicians to high levels of physiological strain. It has been proposed that a perceptual strain index (PeSI) using subjective ratings of thermal sensation and perceived exertion as surrogate measures of core body temperature and heart rate, may provide an accurate estimation of physiological strain. Therefore, this study aimed to determine if the PeSI could estimate the physiological strain index (PSI) across a range of metabolic workloads and environments while wearing heavy EOD and chemical protective clothing. **Methods:** Eleven healthy males wore an EOD and chemical protective ensemble while walking on a treadmill at 2.5, 4 and 5.5 $km \cdot h^{-1}$ at 1% grade in environmental conditions equivalent to wet bulb globe temperature (WBGT) 21, 30 and 37 °C. WBGT conditions were randomly presented and a maximum of three randomised treadmill walking trials were completed in a single testing day. Trials were ceased at a maximum of 60-mins or until the attainment of termination criteria. A Pearson's correlation coefficient, mixed linear model, absolute agreement and receiver operating characteristic (ROC) curves were used to determine the relationship between the PeSI and PSI. **Results:** A significant moderate relationship between the PeSI and the PSI was observed [$r = 0.77$; $p < 0.001$; mean difference = 0.8 ± 1.1 a.u. (modified 95% limits of agreement -1.3 to 3.0)]. The ROC curves indicated that the PeSI had a good predictive power when used with two, single-threshold cut-offs to differentiate between low and high levels of physiological strain (area under curve: PSI three cut-off = 0.936 and seven cut-off = 0.841). **Conclusions:** These findings support the use of the PeSI for monitoring physiological strain while wearing EOD and chemical protective clothing. However, future research is needed to confirm the validity of the PeSI for active EOD technicians operating in the field.

Key Words: Thermoregulation, Heat Strain, Subjective Measures, Thermal Sensation, Perceived Exertion

1. Introduction

The use of improvised explosive devices in modern warfare has led to an increased role for explosive ordnance disposal (EOD) technicians, faced with the arduous task of identifying, disarming and clearing these devices [1]. If the relative chemical and biological risk is unknown, EOD technicians may be required to wear multiple protective garments in combination [2]. Personal protective clothing (PPC) may consist of multiple layers of vapour impermeable materials and is often heavy and fully encapsulating [3]. The combination of the PPC, physical nature of the work and potentially challenging environment can result in substantial thermoregulatory and cardiovascular strain [3,4]. Recent field [5,6] and laboratory [1,7] based investigations have reported high levels of thermoregulatory and cardiovascular strain when completing simulated operational tasks in an EOD ensemble. These high levels of strain have resulted in EOD technicians reporting symptoms of light headedness, nausea, confusion, irrational behaviour and altered levels of consciousness [5,6]. These symptoms arise from exposure to conditions of uncompensable heat stress where evaporative heat loss is compromised, impairing thermoregulation [4,8].

Prolonged exposure to uncompensable heat stress results in an uncontrollable elevation in core body temperature (T_C), increasing heat strain and thus increasing the risk of heat injury and illness (including heat syncope, physical exhaustion and heat stroke) [3,9]. Between 1980 and 2002, 37 American military personnel deaths resulted from heat-related injuries [10]. Recent deployments of military troops to hot regions of the world such as Iraq and Afghanistan have resulted in a significant number of hospitalisations due to heat-related injuries, with more than 1,050 heat injury cases reported in American soldiers serving in these regions from 2008 to 2012 [11]. As a result of this occupational hazard it is imperative that heat strain is monitored, to ensure the safety of personnel [12].

The most common method used to assess heat strain is via the physiological strain index (PSI) developed by Moran and colleagues in the late 1990's [13]. Attributing equal weight to thermoregulatory and cardiovascular strain via the physiological measures of T_C and heart rate (HR), the PSI classifies strain from zero to 10, where zero represents 'no strain' and 10 'very high strain' [13]. The PSI has been validated during rest, exercise and recovery [13], across genders [14], under differing levels of hydration [15], clothing types [16] and environmental conditions [16]. Unfortunately, calculation of the PSI is reliant on physiological measures requiring direct contact with the individual and sensitive equipment not suitable for extreme environments. Moreover, in the absence of prior planning, expensive telemetry, or the necessary resources for large cohorts, the measurement of the PSI may not be possible.

Alternatively, it has been proposed that the subjective measures of thermal sensation and perceived exertion, whereby an individual expresses their satisfaction with elements of their environment (e.g., temperature, physical task) may offer an insight into physiological strain from a psychological perspective [17]. Previous research has suggested that a perceptual strain index (PeSI) may be able to estimate the PSI, by using thermal sensation and perceived exertion as surrogate measures of T_C and HR respectively [17]. To date, only three studies [17-19] have investigated the relationship between a PeSI and the PSI during physical exertion while wearing PPC. The findings from these studies suggest the existence of a moderate correlation [18,19] and no significant difference [17] between the PeSI and PSI. This research has incorporated short duration high intensity [18,19] or long duration low intensity physical tasks [17], with garments weighing ~ 25 kg or less [17-19] in a single climate [17-19]. A moderate correlation between the two indices suggests a PeSI may be able to estimate the PSI, however further investigations are required [17,18].

