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Title Page

The Physiological Strain Index Modified for Trained Heat Acclimatized Individuals in Outdoor Heat

Original Investigation

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Abstract

Purpose: To determine if the physiological strain index (PSI), in original or modified form, can evaluate heat strain on a 0-10 scale, in trained and heat acclimatized men undertaking a competitive half-marathon run in outdoor heat.

Methods: Core (intestinal) temperature (TC) and heart rate (HR) were recorded continuously in 24 males (mean ± SD age: 26 ± 3 years; VO_{2peak}: 59 ± 5 ml·kg·min^{-1}). Four versions of the PSI were computed: original PSI with upper constraints of TC 39.5°C and HR 180 b·min^{-1} ($PSI_{39.5/180}$); and three modified versions of PSI with each having an age-predicted maximal HR constraint and graded TC constraints of 40.0°C ($PSI_{40.0/PHRmax}$), 40.5°C ($PSI_{40.5/PHRmax}$), and 41.0°C ($PSI_{41.0/PHRmax}$).

Results: In a warm (26.1-27.3°C) and humid (79-82%) environment, all runners finished the race asymptomatic in 107 ± 10 (91-137) minutes. Peak TC and HR were 39.7°C ± 0.5 (38.5-40.7°C) and 186 ± 6 (175-196) b·min^{-1}, respectively. Sixty-three percent exceeded TC 39.5°C, 71% exceeded HR 180 b·min^{-1}, and 50% exceeded both of the original PSI upper TC and HR constraints. The computed heat strain was significantly greater with $PSI_{39.5/180}$ than all other methods ($P < 0.003$). PSI >10 was observed in 63% of runners with $PSI_{39.5/180}$, 25% for $PSI_{40.0/PHRmax}$, 8% for $PSI_{40.5/PHRmax}$, and 0% for $PSI_{41.0/PHRmax}$.

Conclusion: The PSI was able to quantify heat strain on a 0-10 scale in trained and heat acclimatized men undertaking a half-marathon race in outdoor heat, but only when the upper TC and HR constraints were modified to 41.0°C and age-predicted maximal HR, respectively.

Introduction

During exercise in hot environments, heat stress refers to the thermal load imposed by environmental and metabolic conditions whereas heat strain refers to the physiological consequences of heat stress.[1] The ability to monitor the heat strain of individuals in the field is an attractive proposition, as this would provide useful data on heat strain during training and competition, heat acclimatization status, and the effectiveness of interventions aimed at mitigating heat strain. A potential candidate is the physiological strain index (PSI), introduced by Moran and colleagues in 1998[2] as a novel and simple method of evaluating heat strain with potential for universal use.[3] The PSI combines normalized increases in core temperature (TC) and heart rate (HR) to produce an instantaneous measure of strain on a 0-10 scale[2,3]. The PSI has demonstrated validity in discriminating between levels of heat strain during laboratory experimental manipulations of environmental heat,[2] heat acclimation status,[4] aerobic fitness status,[4] hydration status,[5] and exercise intensity levels.[5] The merits of the PSI include its simple calculation, use of a 0-10 scale with ease of interpretation, sensitivity to rest and recovery periods, and potential for real-time use.[3] By employing two physiological responses (i.e. TC and HR) that can be measured simultaneously in the field,[6-8] the PSI offers utility as a heat strain monitoring tool for individuals performing in the natural environment.

The external validity and utility of the PSI for trained and heat acclimatized individuals is currently limited by the upper TC and HR constraints of 39.5°C and 180 b·min^{-1}, respectively; which serve to constrain TC and HR contributions to 0-5 values and their sum to a 0-10 scale. The original choice of these constraints is understandable since the PSI was developed and validated on databases of humans exercising in simulated laboratory heat where these physiological thresholds (i.e. TC 39.5°C and HR 180 b·min^{-1}) are typical ethical ceiling end-points.[2,4,5] Whilst these constraints may be appropriate for maintaining safety in laboratory studies, our premise is that they are too low for application to trained and heat acclimatized individuals who commonly exceed TC 39.5°C and HR 180 b·min^{-1}. Widespread evidence of trained individuals exceeding TC 39.5°C and/or HR 180 b·min^{-1} during training and competition in a variety of sports exists (e.g. cycling,[9,10] distance running,[6,11] football codes,[8,12,13] and tennis[14]). In 11 runners undertaking an 8 km running race in WBGT 26-28°C, Ely et al.[7] observed that 100% of runners had peak TC >39.5°C (39.7-40.9°C) and peak HR was 186 (175-195) b·min^{-1}. Unless the upper TC and HR constraints of the PSI are increased to accommodate these higher physiological responses, the PSI will over-estimate the heat strain of trained individuals, and their physiological responses could result in PSI ratings exceeding and invalidating the 0-10 scale.

Endurance trained individuals have the potential to produce TC >39.5°C due to their higher rates of metabolic heat production[15,16] and enhanced tolerance to high TC.[17,18] The potential to produce HR >180 b·min^{-1} is due to this value representing a high but submaximal HR until >40 years of age,[19,20] the high exercise intensities produced in training and competition[7,8,10,12,21,22] and the elevated HR response associated with heat stress.[1,23] Our premise is that modification of PSI TC and HR upper constraints is required to reflect the magnitude of the physiological responses produced by trained and heat acclimatized individuals in heat. Support for this premise was provided by Tikuisis et al.[24] who reported that PSI and a perceptual strain equivalent were significantly different in trained (lower perceived strain) but not untrained individuals when the TC constraint was 39.5°C. This difference was eliminated in the trained sample when the TC constraint was raised to 40.1°C and the authors suggested adjusting the TC constraint to a more appropriate value for trained individuals.[24] We propose that more appropriate upper TC and HR PSI constraints than 39.5°C and 180 beats·min^{-1} are required to: i) ensure a PSI of 10 represents maximal physiological heat strain (i.e. maximal TC and HR) and; ii) avoid violating the 0-10 scale. Therefore, the aim of the current study was to determine if the PSI, in original or modified form, could quantify strain on a 0-10 scale in trained and heat acclimatized men undertaking a competitive 21.1 km outdoor run in heat. Our first objective was to employ the PSI with original TC and HR upper constraints (i.e. 39.5°C & 180 $b \cdot min^{-1}$). Our second objective was to investigate the influence of employing higher PSI TC constraints more appropriate to the higher TC responses produced by trained individuals (i.e. 40.0, 40.5°C & 41.0°C) and a HR constraint based on the individual's age-predicted maximal HR.[20]

