Skin Temperature and Heart Rate Can Be Used to Estimate Physiological Strain During Exercise in the Heat in a Cohort of Fit and Unfit Males

John S. Cuddy, MS*; Mark Buller, MS†; Walter S. Hailes, MS*; Brent C. Ruby, PhD*

ABSTRACT  Objective: To evaluate the previously developed physiological strain index (PSI) model using heart rate and skin temperature to provide further insight into the detection and estimation of thermal and physiological heat strain indices. A secondary aim was to characterize individuals who excel in their performance in the heat. Methods: 56 male participants completed 2 walking trials (3.5 miles per hour, 5% grade) in controlled environments of 43.3°C and 15.5°C (40% humidity). Core and skin temperature, along with heart rate and PSI, were continually monitored during exercise. Participants completed a physical fitness test. Results: The logistic regression model exhibited 4 false positives and 1 false negative at the 40% decision boundary. The “Not at Risk” group (N = 33) had higher body weight (84 ± 13 vs. 77 ± 10 kg, respectively) compared to the “At Risk” (N = 23) group, p < 0.05. The “Not at Risk” group had a faster 3-mile run time compared to the “At Risk” group (21:53 ± 3:13 vs. 25:16 ± 2:37, respectively), p < 0.05. During the Heat Trial, the “At Risk” group had a higher rating of perceived exertion at 60 and 90 minutes compared to the “Not at Risk” group (13.5 ± 2.8 vs. 11.5 ± 1.8 and 14.8 ± 3.2 vs. 12.2 ± 2.0 for “At Risk” vs. “Not at Risk” at 60 and 90 minutes, respectively), p < 0.05. Conclusions: The previously developed model relating heart rate and skin temperature to PSI is highly accurate at assessing heat risk status. Participants classified as “At Risk” had lower physical performance scores and different body weights compared to the “Not at Risk” group and perceived themselves as working harder during exercise in the heat.

INTRODUCTION

Heat-related illness (HRI) is an ever present threat to athletes, military personnel, and occupational athletes, as the combination of physical exertion in hot environments makes individuals susceptible to heat stroke, heat exhaustion, and heat cramps. Although difficult to determine who is going to have a HRI and when this might occur, the incidence of HRI is more prevalent in those with higher body fat and/or body mass index (BMI) as well as a lower fitness level. With the continued growing obesity epidemic and decreased physical activity, HRI will continue to be a problem, especially for military populations who are engaged in routine physical activity. The U.S. military is not immune to the deleterious effects of the increased overweight and obese population, as inadequate fitness levels and increased body fat hinder recruiting and operational efforts.

Modeling for physiological responses in the heat has been investigated in the laboratory and field environment, with an emphasis on predicting core temperature response during physical work scenarios. Although core temperature response to physical activity is beneficial in predicting heat strain (and thus risk of HRI), collection/monitoring in real-life settings is difficult, impractical, and expensive. Although a core temperature exceeding 40°C is the clinical threshold for exertional heat stroke, it has been shown that athletes are capable of tolerating high temperatures (>40°C) during physical activity, as long as the conditions exist to adequately dissipate heat. As a result, core temperature should not be used as a stand-alone measure to estimate real-time heat strain, as the interplay among environment, clothing, individual anthropometrics, fitness, and intensity of physical work in the development of HRI is multifaceted.

Thermoregulatory balance during strenuous exercise depends on the interaction of metabolic heat production and exchange with the environment. In cooler environments, it is easier to lose heat to the environment since there is a larger gradient between skin and ambient temperatures. Recent studies have shown the importance of high skin temperature (and thus a narrowed core-skin temperature) on degrading aerobic performance, likely as a result of increased skin blood flow requirements. Specifically, Keneff and al determined that at skin temperatures >29°C, 4% hypohydration degraded aerobic performance by ~1.6% for each additional 1°C skin temperature. It can be presumed that during euhydration, this decline would be slightly mitigated. Since skin temperature can be collected noninvasively, it has been used in concert with heart rate (HR) to predict physiological strain during exercise.
in the heat, rather than the classic method of estimating physiological strain with heart rate and core temperature.