EOD technicians would benefit from a valid, non-invasive, inexpensive and more practical measure of physiological strain. Therefore, the purpose of the present study was to examine the relationship between a PeSI and the PSI across a range of environments and workloads, while wearing heavy EOD and chemical PPC.

2. Methods

2.1 Participants

Eleven healthy, unacclimatised young males recruited from the university community, participated in this study (age: 24.0 ± 2.8 years; height: 181 ± 5.5 cm; body mass: 76.9 ± 8.7 kg; sum of eight-site skin fold thickness: 77.0 ± 32.2 mm; body surface area: 2.0 ± 0.1 m^2; $\dot{V}O_{2max}$: 57.1 ± 4.8 $ml \cdot kg^{-1} \cdot min^{-1}$; maximal HR: 195 ± 8.7 bpm; 90% maximal HR: 175 ± 7.9 bpm). Prior to testing, participants provided written informed consent indicating that they understood the risks associated with the study. All experimental procedures were approved by the university human research ethics committee at the Queensland University of Technology and all participants completed an informed consent form and medical history questionnaire.

2.2 Personal Protective Clothing

During each trial participants wore a National Fire and Protection Association (NFPA) 1994 Class 3 chemical protective garment (Emergency Response Suit, Lion Apparel, Dayton, Ohio, USA) underneath an explosive ordnance disposal suit and helmet (Med-Eng™ EOD9, Allen Vanguard, Ogdensburg, New York, USA). The NFPA Class 3 chemical protective undergarment consisted of a one-piece fully encapsulating suit, outer glove and respirator (DUCOT, Promask NP Facemask, USA) weighing 2.05 kg; and the EOD9 suit consisted of a jacket, trousers, groin protection and a helmet weighing 33.35 kg. Participants' base clothing consisted of a t-shirt, shorts, socks, and underwear and athletic shoes with a soft rubber sole were also worn during testing. These base ensemble requirements are standardised in accordance with American Society for Testing and Materials F2688-07 [20].

2.3 Environmental Conditions and Metabolic Workloads

Trials were completed in an environmental chamber with a 4.7 $km \cdot h^{-1}$ simulated wind speed. The wet bulb globe temperature (WBGT) 21, 30, and 37 °C conditions were obtained by the following ambient temperatures and relative humidity's: 24 °C, 50%; 32 °C, 60%; and 48 °C, 20%, respectively. WBGT conditions were randomly presented and a maximum of three trials were completed per day. Between visits, participants had a minimum of seven days' rest. Within each WBGT condition the following treadmill-walking trials were randomly presented: 2.5, 4 and 5.5 $km \cdot h^{-1}$ with a 1% grade.

2.4 Pre-experimental and Experimental Protocol

The initial visit to the laboratory consisted of the acquisition of $\dot{V}O_{2max}$, body composition and a familiarisation with the protective clothing, perceptual scales and testing procedures. During this visit the participants donned the protective clothing and practiced walking at each of the three work intensities (2.5, 4 and 5.5 $km \cdot h^{-1}$) on the treadmill. On trial days participants rested for 10 minutes allowing the recording of baseline measurement. Participants then donned the EOD and chemical PPC and entered the environmental chamber to commence the trial. Standard termination criteria were applied in accordance with the American Society for Testing and Materials guidelines F2688-07 [20]: (1) T_C reaching 39 °C; (2) 60-mins trial time; (3) HR reaching 90% of maximum; or (4) due to fatigue or nausea. Following the attainment of one of the termination criteria the participant exited the environmental chamber and removed all PPC. Participants were then instructed to rest in an air-conditioned room. In the following recovery

period participants were provided with food and fluid. This has previously been shown to ensure adequate recovery of body mass and hydration status prior to commencement of subsequent trials [1,7]. Core temperature and heart rate were continuously monitored and following their return to baseline levels, baseline thermal sensation was recorded and the participant commenced donning the EOD protective clothing for the subsequent trial. A maximum of three trials were conducted in this manner per trial day.

2.5 Physiological Outcome Measures

HR was measured using a polar monitor and a chest strap (Polar Team^2, Kempele, Finland). T_C was obtained using an ingestible T_C sensor and radio receiver (CorTemp, HQ Inc., Palmetto, FL, USA). Participants were provided with an ingestible T_C sensor to swallow a minimum of six hours prior to arriving at the laboratory. This was to allow sufficient time for the sensor to pass from the stomach to the gastrointestinal tract avoiding the confounding effect of food and fluid [21,22]. HR and T_C were recorded at 15-min intervals in addition to baseline and immediately prior to trial termination, allowing the PSI to be calculated at these same intervals. These intervals were selected based on a previous investigation [17]. The PSI employed in the current study was originally developed by Moran et al. [13] and later modified by Tikuisis et al. [17]. Presented in Equation 1, the PSI attributes equal weight to thermoregulatory and cardiovascular parameters, and rates physiological strain on a zero to 10 scale.