Methods

Participants and Design

The database from the observational study of Lee et al.[25] was used in this study for retrospective analysis. This represented the physiological responses of 31 trained and heat acclimatized males participating in a 21.1 km mass-participation road-running race. They were heat acclimatized due to their prolonged military training in a warm-humid environment. Participants were volunteers and provided written informed consent to participate in the study. The study was approved by the Institutional Review Board and conformed to the standards set by the Declaration of Helsinki. Twenty-four of the 31 participants had complete TC and HR datasets and were included in this study (mean ± SD age: 26 ± 3 y; body mass: 65.5 ± 6.5 kg; height: 1.72 ± 0.05 m; VO_{2peak}: 59 ± 5 (51-68) $ml \cdot kg \cdot min^{-1}$.

Methodology

Four weeks prior to the race, each individual performed an incremental treadmill test to volitional exhaustion for the determination of VO_{2peak} and maximal HR. On race day, the 21.1 km mass-participation event started at 0545 hours on a flat course at sea-level. TC and HR were measured at 15 s intervals throughout the race and averaged over one-minute intervals. HR was measured by a telemetry system (Polar Vantage, Polar EleTCtro Oy, Kempele, Finland). Ingestible telemetric temperature sensors and ambulatory data recorders measured gastro-intestinal temperature as an index of TC using CorTemp™ (HQ Inc., Palmetto, Florida, USA) and VitalSense® (Phillips Respironics, Bend, Oregon, USA) systems.[26] Pre-race resting TC and HR values were obtained during a five minute period of seated rest. Measures of pre-race hydration status (including urine specific gravity) and fluid balance were assessed as previously described.[25] Environmental conditions were measured throughout the race. Heat balance parameters and the heat stress index (i.e. ratio of required evaporative cooling to maximum evaporative capacity of the environment) were estimated using the methods described by Brotherhood.[27] Heat strain was quantified by four PSI methods and categorized according to Table 1.

**** Insert Table 1 Here ****

Original PSI ($PSI_{39.5/180}$)

The original PSI with TC and HR constraints of 39.5°C and 180 b·min^{-1} (i.e. $PSI_{39.5/180}$), respectively, was computed at one-minute intervals as follows (Equation 1):

$$\mathrm{PSI}_{39.5/180} = 5(\mathrm{TC_t} - \mathrm{TC_0}) \div (39.5 - \mathrm{TC_0})^{-1} + 5(\mathrm{HR_t} - \mathrm{HR_0}) \div (180 - \mathrm{HR_0})^{-1} \qquad (1)$$

where TC_0 and HR_0 are the pre-race measured resting TC and HR, respectively; and TC_t and HR_t are simultaneous measurements taken at any time.

Modified PSI ($PSI_{40.0/PHRmax}$, $PSI_{40.5/PHRmax}$, $PSI_{41.0/PHRmax}$)

Three modified versions of the PSI were computed with each having a HR constraint based on the individual's age-predicted maximal HR and graded TC constraints of 40.0°C (Equation 2), 40.5°C (Equation 3), and 41.0°C (Equation 4). PSI was computed at one-minute intervals as follows:

$$\mathrm{PSI}_{40.0/\mathrm{PHRmax}} = 5(\mathrm{TC_t} - \mathrm{TC_0}) \div (40.0 - \mathrm{TC_0})^{-1} + 5(\mathrm{HR_t} - \mathrm{HR_0}) \div (\mathrm{PHRmax} - \mathrm{HR_0})^{-1} \qquad (2)$$

$$\mathrm{PSI}_{40.5/\mathrm{PHRmax}} = 5(\mathrm{TC_t} - \mathrm{TC_0}) \div (40.5 - \mathrm{TC_0})^{-1} + 5(\mathrm{HR_t} - \mathrm{HR_0}) \div (\mathrm{PHRmax} - \mathrm{HR_0})^{-1} \qquad (3)$$

$$\mathrm{PSI}_{41.0/\mathrm{PHRmax}} = 5(\mathrm{TC_t} - \mathrm{TC_0}) \div (41.0 - \mathrm{TC_0})^{-1} + 5(\mathrm{HR_t} - \mathrm{HR_0}) \div (\mathrm{PHRmax} - \mathrm{HR_0})^{-1} \qquad (4)$$

where TC_0 and HR_0 are the pre-race measured resting TC and HR, respectively; TC_t and HR_t are simultaneous measurements taken at any time; and PHRmax is the age-predicted maximal HR using the Nes et al.[20] formula: PHRmax (b·min^{-1}) = 211 – 0.64 × Age.