The purpose of this study is to evaluate the previously developed physiological strain index (PSI) model using heart rate and skin temperature to provide further insight into the detection and estimation of thermal and physiological heat strain indices. A secondary aim was to characterize those individuals who excel in their thermoregulatory performance in the heat.

METHODS
Participants
56 male participants (22 ± 3 years, 181 ± 9 cm, 81 ± 12 kg, 4.2 ± 0.6 L·min⁻¹) were enrolled in the study. Subjects completed a Physical Activity Readiness Questionnaire and were briefed on the experimental protocol and possible risks before giving written informed consent. All procedures were approved by the University Institutional Review Board.

Preliminary Testing
Body composition was measured using hydrodensitometry. Underwater mass was measured with a digital scale (ExerTech, Dresher, Minnesota). Body density was corrected for estimated residual lung volume and converted to percent body fat using the race appropriate Siri equation. A graded maximal exercise test (Bruce protocol) was completed on a motorized treadmill (Trackmaster, Full Vision, Newton, Kansas) to determine maximal aerobic capacity (VO₂ max). Expired gases were measured during the test using a calibrated Parvo Medic TrueOne 2400 metabolic cart (ParvoMedics, Salt Lake City, Utah).

Experimental Protocol
Design
Participants completed 2 trials using a randomized, counterbalanced, crossover design over the span of 2 weeks, with a minimum of 7 days between trials. All trials were completed in a temperature- and humidity-controlled environmental chamber (Tescor, Warminster, Pennsylvania) in ambient conditions of 43.3°C and 40% relative humidity (Heat Trial) and 15.5°C and 40% relative humidity (Cool Trial). Preceding the first trial, participants were free to exercise as they wished 2 days before the trial but were instructed to abstain from exercise 24 hours before the trial. Participants were free to eat whatever they wished 1 day before the initial trial. The exact exercise and diet routine for the 2 days preceding the first trial was replicated before the second trial. Following an overnight 12-hour fast, participants arrived at the laboratory in the early morning and had nude body mass measured (CW-11, Ohaus Corporation, Pine Brook, New Jersey). Participants were equipped with core and skin temperature sensors and a heart rate monitor and then performed a 90-minute steady state walk at 3.5 miles per hour and 5% incline. Participants consumed 18 mL·kg⁻¹ of 6% liquid carbohydrate beverage during the walk. Immediately after the walk, subjects towed off and provided another nude body mass measurement. Of the 56 participants, 5 were unable to complete the 90-minute walk in the heat.

Participants completed a United States Marine Corps (USMC) physical fitness test (PFT) within 2 weeks after completing their second lab trial per organization directions. Briefly, the test consists of pull-ups, crunches, and a 3-mile run. Pull-ups were started from a dead hang with hands facing either palm forward or to the rear, and one repetition consisted of raising the body until the chin was above the bar and then lowering the body until arms were fully extended. There was no time for this event, as participants were instructed to complete as many repetitions as possible before dropping from bar. Crunches were completed within a 2-minute time limit. Participants started with their backs flat on the ground, arms folded across the chest, buttocks on the ground, knees bent, and with an assistant holding their legs and feet. One repetition was counted when the elbows touched the knees and their back returned to the ground. The 3-mile run was completed on a measured 440-yard track. Participants were provided lap counts every lap, and their 1- and 2-mile times. Scoring for all 3 components ranged from 0 to 100 for each component based on Marine Corps Order P6100-12.

Measures
Core and Skin Temperature
Core and skin temperature were continually monitored during each laboratory trial with a digital data logger (Physitemp Instruments, Clifton, New Jersey). These measures were not collected during the USMC PFT. A rectal thermistor was inserted 12 cm past the anal sphincter, and a skin temperature thermistor was placed on the left pectoralis muscle 2.5 cm medial and 2.5 cm superior from the nipple. Data were collected every half second, and the temperatures at each minute were used for analysis.