Equation 1. Physiological strain index

$$\mathrm{PSI} = 5 \cdot ((\mathrm{T_{CT}} - \mathrm{T_{C0}})/(39.5 - \mathrm{T_{C0}})) + 5 \cdot ((\mathrm{HR_T} - 60)/(\mathrm{HR_{max}} - 60))$$

In the equation, T_{CT} and HR_T are the T_C and HR recordings at the time of interest; T_{C0} is initial T_C; and HR_{max} is the individuals maximal attainable HR. For the purpose of this study, strain was considered as: no/little (0 – 2.9), low-moderate (3 – 6.9) and high-very high (7 – 10) [13]. Classifying strain in this manner allowed the adoption of corresponding green (no/little), amber (low-moderate) and red (high-very high) strain 'warning' levels; the relevance of which will be discussed in a subsequent section (see 4. *Discussion*).

2.6 Perceptual Outcome Measures

Thermal sensation was measured using a modified Gagge 7-point scale which had previously been validated [23], where thermal sensation ratings and corresponding anchors ranged from seven 'neutral' to 13 'unbearably hot'. RPE was obtained using the previously validated [24] Borg 15-point scale where ratings and corresponding written anchors of exertion range from six 'very, very light' to 20 'very, very hard'. This RPE was used due to its sensitivity in determining exertion compared to the Borg 10-point RPE [12,25]. The thermal sensation and RPE scales were visually presented to participants and accompanied with the standardised written and verbal instructions of 'rate your perception of thermal sensation in the current environment' [23] and 'currently, how hard do you feel the work rate is' [24], to which participants verbally responded. For a direct comparison of the PeSI and PSI, thermal sensation and RPE were recorded at 15-min intervals and immediately prior to trial termination. A modified PeSI first proposed by Tikuisis et al. [17] and later adapted by Petruzzello et al. [18] was used (see Equation 2).

Equation 2. Modified perceptual strain index

$$\mathrm{PeSI} = 5 \cdot ((\mathrm{T_{ST}} - 7)/6) + 5 \cdot ((\mathrm{RPE_T} - 6)/14)$$

In the equation, T_{ST} and RPE_T are the thermal sensation and RPE recordings at the time of interest. Similarly to the PSI, strain was considered as: no/little (0 – 2.9), low-moderate (3 – 6.9) and high-very high (7 – 10).

2.7 Statistical Analysis

The normal distribution of data was confirmed using descriptive methods (skewness, outliers and distribution plots) and inferential statistics (Shapiro-Wilk Test). Multiple statistical methods were used to assess the relationship between the PeSI and PSI. Firstly, the absolute agreement between PeSI and PSI was assessed by calculating the mean difference (MD) and limits of agreement (LoA) across the entire zero to ten scale, in addition to three arbitrary physiological strain categories of no/little (0 – 2.9), low-moderate (3 – 6.9) and high-very high (7 – 10) outlined by Moran et al. [13]. To account for the repeat measures on each participant, the LoA were calculated using a modified standard deviation (SD) according to the equation proposed by Bland and Altman (see Equation 3) [26].

Equation 3. Modified standard deviation

$$Modified\ SD = \sqrt{\left((MSB - MSW)/(((\sum m_i)^2 - \sum m_i^2)/((n-1)\sum m_i))) + MSW\right)}$$

In the equation, *MSB* and *MSW* are the between-participant and within-participant mean sums of squares computed by a one-way ANOVA; i is the participant; m_i is the number of observations on a participant; and n is the number of participants. Thereafter, the modified LoA were calculated as: *MD* ± *1.96* · *modified SD* [26].

Secondly, the predictive ability of the PeSI was evaluated with reference to three arbitrary strain categories previously outlined. It is important to note that due to the bounds of the PSI and PeSI metrics, under the classification system used to assess the predictive ability of the PeSI, physiological strain is unable to be underestimated in the no/little category, or overestimated in the high-very high category.

Thirdly, the predictive power of the PeSI was evaluated by deriving two receiver operating characteristic (ROC) curves [27,28], with the area under the curve quantifying the predictive power of the PeSI (perfect prediction = 1.0; random prediction = 0.5). For these calculations, two arbitrary single-threshold cut-offs were used to differentiate between individuals with low (PSI three cut-off) and high (PSI seven cut-off) levels of physiological strain.

Fourthly, a Pearson's correlation coefficient was used to determine the relationship between the PeSI and PSI, HR and RPE, and T_C and thermal sensation.