Statistical Analysis

Data were analysed with IBM SPSS Statistics 24 and statistical significance was accepted as $P < 0.05$. Descriptive data are presented as mean ± SD and range. A paired-sample t-test compared means for measured and age-predicted maximal HR. Single-factor (Time (7): minutes 15, 30, 45, 60, 75, 90, & final) repeated measures ANOVA investigated changes in TC and HR over time. Two-factor (Time (7) x PSI method (4)) repeated measures ANOVA compared PSI method (i.e. $PSI_{39.5/180}$, $PSI_{40.0/PHRmax}$, $PSI_{40.5/PHRmax}$, and $PSI_{41.0/PHRmax}$) over time for total PSI, PSI TC component, PSI HR component, and percent TC and HR contribution to total PSI. Bonferroni follow-up tests were employed with adjustments for multiple comparisons. Mean differences are presented with 95% confidence intervals (95% CI). The standardized mean difference effect size (Cohen's *d*) was calculated and interpreted as: trivial (< 0.2); small (≥ 0.2); medium (≥ 0.5); and large (≥ 0.8). Multiple regression analyses were conducted to determine the significant predictors of final and peak $PSI_{41.0/PHRmax}$. The dependent variables considered related to endurance parameters (e.g. VO_{2peak}, $\%VO_{2peak}$), anthropometry (e.g. body mass, body surface area, % fat), hydration status and fluid balance (e.g. pre-race urine specific gravity, fluid intake, % dehydration), and heat production (e.g. W, W·kg^{-1}, W·m^2). A stepwise forward entry method was used based on entry of the dependent variable correlating highest with the independent variable, followed by the highest correlate with the standardized residual variance, until there were no significant correlates with the residual variance.

Results

Environmental Conditions & Race Performance

Environmental conditions varied minimally throughout the race, being warm (dry bulb temperature = 26.1-27.3C°), humid (relative humidity = 79-82%), and calm (air velocity = 0.0-1.1 $m \cdot s^{-1}$). The heat stress index (HSI) indicated a physiologically compensable environment (HSI = 0.82 ± 0.08 (0.65-0.97)). All 24 participants completed the race asymptomatic and their performance and physiological responses are illustrated in Table 2.

**** Insert Table 2 Here ****

Core Temperature & Heart Rate Responses

Fig 1 illustrates the continuous individual TC and HR responses and Table 2 illustrates mean, peak values, and final values. For peak TC, 63% of runners recorded TC >39.5°C, 33% >40.0°C, 8% >40.5°C, and 0% >41.0°C. For peak HR, 71% of runners recorded HR >180 $b \cdot min^{-1}$. Fifty percent of runners exceeded both 39.5°C and 180 $b \cdot min^{-1}$. Significant increases in TC were observed at 30-, 75-, and 90-min ($P \leq 0.024$); HR increased significantly from 15-min only at the final minute ($P = 0.006$). HR drift from 15-min (172 ± 8 $b \cdot min^{-1}$) to 90-min (177 ± 9 $b \cdot min^{-1}$) was 5.3 (1.4, 11.9) $b \cdot min^{-1}$ ($P = 0.294$, $d = 0.59$) or 3.1%. Measured maximal HR (193 ± 7 $b \cdot min^{-1}$) was not significantly different from the age-predicted estimate (195 ± 2 $b \cdot min^{-1}$; mean difference = -1.5 (-4.3, 1.3) $b \cdot min^{-1}$, $P = 0.225$, $d = 0.30$) employed in the three modified PSI equations. Two runners exceeded their age-predicted maximal HR by 1 and 2 $b \cdot min^{-1}$ during the race.

**** Insert Figure 1 Here ****

Total PSI

Fig 2A-D illustrate the continuous individual PSI responses according to the four PSI methods. Peak values were 10.7 ± 1.5 (8.1-13.7) for $PSI_{39.5/180}$, 9.0 ± 1.2 (7.1-11.4) for $PSI_{40.0/PHRmax}$, 8.3 ± 1.0 (6.6-10.4) for $PSI_{40.5/PHRmax}$, and 7.8 ± 0.9 (6.2-9.5) for $PSI_{41.0/PHRmax}$. Table 3 illustrates that final PSI was significantly greater with $PSI_{39.5/180}$ than all other methods ($P \leq 0.001$) with large effect sizes and also significantly greater with $PSI_{40.0/PHRmax}$ than $PSI_{41.0/PHRmax}$ (mean difference = 1.2 (0.4, 2.0) units, $P = 0.037$, $d = 0.91$). Fig 3A illustrates that heat strain throughout the race with $PSI_{39.5/180}$ was significantly greater than all other methods ($P < 0.003$) and heat strain with $PSI_{40.0/PHRmax}$ was significantly greater than $PSI_{41.0/PHRmax}$ ($P < 0.001$). Fig 4A-D illustrate that $PSI_{39.5/180}$ categorized the majority (63%) of runners as experiencing heat strain >10, whereas $PSI_{40.0/PHRmax}$ (50%), $PSI_{40.5/PHRmax}$ (63%), and $PSI_{41.0/PHRmax}$ (75%) categorized the majority of runners as experiencing high (i.e. $\geq 7 < 9$) heat strain. $PSI_{40.0/PHRmax}$ and $PSI_{40.5/PHRmax}$ categorized 25% and 8% of runners as experiencing heat strain >10, respectively (see Fig 4B & 4C). Only $PSI_{41.0/PHRmax}$ quantified heat strain on a 0-10 scale for all runners (see Fig 4D). Table 4 illustrates that a two-component multiple regression model (i.e. mean speed and pre-race urine specific gravity) explained 57% of the variation in final

$PSI_{41.0/PHRmax}$ and a single-component model (i.e. mean speed) explained 17% of the variance in peak $PSI_{41.0/PHRmax}$.