Heart Rate
Heart rate was collected using a Polar RS800CX heart rate monitor (Polar Electro, Lake Success, New York). Data were recorded at 5-second intervals, and the heart rate at each minute was used for analysis.

Physiological Strain Index
PSI was determined using the formula designed by Moran et al:

\[
PSI = 5(T_{core(1)} - T_{core(0)}) \left(39.5 - T_{core(0)}\right)^{-1} + 5(H_{HR(1)} - H_{HR(0)}) \left(180 - H_{HR(0)}\right)^{-1}
\]

Because of preexercise anxiety, consistent resting heart rates were not achieved, so a resting heart rate of 71 bpm
was used for all modeling\textsuperscript{22,23}. Using 71 bpm is a potential limitation to the study, as resting heart rates may have had variability among our participants. Measured resting core body temperature was used for analysis, however. Similar to Buller et al.\textsuperscript{22} we used a PSI $<7.5$ to classify “Not at Risk” and a PSI $>7.5$ to classify “At Risk” since a PSI of 7 indicates a “High” PSI, and above this indicates a transition to a riskier/unsafe thermal strain. Participants were classified into “At Risk” or “Not at Risk” groups based on whether they achieved a PSI $\geq 7.5$ before terminating their tests.

**Sweat Rate**

Sweat rate was calculated using the pre- and posttrial nude body weights (BW) and corrected for urine excreted, fluid volume consumed, and expiratory water loss.\textsuperscript{26} Sweat loss was converted to a sweat rate relative to body surface area\textsuperscript{27}:

\[
\text{Sweat Rate (g m}^{-2}\text{ min}^{-1}) = \frac{(\text{BW}_{\text{pre}} + \text{Liquid Ingested}) - (\text{BW}_{\text{post}} + \text{Urine Weight} + \text{Resp Water Loss})}{\text{Body Surface Area}}
\]

**Rating of Perceived Exertion**

Rating of perceived exertion (RPE) was assessed using the Borg 6-20 scale and collected initially and every 30 minutes during the Heat and Cool Trials.

**Probability of Risk Calculation**

The logistic regression coefficients ($w$) provided by Buller et al (2008) were used to map HR and Tskin mapped into a third-order polynomial ($x$) into a probability that PSI $\geq 7.5$ ($y = 1$), using the logistic regression linear algebra equation\textsuperscript{22}:

\[
p(y = 1|x) = \frac{1}{1 + \exp(w^T x)}
\]

**Statistical Analysis**

A confusion matrix was produced to examine the number of errors for the HR and Tskin logistic regression classification algorithm compared to the measured PSI, for decision thresholds set at $p > 0.30$ and $p > 0.40$. Trial differences for core and skin temperature, heart rate, PSI, and sweat rate were determined for the “At Risk” and “Not at Risk” groups using a 2 x 2 mixed design analysis of variance with repeated measures. Anthropometric and fitness differences between “At Risk” and “Not at Risk” groups were determined using independent $t$ tests.

**RESULTS**

On the basis of the highest PSI achieved during the 90-minute walk, 23 participants were classified in the “At Risk” group, whereas 33 participants were classified in the “Not at Risk” group. Of the 5 participants who did not complete the trial, 3 were classified in the “At Risk” group, whereas 2 were classified in the “Not at Risk” group based on whether they achieved a PSI $\geq 7.5$ before terminating their tests.

**Logistic Regression**

The cool-condition data were classified 100% correct as PSI $<7.5$ at all decision boundaries (no participant had a PSI $\geq 7.5$ during the cool condition). Figure 1 shows the hot-condition data broken down by “At Risk” and “Not at Risk” classifications determined from observed PSI, for a decision boundary at $p > 0.4$, showing the misclassifications. Table I shows the confusion matrix for the hot-condition data and breaks down the misclassifications into “false positives” and “false negatives.”

**Anthropometrics**

There were no differences for age, height, BMI, body fat percentage, and fat mass (FM) between groups (Table II). The “Not at Risk” group had higher body weight and fat-free mass (FFM) compared to the “At Risk” group, $p < 0.05$.