Finally, where a moderate relationship was observed ($r > 0.5$ or < -0.5) between the PeSI and PSI, a mixed linear model (dependant variable: PeSI; covariate: PSI; random factors: participant and time; fixed factors: temperature and speed), was used to determine statistical significance.

All statistical analyses were performed using SPSS (Statistical Package for the Social Sciences), version 21.0 (SPSS Inc., Chicago, IL) and statistical significance was set at $p < 0.05$. Values are reported as mean ± standard deviation.

3. Results

In total eleven participants completed 70 trials. Six participants completed three separate testing days at each of the WBGT 21, 30 or 37 °C. Four participants undertook WBGT 21 and either 30 or 37 °C, with one participant completing the WBGT 30 °C only. Five of the eleven

undertook all nine trials; three completed greater than six, with the remaining three participants undertaking two, three or four trials in total.

At the start of each trial, T_C, HR and USG were as follows: T_C: 37.20 ± 0.32 °C; HR 96.5 ± 14.3 bpm; and USG 1.013 ± 0.007. At the termination of each trial T_C and HR were as follows: T_C: 38.12 ± 0.45 °C; and HR: 170.0 ± 13.6 bpm. The majority of trials (57/70; 81.4%) were terminated due to participants' HR exceeding 90% of their maximum. A total of six (8.6%) trials lasted the full duration of 60-mins. Finally, five (7.1%) trials were terminated due to volitional fatigue and two (2.9%) due to T_C reaching 39 °C.

The average tolerance time per trial was 29.8 ± 15.4 mins, producing 150 recordings of both the PSI and PeSI, with an average duration of 89.0 ± 18.0 (57.5 – 136.0) mins recovery between each trial when multiple trials were performed on the same day. The mean bias between the PeSI and PSI across the entire scale (zero to 10) was 0.8 ± 1.1 and the modified 95% LoA ranged from -1.3 to 3.0 (see Figure 1). Further, the mean bias (modified 95% LoA) for the three arbitrary strain categories was: 1.3 ± 0.7 (-0.1 to 2.8) for no/little; 0.8 ± 1.1 (-1.3 to 2.9) for low-moderate; and -0.2 ± 1.0 (-2.2 to 1.9) for high-very high.

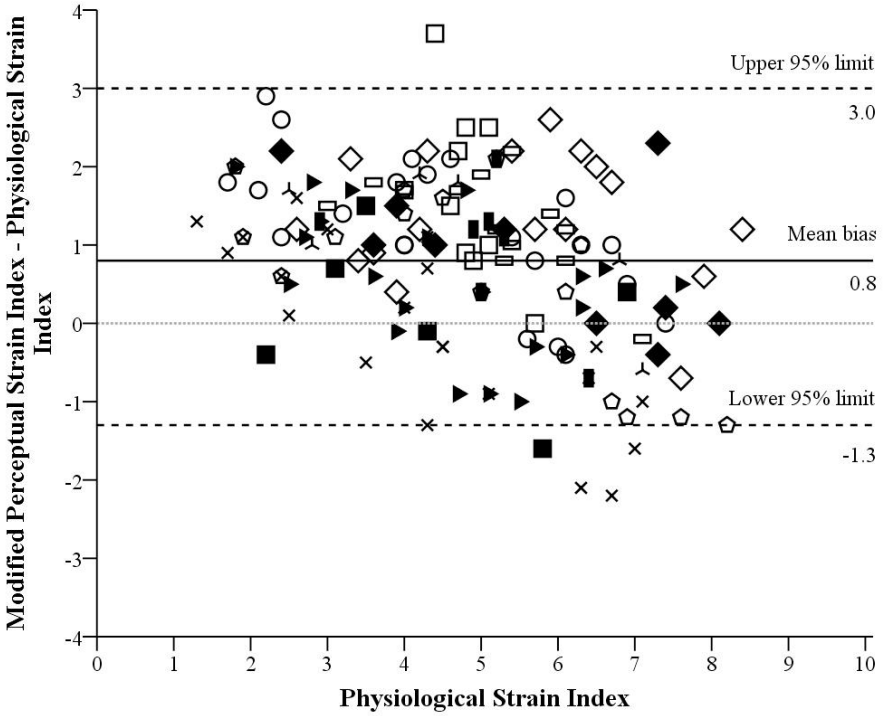

Figure 1. Bland and Altman plot of the physiological strain index and the modified perceptual strain index. Solid line indicates the mean bias; dashed lines represent the modified 95% limits of agreement. Each unique symbol represents data from a single participant.

In total, 66.0% (99/150) of the PeSI responses correctly estimated the PSI, 28.7% (43/150) overestimated and 5.3% (8/150) underestimated the PSI (see Figure 2). When the PSI was considered no/little, the PeSI correctly estimated 16.0% (4/25) and overestimated 84.0% (21/25) of the time. The PSI low-moderate category comprised 110 PeSI responses, of which 80.0% (88/110) correctly estimated and 20.0% (22/110) overestimated the PSI. When the PSI was considered high-very high, 46.7% (7/15) of PeSI responses correctly estimated and 53.3% (8/15) underestimated the PSI.