**** Insert Figure 2 Here ****

PSI TC Component

The PSI TC component exceeded 5.0 in 63% of runners when quantified by $PSI_{39.5/180}$, 33% for $PSI_{40.0/PHRmax}$, 8% for $PSI_{40.5/PHRmax}$, and 0% for $PSI_{41.0/PHRmax}$. Fig 3B illustrates that $PSI_{39.5/180}$ TC was significantly greater than all other methods during the race ($P < 0.003$) and $PSI_{40.0/PHRmax}$ was significantly greater than $PSI_{40.5/PHRmax}$ and $PSI_{41.0/PHRmax}$ (both $P < 0.001$). Table 3 illustrates that final PSI TC was significantly greater with $PSI_{39.5/180}$ than all other methods ($P \leq 0.001$) with moderate-to-large large effect sizes and also significantly greater with $PSI_{40.0/PHRmax}$ than $PSI_{41.0/PHRmax}$ (mean difference = 1.2 (0.6, 1.9) units, $P = 0.007$, d = 1.07). The mean relative contribution of the TC component to total PSI differed significantly between all methods ($P < 0.001$): $PSI_{39.5/180}$ (39.8 (38.0, 41.6) %), $PSI_{40.0/PHRmax}$ (37.7 (35.9, 39.4) %), $PSI_{40.5/PHRmax}$ (34.0 (32.4, 35.7) %), and $PSI_{41.0/PHRmax}$ (31.2 (29.6, 32.9) %).

PSI HR Component

The PSI HR component exceeded 5.0 in 75% of runners when quantified by $PSI_{39.5/180}$ and 8% for the three PSI methods employing the age-predicted maximal HR constraint. Fig 3C illustrates that $PSI_{39.5/180}$ HR component was significantly greater than all other methods during the race ($P < 0.003$). Table 3 illustrates that final PSI HR was significantly greater with $PSI_{39.5/180}$ than all other methods ($P \leq 0.001$) with large effect sizes. The mean relative contribution of the HR component to total PSI differed significantly between all methods ($P < 0.001$): $PSI_{39.5/180}$ (60.2 (58.4, 62.0) %), $PSI_{40.0/PHRmax}$ (62.3 (60.6, 64.1) %), $PSI_{40.5/PHRmax}$ (66.0 (64.3, 67.6) %), and $PSI_{41.0/PHRmax}$ (69.0 (67.4, 70.6) %). The relative contribution of HR to total PSI was significantly higher than the TC contribution until equivalence was reached at 75-min for $PSI_{39.5/180}$ ($P \leq 0.015$), at the final minute for $PSI_{40.0/PHRmax}$ ($P \leq 0.015$), and throughout the race for $PSI_{40.5/PHRmax}$ ($P \leq 0.001$) and $PSI_{41.0/PHRmax}$ ($P \leq 0.001$).

**** Insert Figure 3 Here ****

**** Insert Figure 4 Here ****

**** Insert Table 3 Here ****

**** Insert Table 4 Here ****

Discussion

The main finding of this study is that only when the PSI upper TC and HR constraints are modified (to 41.0°C and age-predicted maximal HR, respectively), does PSI quantify heat strain on a 0-10 scale for trained and heat acclimatized men undertaking competitive endurance exercise in outdoor heat. The original PSI constraints of TC 39.5°C and HR 180 $b \cdot min^{-1}$ were demonstrated as too low for this population, since almost two-thirds of our sample exceeded 39.5°C, nearly three-quarters exceeded 180 $b \cdot min^{-1}$, and half the sample exceeded both. This resulted in 63% of the sample exhibiting heat strain that exceeded the 0-10 scale. Substituting the HR constraint of 180 $b \cdot min^{-1}$ for age-predicted maximal HR and employing higher fixed TC constraints, considered more relevant to a trained and heat acclimatized population, reduced or eliminated the proportion of individuals exceeding the 0-10 scale (i.e. 25% with $PSI_{40.0/PHRmax}$, 8% with $PSI_{40.5/PHRmax}$, and 0% with $PSI_{41.0/PHRmax}$).

The use of predicted or measured maximal HR as the upper PSI HR constraint is a logical and simple solution to the problem of individuals exceeding an arbitrary fixed value. We employed age-predicted maximal HR as we wished to test readily available PSI equations requiring no prior physiological testing. We observed no difference between measured and predicted maximal HR using the Nes et al.[20] formula (mean difference = -1.5 (-4.3, 1.3) $b \cdot min^{-1}$, $P = 0.225$, $d = 0.30$), with only two runners exceeding the age-predicted maximal HR during the race by 1-2 $b \cdot min^{-1}$. Furthermore, a comparison of the PSI HR component calculated with measured and predicted maximal HR revealed no differences in mean PSI HR (mean difference = -0.04 (-0.18, 0.09) units, $P = 1.0$, $d = 0.09$). Employing measured maximal HR may offer marginally greater sensitivity of the PSI, since the between-subject variability in maximal HR at a given age is approximately 7-11 $b \cdot min^{-1}$,[19] whereas the within-subject variability in measured maximal HR is typically 3 $b \cdot min^{-1}$.[28] Previous laboratory studies have computed PSI with measured maximal HR as the upper HR constraint to overcome the issue of individuals exceeding the 180 $b \cdot min^{-1}$ limit.[24,29] Whilst the use of age-predicted maximal HR is a superior approach to the arbitrary 180 $b \cdot min^{-1}$ constraint, when available, the measured maximal HR should be employed as the upper HR constraint to provide greater individualisation of the PSI.

The mean relative exercise intensity (%HRmax) observed in the current study was 90 ± 3 %, which is remarkably consistent with previous observations of HR during competitive 21-km running in cooler environments, such as 91 ± 1 %,[30] 89 ± 3 %,[30] and 91%.[21] Heart rate was consistent throughout the race with a significant increase from 15-min only observed in the final minute of the race. Estimated cardiovascular drift from 15- to 90-min was minimal (i.e. 5 $b \cdot min^{-1}$ or 3 %) and would be predicted to reduce stroke volume by 2-3% and VO_{2peak} by 5-6%.[23] Our runners exhibited a reverse J-shaped pacing profile, characterised by an early slowing of pace and final end-spurt,[25] which is typical of self-paced performance in heat.[1] Such a strategy appears to have been successful in minimising cardiovascular drift and maintaining a cardiovascular reserve.[23]