**Thermoregulatory Variables**

The “At Risk” and “Not at Risk” groups had an elevated core temperature, heart rate, and PSI during the Heat Trial compared to the Cool Trial, interaction effect for trial, $p < 0.05$ (Table III). The “At Risk” group had a higher core temperature, heart rate, and PSI during the Heat Trial compared to the “Not at Risk” group, $p < 0.05$ (Table III). During the Cool Trial, heart rate and PSI were higher for the “At Risk” group compared to the “Not at Risk” group, whereas core temperature was similar...
**TABLE I.** Number of False Negative or False Positives Using the Logistic Regression Decision Boundary Set at 40 and 30%

<table>
<thead>
<tr>
<th>Actual Class</th>
<th>Decision Boundary = 40%</th>
<th>Decision Boundary = 30%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Classified At Risk</td>
<td>Classified Not at Risk</td>
</tr>
<tr>
<td>At Risk (n = 23)</td>
<td>19 (82.6%)</td>
<td>4 (17.4%)</td>
</tr>
<tr>
<td>Not at Risk (n = 33)</td>
<td>1 (3.0%)</td>
<td>32 (97.0%)</td>
</tr>
</tbody>
</table>

Data are expressed as mean ± SD. *p < 0.05.

**TABLE II.** Descriptive Data for the “At Risk” and “Not at Risk” Groups

<table>
<thead>
<tr>
<th>Variables</th>
<th>At Risk</th>
<th>Not at Risk</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>22 ± 4</td>
<td>23 ± 3</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>180 ± 12</td>
<td>182 ± 5</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>77 ± 10</td>
<td>84 ± 13*</td>
</tr>
<tr>
<td>BMI</td>
<td>24 ± 4</td>
<td>25 ± 4</td>
</tr>
<tr>
<td>Body Fat (%)</td>
<td>17 ± 5</td>
<td>15 ± 5</td>
</tr>
<tr>
<td>FFM (kg)</td>
<td>64 ± 8</td>
<td>71 ± 9</td>
</tr>
<tr>
<td>FM (kg)</td>
<td>13 ± 5</td>
<td>13 ± 6</td>
</tr>
</tbody>
</table>

Data indicate the maximal values achieved during the trials and are expressed as mean ± SD. *p < 0.05.

**TABLE III.** Thermoregulatory Variables for the “At Risk” and “Not at Risk” Groups During the Heat and Cool Trials

<table>
<thead>
<tr>
<th>Variables</th>
<th>Groups</th>
<th>Heat</th>
<th>Cool</th>
</tr>
</thead>
</table>
| Core (°C) | At Risk | 38.9 ± 0.4* | 37.8 ± 0.4*
| Not at Risk | 38.0 ± 0.4 | 36.3 ± 0.3* |
| Skin (°C) | At Risk | 37.1 ± 0.9 | 31.0 ± 1.0* |
| Not at Risk | 36.6 ± 0.5 | 30.7 ± 1.0 |
| HR (bpm) | At Risk | 176 ± 12* | 125 ± 9** |
| Not at Risk | 137 ± 16 | 113 ± 12* |
| PSI | At Risk | 8.7 ± 1.0* | 4.2 ± 0.7** |
| Not at Risk | 5.3 ± 1.1 | 3.5 ± 0.7* |
| Sweat Rate (g·m⁻²·h⁻¹) | At Risk | 10.1 ± 1.1 | 2.6 ± 1.0* |
| Not at Risk | 10.7 ± 1.2 | 2.6 ± 1.2 |

Data indicate the maximal values achieved during the trials and are expressed as mean ± SD. *p < 0.05, interaction effect for trial; †p < 0.05, interaction effect for group; ‡main effect for trial.