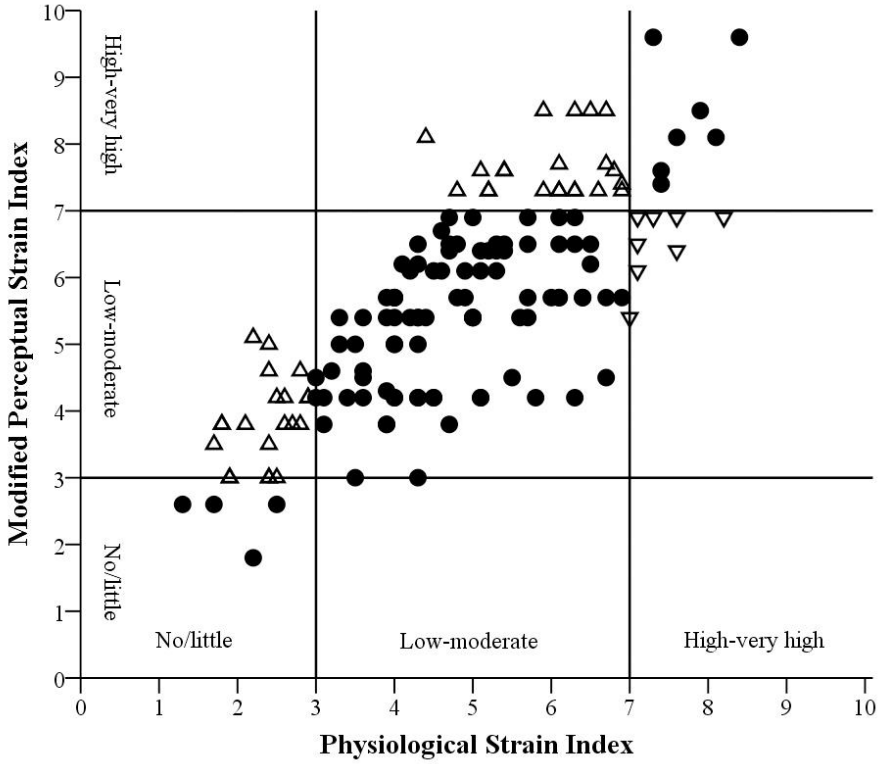

Figure 2. The physiological strain index (PSI) correlated to modified perceptual strain index (PeSI). Vertical and corresponding horizontal reference lines define the three strain categories: no-little (0 – 2.9), moderate (3 – 6.9) and high-very high (7 – 10). Symbols: ● PeSI correctly estimated PSI; △ PeSI overestimated PSI; ▽ PeSI underestimated PSI.

The areas under the ROC curves were 0.936 (95%CI: 0.896 – 0.977) for a PSI of three and 0.841 (95%CI: 0.757 – 0.926) for a PSI of seven (see Figure 3).