The use of a fixed upper PSI TC constraint is appealing as it has practical value that would enable standardised comparisons within or between participants in a sport or between participants across sports. The original constraint of 39.5°C was demonstrated as too low for trained and heat acclimatized individuals competing in heat since we observed 63% of individuals exceeding this limit. In a laboratory study, Tikuisis et al.[24] reported that physiological and perceptual strain were better aligned in trained individuals when the upper PSI TC constraint was 40.1°C rather than 39.5°C. However, our data suggest that a 40.0°C limit is also too low for the trained and heat acclimatized population since one-third exceeded this limit. This is supported by similar studies of 8-km and 21-km running in heat, where peak

TC >40.0°C was observed in 82%[7] and 50%[6] of the study samples, respectively. Evidence also suggests that trained individuals exceed TC 39.5°C and 40.0°C when competing in cycling,[9] football codes[8,12,13], and tennis.[14] In our study, applying TC constraints of 40.5°C and 41.0°C produced TC component and total PSI values that were not significantly different from each other (see Table 4 & Fig 3A&B) and the categorisation of heat strain between the two methods was not meaningfully altered (see Fig 4C&D). Although, the constraint of 40.5°C was exceeded by only 8% (2/24) of runners, it was only by applying a TC constraint of 41.0°C that we could accommodate all TC responses. A 41.0°C TC constraint would accommodate the recently reported range of peak TC values for trained individuals undertaking an 8-km track running race (39.7-40.9°C) and a 40.3-km cycling time trial (39.6-41.0°C).[7,9] However, not all TC responses would be accommodated since observations of TC >41.0°C in asymptomatic distance runners are observed, albeit infrequently.[6,31-34] With the minimal lethal TC for humans being approximately 42°C,[1] a TC constraint of 41°C strikes a balance between capturing the majority of TC responses and maintaining a safety threshold. Therefore, for future use of PSI with trained and heat acclimatized individuals, we recommend employing an upper TC constraint of 41°C.

Mean speed (ΔR^2 = .48) and pre-race urine specific gravity (ΔR^2 = .13) were identified as significant predictors of final $PSI_{41.0/PHRmax}$, explaining 57% of the variance. Running speed has frequently been observed to correlate positively with final TC in field studies[35,36] and our findings extend this relationship to PSI. Running speed was positively associated with both final PSI TC (R^2 = .45, P < 0.001) and HR components (R^2 = .28, P = 0.008). Cramer and Jay[16] recently demonstrated that heat production in $W \cdot kg^{-1}$ was the single best predictor of ΔTC during 60 min of laboratory cycling, explaining 50% of the variance. We suggest that mean speed in the current study represents the best surrogate measure of metabolic heat production. Mean speed was most strongly and positively associated with predicted mean heat production expressed in $W \cdot kg^{-1}$ (R^2 = .72, P < 0.001) and predicted heat production in $W \cdot kg^{-1}$ was also positively associated with peak (R^2 = .20, P = 0.028) and final $PSI_{41.0/PHRmax}$ (R^2 = .31, P = 0.005). Pre-exercise urine specific gravity, as a measure of hydration status, was also positively associated with both final PSI TC (R^2 = .21, P = 0.025) and HR components (R^2 = .41, P = 0.001) and independently explained 13% of the variance in final $PSI_{41.0/PHRmax}$. Armstrong et al.[37] reported that a urine specific gravity in the range 1.018-1.020 represents euhydration and our values ranged from 1.001-1.025. Our findings provide general support to the concept that PSI is sensitive to pre-exercise hydration status.[5]

Practical Applications

The PSI is a simple tool requiring the simultaneous measurements of HR and TC to provide a heat strain rating on a 0-10 scale, which can be employed by the sports physiologist in the field. Simple modifications to the upper TC and HR constraints (i.e. 41.0°C and age-predicted or measured maximal HR) will increase the utility of the PSI for trained and heat acclimatized individuals. The index should prove valuable in providing objective evidence of heat adaptation and the effectiveness of heat strain mitigation interventions (i.e. reduced PSI during constant load exercise), and the magnitude of heat strain experienced during training and competition in environmental heat. The participants in this study were naturally heat acclimatized as a result of their prolonged military training in a warm-humid environment and our findings are generalizable to individuals with prolonged heat acclimatization and thermal tolerance status. Our study data should prove useful in providing comparative data for such individuals undertaking competitive endurance exercise in natural environmental heat.

Consideration should be given to appropriate PSI constraints for non-endurance trained and non-heat acclimatized populations. Tikuisis et al.[24] observed that physiological and perceptual strain were aligned in untrained and unacclimatized individuals with constraints of 39.5°C/maximal HR and 40.1°C/maximal HR for trained and unacclimatized individuals. We support the use of these constraints for the specific populations and recommend the 40.5°C and 41.0°C constraints are reserved for the endurance trained and fully heat acclimatized individuals. Consideration of the training and heat acclimatization status of the individual by the sports physiologist and sports medicine practitioner should inform selection of appropriate PSI constraints

Future research and practice may wish to establish individualised PSI equations based on an individual's measured maximal HR and a maximal TC established during a competitive effort. The between-subject variability in TC response to self-paced exercise is typically large (e.g. peak TC 38.2-40.7°C in current study), variability remains even in highly controlled settings,[15,16] and therefore a within-subject approach would be expected to increase the sensitivity of the PSI. A high skin temperature in combination with a high TC impairs aerobic exercise performance in heat[38] and therefore future physiological heat strain indices should investigate the incorporation of skin temperature.

Study Limitations

We acknowledge that the alternative to applying different TC and HR constraints based on the population under study is to apply the original 39.5°C/180 beats·min^{-1} constraints and interpret the heat strain output differently for specific populations. However, as demonstrated in the current study, this will likely result in a large proportion of PSI responses exceeding the value of 10. We believe the simple 0-10 scale is a major strength of PSI and this feature should be retained by simple modification of PSI constraints based on the population under study.