**TABLE IV.** Physical Performance Data for the “At Risk” and “Not at Risk” Groups

<table>
<thead>
<tr>
<th>Variables</th>
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<th>Not at Risk</th>
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<tr>
<td>Treadmill Time (Minutes)</td>
<td>12:41 ± 0:54</td>
<td>14:21 ± 1:46*</td>
</tr>
<tr>
<td>VO₂ max (L·min⁻¹)</td>
<td>3.76 ± 0.44</td>
<td>4.58 ± 0.46*</td>
</tr>
<tr>
<td>VO₂ max (mL·kg⁻¹·min⁻¹)</td>
<td>48.9 ± 4.7</td>
<td>55.4 ± 6.8*</td>
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<tr>
<td>Run Time (Minutes)</td>
<td>25:16 ± 2:37</td>
<td>21:53 ± 3:13*</td>
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<tr>
<td>Pull-Ups</td>
<td>10 ± 5</td>
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<td>Crunches</td>
<td>79 ± 18</td>
<td>86 ± 16</td>
</tr>
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<td>PFT Score (USMC)</td>
<td>186 ± 45</td>
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### DISCUSSION

Participants in this study completed 90 minutes of walking on a treadmill in a hot (43.3°C) and cool (15.5°C) environment and were classified as either “At Risk” or “Not at Risk” based on whether their maximal PSI ≥7.5 during the Heat Trial. The modest exercise intensity (VO₂ = 21 mL·kg⁻¹·min⁻¹) was chosen because the goal was not to induce a high metabolic load and have the exercise be the limiting factor, but rather incur an overwhelming thermoregulatory load via heat on the participants to see how well they could cope with a thermally challenging environment. The primary finding of the current cross validation study is that the heat strain risk classifier developed by Buller et al²² accurately identified participants with a PSI ≥7.5 with minimal false negative errors. In addition, despite the ability to tolerate the exercise in the cool environment with minimal metabolic and thermoregulatory strain, participants in the “At Risk” group had lower physical performance (Table IV) and showed a reduced capacity to dissipate heat, evidenced by a disproportionate rise in PSI compared to those in the “Not at Risk” group (Fig. 3).

The logistic regression model successfully classified all participants as “Not at Risk” during the Cool Trial, and during the Heat Trial exhibited 4 false positives and 1 false negative at the 40% decision boundary, whereas showing 2 false positives and 2 false negatives at a 30% decision boundary. Out of the 4 false negatives at the 40% decision boundary, 3 experienced minimal time at a PSI ≥7.5 (7, 4, and 1 minutes, respectively), whereas 1 participant had a rather extended time frame (31 minutes) at a PSI ≥7.5. The 3 participants with minimal time at PSI ≥7.5 experienced compared to the previous time point, main effect for time, p < 0.05 (Fig. 2B).

**Physical Performance**

The “Not at Risk” group had a longer run time during the Bruce protocol, higher absolute and relative VO₂ max, faster 3-mile run time, and a higher PFT score, p < 0.05 (Table III). There was no difference between groups for pull-ups and crunches (Table IV).

**Rating of Perceived Exertion**

During the Heat Trial, the “At Risk” group had a higher RPE at 60 and 90 minutes compared to the “Not at Risk” group, p < 0.05 (Fig. 2A). RPE was higher for both groups at each time point compared to the previous time point, interaction effect for time, p < 0.05. During the Cool Trial, there were no differences between the “At Risk” and “Not at Risk” groups, but RPE was higher at each time point between groups. There was a main effect for trial (Heat vs. Cool Trial) for skin temperature and sweat rate.

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this score in the last few minutes of his respective trial. Thus, the logistic regression model only had 1 false negative “hit” where the participant experienced extended time at a PSI $\geq 7.5$. Perhaps, a future model could classify people as “At Risk” only after they have accumulated a certain amount of time above PSI $\geq 7.5$.