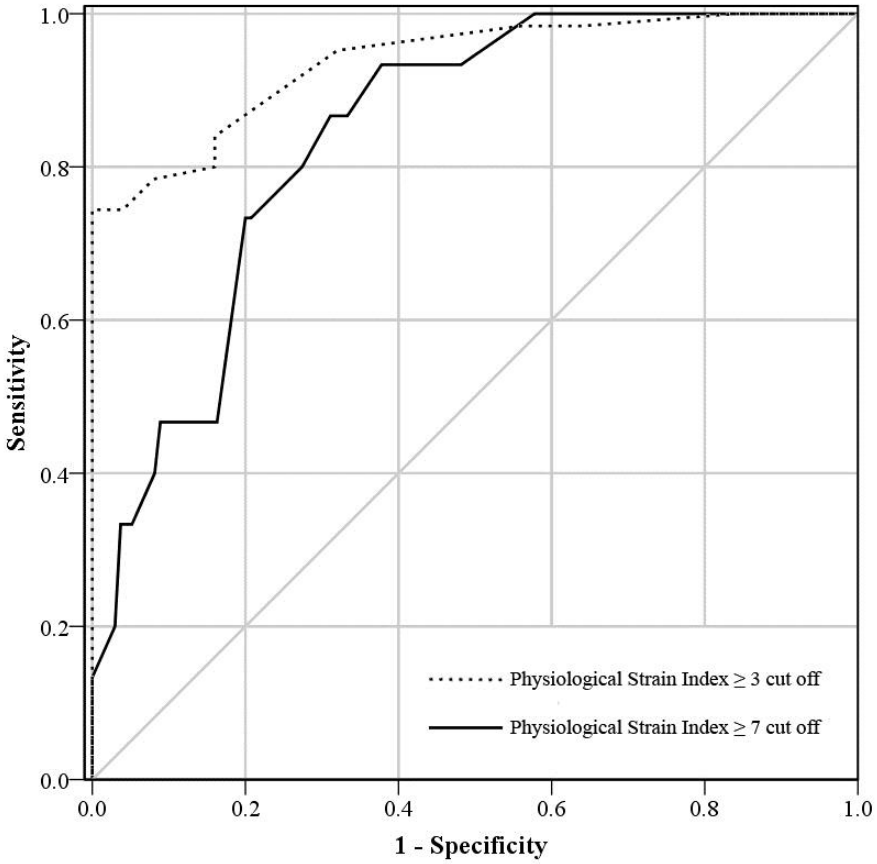

Figure 3. The receiver operating characteristic curves for the modified perceptual strain index with reference to two arbitrary cut-offs of low (PSI of three) and high (PSI of seven) physiological strain. The areas under these curves are 0.936 (95% confidence interval 0.896 to 0.977) and 0.841 (95% confidence interval 0.757 to 0.926). A perfect prediction will have an area of 1.0, while completely random predictions will have an area of 0.5.

A moderate correlation was observed between the PeSI and PSI (r = 0.77; see Figure 4), HR and RPE (r = 0.81), and T_C and thermal sensation (r = 0.62). The mixed linear model revealed the correlation between the PSI and PeSI was significant ($p < 0.001$).

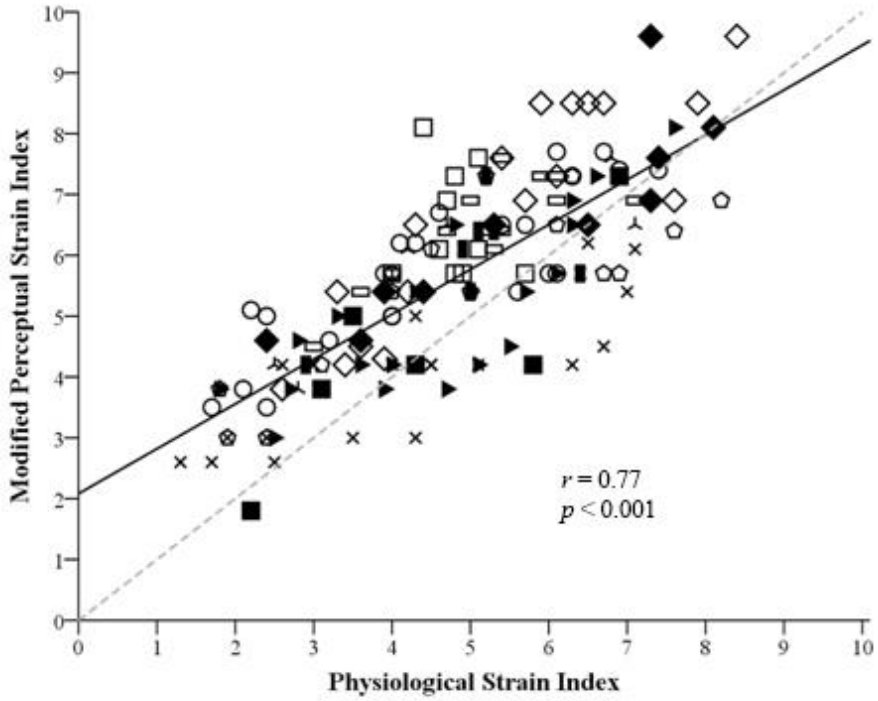

Figure 4. Regression of the physiological strain index and the modified perceptual strain index for all participants across all trials and time points. Solid line represents the trend line; each participant is represented by a unique symbol; the dashed line represents the line of identity.

4. Discussion

This is the first study to examine the ability of a PeSI to estimate the PSI across a range of workloads and environments while wearing heavy PPC. The primary findings to emerge from this research are: (1) a statistically significant moderate relationship exists between the PeSI and PSI; and (2) the PeSI correctly or conservatively (over) estimated the PSI 94.7% of the time. These findings suggest that the PeSI provides a good estimation of physiological strain while wearing heavy encapsulating PPC across a range of environmental and metabolic work intensities.

The current study employed multiple statistical methods to examine the relationship between the PeSI and PSI. In agreement with a previous investigation by Petruzzello et al. [18], a significant moderate relationship existed in the present study between the PeSI and PSI (see Figure 4). In addition, moderate relationships between the interrelated variables of T_C and thermal sensation and HR and RPE were also observed. These findings are consistent with those of Gallagher et al. [19] who reported moderate-to-strong relationships between T_C and thermal sensation (r = 0.679 - 0.826) and HR and RPE (r = 0.862 - 0.916). Furthermore the current study highlights the absolute agreement between the PeSI and PSI improved with increasing physiological strain. Collectively, the findings to emerge from the current

investigation confirm and expand the results observed by Petruzzello et al. [18] and Gallagher et al. [19], as a moderate relationship between a PeSI and the PSI has now been demonstrated across a range of environments and workloads.