Conclusions

The physiological strain index was able to quantify heat strain on a 0-10 scale in trained and heat acclimatized men undertaking a competitive half-marathon running race in heat, but only when the upper TC and HR constraints were modified to 41.0°C and age-predicted maximal HR, respectively. We recommend simple modifications to the upper TC and HR constraints (i.e. 41.0°C and age-predicted or measured maximal HR value) to increase the utility of this heat strain index for trained and heat acclimatized individuals.

Conflict of Interest

None declared.

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Table 1: Evaluation and categorization of heat strain by PSI.

PSI	Strain
0	
1	No to little
2	
3	Low
4	
5	Moderate
6	
7	High
8	
9	Very high
10	Maximal

Adapted from Moran et al.[2] to indicate a PSI of 10 represents maximal physiological strain i.e. attainment of maximal heart rate and maximal delineated core temperature for the population under study.

Table 2: Summary of the physiological responses to the 21-km race.

	Mean ± SD	Range
Pre-race urine specific gravity (units)	1.013 ± 0.007	1.001-1.025
Mean speed ($km \cdot h^{-1}$)	11.7 ± 1.0	9.1-13.7
Mean TC (°C)	39.0 ± 0.3	38.1-39.5
Peak TC (°C)	39.7 ± 0.5	38.5-40.7
Final TC (°C)	39.6 ± 0.6	38.2-40.7
Mean HR ($b \cdot min^{-1}$)	173 ± 7	161-187
Peak HR ($b \cdot min^{-1}$)	186 ± 6	175-196
Final HR ($b \cdot min^{-1}$)	181 ± 10	159-195
Mean %HRmax	90 ± 3	84-97
Peak %HRmax	96 ± 3	90-100
Final %HRmax	94 ± 5	83-100
Mean VO_2 ($ml \cdot kg \cdot min^{-1}$)	43 ± 4	35-49
Mean $\%VO_{2peak}$	72 ± 5	59-80
Mean heat production		
W	943 ± 114	739-1132
$W \cdot m^2$	531 ± 52	448-622
$W \cdot kg^{-1}$	14.4 ± 1.4	12.2-16.9
Fluid intake (L)	0.29 ± 0.21	0-0.74
Sweat loss (L)	2.58 ± 0.59	1.54-4.40
Sweat rate ($L \cdot h^{-1}$)	1.45 ± 0.33	0.85-2.28
Body mass loss (kg)	2.58 ± 0.61	1.73-4.46
Dehydration (%)	3.93 ± 0.80	2.53-6.20

Table 3: Comparison of final values for PSI total score, PSI TC component, and PSI HR component across four PSI computational methods, and mean differences from $PSI_{39.5/180}$ for each modified PSI method.

	Mean ± SD (range)	Mean Difference (95% CI)	*P* value	Effect Size (*d*)
PSI Total				
$PSI_{39.5/180}$	10.3 ± 1.8 (5.7-13.7)			
$PSI_{40.0/PHRmax}$	8.8 ± 1.5 (4.9-11.4)	1.6 (0.4, 2.7)	0.002	0.94
$PSI_{40.5/PHRmax}$	8.1 ± 1.3 (4.7-10.3)	2.2 (1.1, 3.4)	0.000	1.41
$PSI_{41.0/PHRmax}$	7.6 ± 1.1* (4.5-9.5)	2.8 (1.6, 3.9)	0.000	1.80
PSI TC Component				
$PSI_{39.5/180}$	5.3 ± 1.6 (1.6-8.2)			
$PSI_{40.0/PHRmax}$	4.3 ± 1.3 (1.3-6.5)	1.0 (0.1, 2.0)	0.026	0.73
$PSI_{40.5/PHRmax}$	3.6 ± 1.0 (1.1-5.4)	1.7 (0.8, 2.7)	0.000	1.30
$PSI_{41.0/PHRmax}$	3.1 ± 0.9† (0.9-4.6)	2.2 (1.3, 3.1)	0.000	1.72
PSI HR Component				
$PSI_{39.5/180}$	5.1 ± 0.4 (4.1-5.7)			
$PSI_{40.0/PHRmax}$	4.5 ± 0.4 (3.6-5.0)	0.5 (0.2, 0.7)	0.000	1.36
$PSI_{40.5/PHRmax}$	4.5 ± 0.4 (3.6-5.0)	0.5 (0.2, 0.7)	0.000	1.36
$PSI_{41.0/PHRmax}$	4.5 ± 0.4 (3.6-5.0)	0.5 (0.2, 0.7)	0.000	1.36

*Indicates mean is significantly less than $PSI_{40.0/PHRmax}$, *$P = 0.037$; †$P = 0.007$.

Table 4: Multiple regression models for the prediction of final and peak $PSI_{41.0/PHRmax}$.

	B	*SE B*	*β*	*P* value	R^2
Final PSI					
Constant	-62.56	23.43			
Mean Speed ($km \cdot h^{-1}$)	0.62	0.16	.57	0.001	.48
Pre-race urine specific gravity (units)	62.06	23.69	.38	0.016	.13
Adjusted R^2					.57
Peak PSI					
Constant	3.20	1.97			
Mean Speed ($km \cdot h^{-1}$)	0.39	0.17	.45	0.028	.20
Adjusted R^2					.17

Pre USG, pre-race urine specific gravity.