Subjective ratings of RPE should be considered by those who are in a position to monitor others exercising in hot environments. RPE was higher in the “At Risk” group at 60 and 90 minutes compared to the “Not at Risk” group (Fig. 2A), coinciding with the differences between groups in core temperature, heart rate, and PSI. This is in agreement with past research that shows an elevated RPE in the heat compared to a cooler environment.21,28,29 Subjective perception of heat stress increased with increasing exercise time during the Heat Trial, and those experiencing greater heat stresses as indicated by PSI (“At Risk” group) appropriately self-assessed their conditions. One of the false negative participants was unable to complete the 90-minute walk, terminating his test at 78 minutes because of feeling light headed. The model did not classify him “At Risk,” but he was unable to continue exercising, showing the limitations of using mathematical models to perfectly predict human responses. Interestingly, the false positive participant was unable to complete the 90-minute walk, ending his trial at 59 minutes because of feeling excessively hot. Therefore, it is suggested that the model accurately predicted a participant exhibiting “At Risk” heat stress despite his PSI classifying him as “Not at Risk.” These data suggest the importance of coupling subjective perceptions of thermal strain with accurate objective data to increase the specificity of detecting risk for heat-related injury. Together, subjective and objective data can effectively determine a person’s heat strain status with a high degree of accuracy.

This study’s determination of risk was based on heart rate and skin temperature during exercise in the heat, not physical performance capacity. In spite of this, the “At Risk” group had shorter treadmill time to exhaustion, slower 3-mile run times, and a lower VO$_2$ max compared to the “Not at Risk” group. In this study, participants ($N = 17$) who completed the 3-mile run in less than 21 minutes were all classified in the “Not at Risk” group, whereas 70% of those who ran slower than 24 minutes ($N = 20$) were in the “At Risk” group (Fig. 4). Those who ran between 21 and 24 minutes ($N = 19$) had about an equal chance of being classified as “At Risk” (47%) or “Not at Risk” (53%). This coincides with data from the USMC, which found that those running 3 miles with run time $\geq 23$ minutes had substantially higher risk (4.2 fold) for exertional heat illness during 12-week recruit training compared with those with run time <20 minutes.5 In addition, another USMC study showed similar findings using the 1.5-mile run, determining risk for
exertional heat illness (EHI) to be almost six times greater in male recruits with run times ≥12.9 minutes compared with those with run times <10.3 minutes.5 Taken together, the previous and current data suggest that those considered “At Risk” not only exhibit lower physical performance scores but also have a reduced capacity to tolerate the heat strain imposed by their exercise trial.

Participants in both the “At Risk” and “Not at Risk” groups had a similar BMI score and similar body fat percentage. Higher BMI has been implicated in increasing the chance for EHI,5,6 although Wallace et al showed that BMI, later in training, was no longer an important risk factor for EHI.6 Previous literature has shown that increased body fat percentage predisposes someone to greater risk for EHI,3 so the current findings with no difference between groups is somewhat surprising. However, it is possible that the modest exercise intensity (VO2 = 21 mL·kg·min⁻¹) was too low to see a difference in body fat percentage, as the amount of exertional heat generation was low. Unexpectedly, the “Not at Risk” group had a higher body weight and fat-free mass compared to the “At Risk” group. Perhaps, an increased fat-free mass (if body fat percentage is similar) may be a benefit for reducing heat strain, as there is potentially a greater amount of total body water available for sweating. In this study, there was no difference in sweat rates between groups, although the p value approached statistical significance (p = 0.056) for an interaction effect.

In conclusion, these data could be implemented into practice by the end user as a tiered assessment strategy to reduce HRI. Although this study does not show increased BMI and body fatness as factors for impaired heat tolerance, this could be the first assessment since it is the easiest (the substantial amount of literature implicating these includes a substantial participant pool).3,5,6 Fitness levels, determined by run performance, may be the next determinant of potential for HRI. Fitness alone might be the best independent screening tool, as it might account for/override differences in body composition. In addition, for leaders who know their subordinates and can trust their subjective feedback during strenuous activity, the use of RPE could be an effective tool to accurately assess their physiological status. Subsequently, real-time physiological monitoring of heart rate and skin temperature can be used as an objective tool to simply and accurately estimate the PSI. Because PSI provides an indication of metabolic and thermal loads, this approach could be effectively leveraged to mitigate HRI during strenuous tasks and/or dangerously hot environmental conditions for those at increased risk as determined by body composition and the physical performance test.

ACKNOWLEDGMENT

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REFERENCES


Case Report