The ROC curves (Figure 3) further indicated that the PeSI was a good predictor of the PSI when used with two arbitrary, single cut-offs to differentiate between low (PSI three cut-off) and high (PSI seven cut-off) levels of physiological strain. These arbitrary cut-offs could be adopted as corresponding warning stages: green (no/little strain), amber (low-moderate strain) and red (high-very high strain), creating a 'traffic light' warning system [29]. From a practical standpoint, the PeSI could potentially be employed as an additional field monitoring tool, as an individual's relative risk of suffering a heat related injury is easily identifiable when adopting these warning stages. Occupational safety standards often employ multi-staged warning systems to ensure that a worker can complete the critical task associated with their occupation without undue risk to their health [30]. Perhaps surprisingly, current safety standards do not include perceptual outcome measures for the monitoring of an individual's physiological condition [12,31]. Insight from a psychological perspective would allow a more holistic evaluation of an individual's readiness for further work, potentially leading to a safer working environment. Therefore, future occupational safety standards should consider incorporating perceptual indices in addition to traditional physiological measures.

In the current investigation 34% of the total PeSI responses did not correctly estimate the PSI (see Figure 2). This may be explained by: (1) the thermal sensation and RPE indices used in the current investigation are not appropriately sensitive and therefore not accurate in providing surrogate measures of T_C and HR respectively; or (2) the potential for factors other than thermoregulatory and cardiovascular parameters influencing perception during exercise-heat exposure. In the no/little strain category, the PeSI overestimated the PSI 84% (21/25) of the time compared to the low-moderate category where PeSI overestimated the PSI 20% (22/110) of the time. A potential learning effect [32] may in part explain the initial over estimation of the PSI (via the PeSI) regarding the familiarisation and use of the thermal sensation and RPE scales. Despite familiarising participants with these perceptual scales during the pre-experimental protocol, a potential learning effect may exist. Furthermore, perception may be influenced by a number of physiological (e.g., sleep deprivation, physical fatigue), psychological (e.g., mood state, task incentives, emotional stress) and metabolic (e.g., overtraining) factors [33-36].

To our knowledge, this is the first study to assess the relationship between a PeSI and PSI across a range of workloads and environments. Previous investigations have used either

single [17,18] or interval workloads [18,19] in a solitary environment [17-19]. Furthermore, the weight of PPC used in the current study is considerably heavier compared to previous investigations [17-19]. Only one study [18] has explicitly stated garment weight, reported to be approximately 20 kg, while other studies [17,19] have used fire-fighting (including a self-contained breathing apparatus) and chemical protective garments, which are ~ 10 kg lighter than the EOD and chemical PPC ensemble used in the present study.

Previous research by Tikuisis et al. [17] observed no difference between a PeSI and the PSI when analysing the combined participant data from trained and untrained groups. However, when analysing these groups individually, Tikuisis et al. [17] found that trained participants significantly underestimated the PSI during the first 60-mins of treadmill walking (3.5 $km \cdot h^{-1}$, 0% grade) to volitional fatigue while wearing semi-permeable PPC (weight not specified). Compared to previous literature, the participant cohort of the current study is similar to the 'trained' group recruited by Tikuisis et al. [17] based on age, aerobic capacity and anthropometric data. Tikuisis's observations (that trained individuals underestimated the PSI) are not consistent with those from the present investigation [17]. Indeed, the results of the current study suggest that individuals are more likely to overestimate physiological strain when considered no/little and low-moderate. The discrepancy in findings observed by Tikuisis et al. [17] and the current investigation may be explained by differences in thermoregulatory strain experienced by participants in both studies.

The disparity between these termination data may be explained by the substantial cardiovascular burden created by the higher work intensities and PPC ensemble used in the present investigation [7]. PPC garments are known to increase an individual's metabolic requirement and decrease movement efficiency, while the use of an air purifying respirator is associated with a reduction in maximal oxygen consumption; all of which exacerbate cardiovascular strain [37,38]. The effects of the cardiovascular strain experienced by participants in the present investigation are clear, with 82% of trials terminated due to the attainment of the maximal HR criteria. Therefore, participants in the current investigation were primarily limited by cardiovascular as opposed to thermoregulatory strain. In contrast, Tikuisis et al. [17] observed no trials terminated due to the attainment of maximal HR criteria. The termination and final physiological data of Petruzzello et al. [18] and Gallagher et al. [19] are not known, making further comparisons not possible.

There are several methodological discrepancies between the current study and the three previous studies investigating the relationship between the PeSI and PSI in PPC. Firstly, the present investigation and Petruzzello et al. [18] used the Borg 6-20 RPE. Borg's 6-20 RPE is

considered more sensitive and closely correlated to HR in comparison to the Borg 10-point [17] and OMNI [19] RPE scales. Primarily this can be attributed to the 6-20 RPE's greater response range [24]. This sensitivity is particularly important in the formulation of the PeSI, as the calculation is reliant on RPE providing a surrogate measure of HR.