Figure Captions

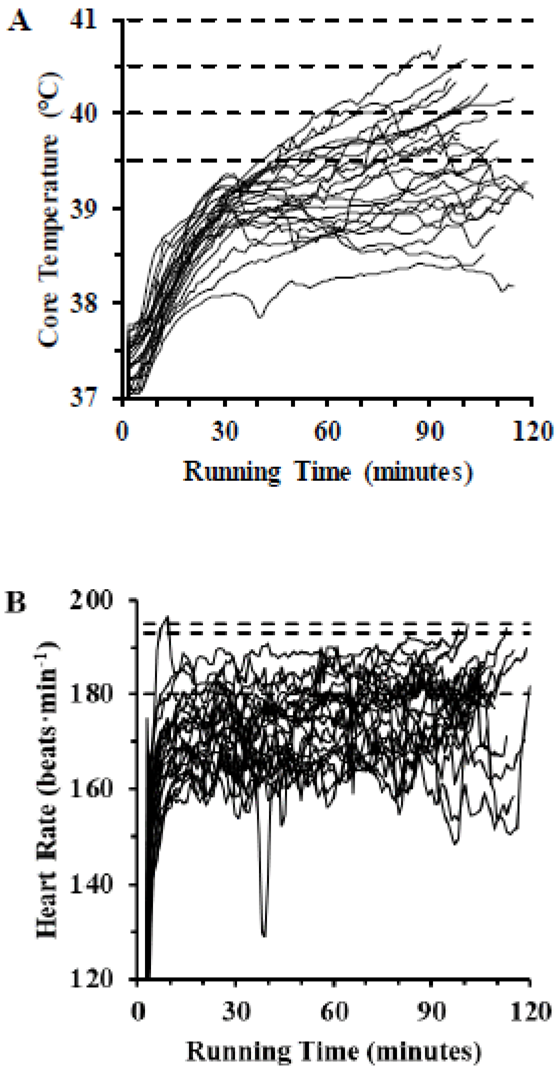
Figure 1: Individual core temperature (**A**) and heart rate (**B**) responses to the race. Dashed lines illustrate the PSI TC constraints of 39.5, 40.0, 40.5, and 41.0°C (**A**); the PSI HR constraint of 180 $b \cdot min^{-1}$, measured mean maximal HR of 193 $b \cdot min^{-1}$, and predicted mean maximal HR of 195 $b \cdot min^{-1}$ (**B**). For clarity, chart is truncated for two runners finishing >120-min (126- & 137-min).

Figure 2: Individual PSI responses of the 24 participants to the 21.1 km race according to PSI calculation method: (**A**) $PSI_{39.5/180}$; (**B**) $PSI_{40.0/PHRmax}$; (**C**) $PSI_{40.5/PHRmax}$; (**D**) $PSI_{41.0/PHRmax}$. Dashed lines represent the theoretical maximal PSI rating of 10. For clarity, chart is truncated for two runners finishing >120-min (126- & 137-min).

Figure 3: PSI total (**A**), PSI TC component (**B**), and PSI HR component (**C**) responses to the race according to PSI method. Symbols indicate main effect for PSI method: $^{*}PSI_{39.5/180}$ is significantly greater than $PSI_{40.0/PHRmax}$, $PSI_{40.5/PHRmax}$ and $PSI_{41.0/PHRmax}$ ($P < 0.003$); $^{‡}PSI_{40.0/PHRmax}$ is significantly greater than $PSI_{40.5/PHRmax}$ ($P < 0.001$); and $^{†}PSI_{40.0/PHRmax}$ is significantly greater than $PSI_{41.0/PHRmax}$ ($P < 0.001$).

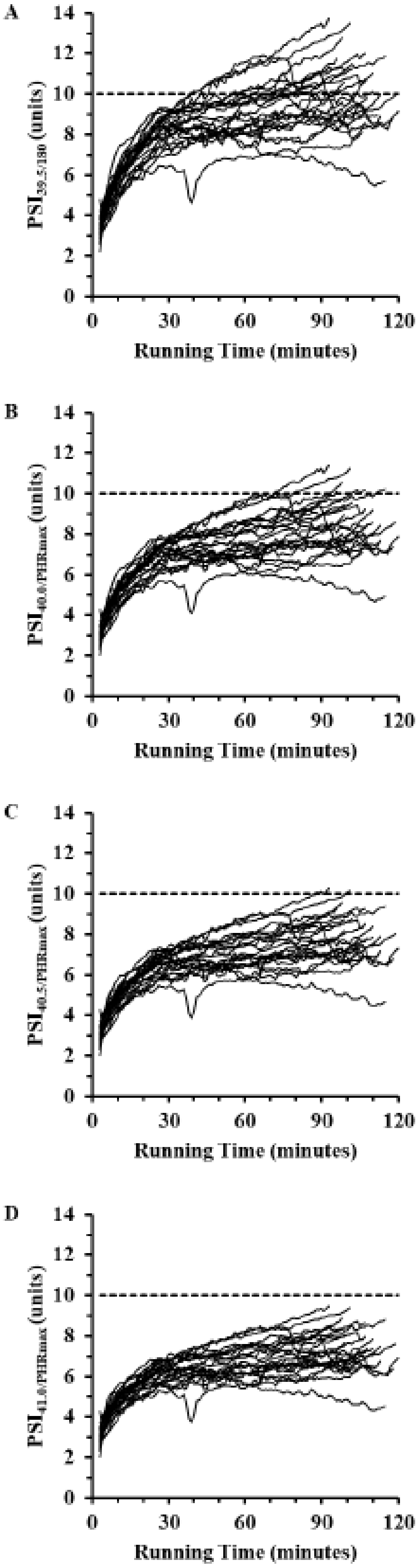
Figure 4: Proportion of sample categorized to a heat strain rating based on peak PSI and according to PSI calculation method: (**A**) $PSI_{39.5/180}$; (**B**) $PSI_{40.0/PHRmax}$; (**C**) $PSI_{40.5/PHRmax}$; and (**D**) $PSI_{41.0/PHRmax}$.

Figure 1:



A
41
40
39
38
37
Core Temperature (ºC)
0
30
60
90
120
Running Time (minutes)
B
200
180
160
140
120
Heart Rate (beats·min-1)
0
30
60
90
120
Running Time (minutes)

Figure 2:



A
PSI39.5/180 (units)
Running Time (minutes)
B
PSI40.0/PHRmax (units)
Running Time (minutes)
C
PSI40.5/PHRmax (units)
Running Time (minutes)
D
PSI41.0/PHRmax (units)
Running Time (minutes)

Figure 3:

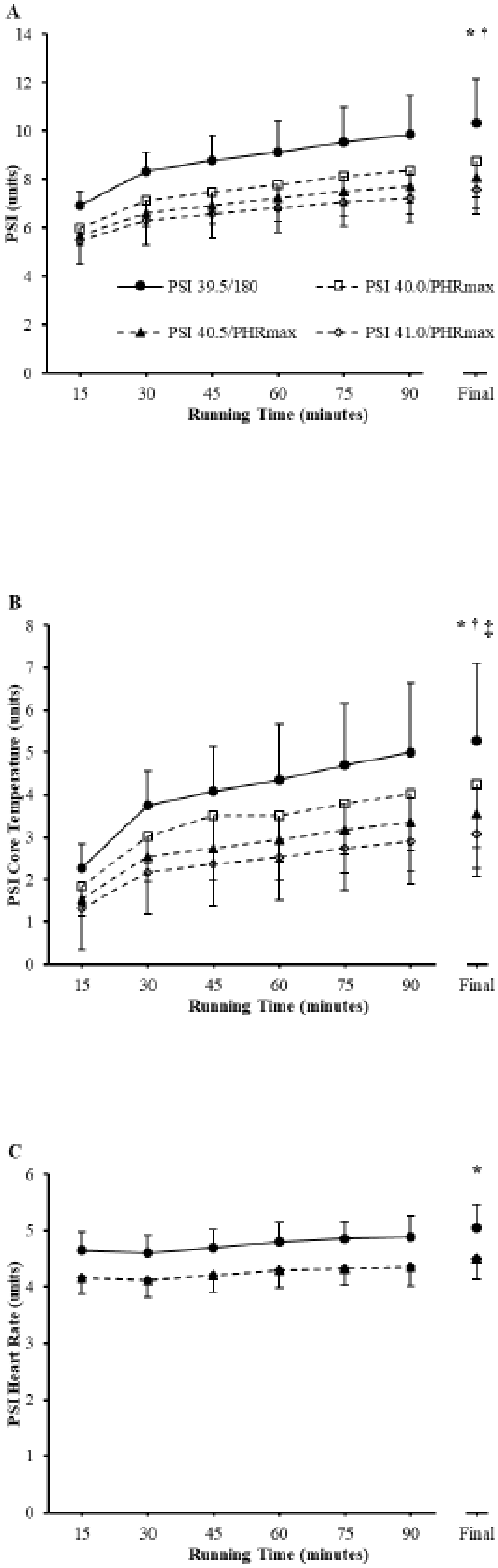
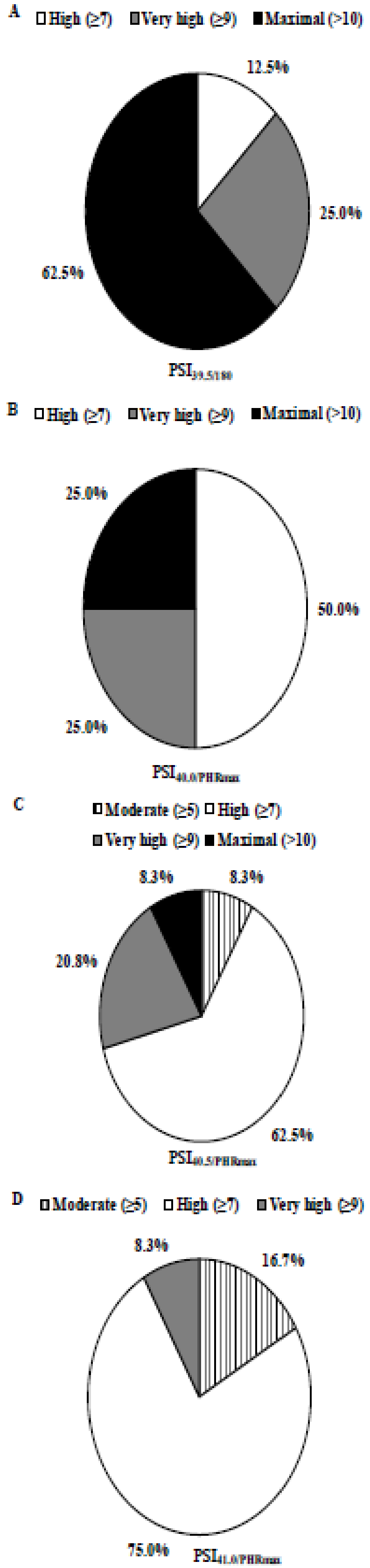

A
14
12
10
8
6
4
2
0
PSI (units)
* †
PSI 39.5/180
PSI 40.0/PHRmax
PSI 40.5/PHRmax
PSI 41.0/PHRmax
15
30
45
60
75
90
Final
Running Time (minutes)
B
8
7
6
5
4
3
2
1
0
PSI Core Temperature (units)
* † ‡
15
30
45
60
75
90
Final
Running Time (minutes)
C
6
5
4
3
2
1
0
PSI Heart Rate (units)
*
15
30
45
60
75
90
Final
Running Time (minutes)

Figure 4:


A
High (≥7)
Very high (≥9)
Maximal (>10)
12.5%
25.0%
62.5%
PSI39.5/180
B
High (≥7)
Very high (≥9)
Maximal (>10)
25.0%
50.0%
25.0%
PSI40.0/PHRmax
C
Moderate (≥5)
High (≥7)
Very high (≥9)
Maximal (>10)
8.3%
8.3%
20.8%
62.5%
PSI40.5/PHRmax
D
Moderate (≥5)
High (≥7)
Very high (≥9)
8.3%
16.7%
75.0%
PSI41.0/PHRmax