Petruzzello et al. [18] and Gallagher et al. [19] used different thermal sensation scales in comparison to Tikuisis et al. [17] and the current study. The current study observed only a moderate (r = 0.62) relationship between T_C and thermal sensation. Despite Gallagher et al. [19] using a less sensitive thermal sensation index due to the small scale range compared to the Gagge 7-13 thermal sensation used in the current investigation, a similar correlation between T_C and thermal sensation was observed (r = 0.679). This suggests that these thermal sensation scales are not sufficiently sensitive in providing a surrogate measure of T_C. Indeed, a recent study by Savage et al. [39] concluded that the subjective reporting of thermal sensation was a poor and unreliable means of gauging T_C. Perhaps the use of a stronger surrogate measure of T_C is required in the formulation of the PeSI. Arguably this may lead to a stronger overall relationship between the PeSI and PSI.

The current study and Petruzzello et al. [18] used a modified PSI which incorporated each individual's maximal HR. Comparatively, Tikuisis et al. [17] employed a PSI with a nominal maximal HR of 180 bpm for all participants, only incorporating an individual's age-predicated maximal HR when this nominal HR value was exceeded in any given trial. In the current investigation, theoretical analysis indicated that replacing a participant's calculated maximal HR with the arbitrary value of 180 bpm, the PSI values at the termination of the trials would have increased on average by 0.5 au or 5%. Therefore, variations in the formulation of PSI have the potential to affect the overall relationship observed between the PeSI and PSI. It is noteworthy that the current findings may not reflect a true upper level of physiological strain due to the maximal constraints of T_C and HR used in the calculation of PSI. The ethical constraints of the termination criteria and subsequent formulation of the PSI used in the present study made it impossible for an individual to achieve a PSI value of 10. Theoretical analysis indicated the maximal attainable PSI value achievable was 8.4 a.u.

Previous research has shown that commencing tolerance tests in a hypohydrated state has led to a 20% reduction in performance time [40,41]. Participants in the current study were subject to a more stringent USG value determining euhydration (USG $\leq$ 1.020) in comparison to Gallagher et al. [19] (USG $\leq$ 1.025). Conversely, Tikuisis et al. [17] and Petruzzello et al. [18] did not consider participant pre-trial hydration status. The encapsulating nature of the PPC ensemble and the respirator used in the current investigation made fluid consumption during

trials unfeasible; therefore a more rigorous euhydration measure was adopted prior to the commencement of trials. Moreover, fluid consumption during exercise with PPC in the heat is known to improve tolerance time and decrease perceptual strain [42,43]. Therefore, the absence of fluid consumption during trials in the current study limits the potential confounding of perceptual strain, which may have been present in the study by Tikuisis et al. [17] who allowed participants to consume fluid during trials.

These findings may have limited application in females and individuals with lower aerobic fitness. Given that females are employed as EOD technicians, and previous studies have reported some EOD technicians as having lower aerobic fitness levels (average participant $\dot{V}O_{2max}$ ~ 46 $ml \cdot kg^{-1} \cdot min^{-1}$) [6], this may limit the application of findings from the current investigation. It has been suggested that repeated exercise with PPC results in a psychological habitual adaptation, partially attributed to an improved ability to tolerate the psychological discomfort associated with high levels of skinwettedness [44-46]. Although residents in a sub-tropical region, participants in the current investigation were not acclimatised to each of the environments used in the experimental design. Moreover, it is debatable whether three trials randomised across three environments, each separated by a minimum of one-week would have any influence on psychological heat adaptation; however, dose-response conclusions of heat acclimation remain limited [47].

Future research should consider the relationship between the PeSI and PSI in a broader cross-section of individuals (e.g., gender, age, body composition and surface area), during very high levels of physiological strain and using a more sensitive thermal sensation scale. Finally, exploring the relationship between the PeSI and PSI under field conditions may establish if these laboratory findings are able to be translated to situations of an uncontrolled working environment.

5. Conclusion

This is the first study to explore the ability of a non-invasive, inexpensive PeSI to estimate the PSI across a range of workloads and environments. In the present study, the PeSI correctly or conservatively estimated the PSI 94.7% of the time. Similar predictive precision was observed when these same data were analysed using ROC curves and the absolute agreement between the PeSI and PSI. Moreover, a significant moderate relationship was observed between the PeSI and PSI. Collectively, these results support the use of a PeSI comprised of the Gagge 7-13 thermal sensation and Borg 6-20 RPE in providing an estimation

of physiological strain in young, healthy, aerobically fit males across a range of workloads and environments during prolonged walking (up to 60-mins) while wearing PPC weighing approximately 35 kg. Moreover, these findings suggest the PeSI has the potential to be used as a monitoring tool for physiological strain, although future research is needed to confirm the validity and utility of the PeSI during field operations.

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