Can gender differences during exercise-heat stress be assessed by the physiological strain index?

Moran, Daniel S., Yair Shapiro, Arie Laor, Sharona Izraeli, and Kent B. Pandolf. Can gender differences during exercise-heat stress be assessed by the physiological strain index (PSI) based on rectal temperature (Tre) and heart rate (HR)? Recently suggested to evaluate exercise-heat stress. The purpose of this study was to evaluate PSI for gender differences under various combinations of exercise intensity and climate. Two groups of eight men each were formed according to maximal rate of O2 consumption (VO2max). The first group of men (M) was matched to a group of nine women (W) with similar (P > 0.001) VO2max (46.1 ± 2.0 and 43.6 ± 2.9 ml·kg⁻¹·min⁻¹, respectively). The second group of men (MF) was significantly (P  < 0.001) more fit than M or W with VO2max of 59.1 ± 1.8 ml·kg⁻¹·min⁻¹. Subjects completed a matrix of nine experimental combinations consisting of three different exercise intensities for 60 min (low, moderate, and high (300, 500, and 650 W, respectively) at each of three climates (comfortable, hot wet, and hot dry [20°C 50% relative humidity (RH), 35°C 70% RH, and 40°C 35% RH, respectively]). No significant differences (P > 0.05) were found between matched genders (M and W) at the same exposure for sweat rate, relative VO2max (%VO2max), and PSI. However, MF had significantly (P < 0.05) lower strain than M and W as reflected by %VO2max, and PSI. In summary, PSI applicability was extended for exercise-heat stress and gender. This index continues to show potential for wide acceptance and application.

Heart rate; heat strain; indexes; men; rectal temperature; women

PHYSIOLOGICAL RESPONSES to exercise-heat stress may be different between genders because of several factors. Compared with men, women generally have lower cardiorespiratory fitness, higher percent of body fat, lower body weight, lower body surface area, and higher surface area-to-mass ratio (11, 17, 18, 26). In addition, hormonal fluctuations of estrogen and progesterone associated with the menstrual cycle may alter women's performance and tolerance to exercise-heat stress (19, 20).

Several investigators have shown that women thermoregulate less effectively than men when exposed to acute heat stress and exercise (4, 12, 22, 23). In her review of 1978, Nunnally (16) concluded that under the same thermal load women compared with men had higher core and skin temperatures (Tsk), higher heart rates (HR), and lower sweating rates (msw). However, these physiological differences were mainly attributable to lifestyle-related inequalities in fitness and acclimation. Although heat acclimation eliminated many of these gender-related physiological differences, msw still remained lower for women (1, 27). Stephenson and Kolka (24) suggested that the general belief that women were less tolerant to heat strain was based on comparatively unmatched genders, mainly aerobically fit men to relatively unfit women. There are some studies that found that when genders were matched for aerobic fitness and physical characteristics, many of the physiological differences were narrowed, especially during light exercise (2, 5, 7, 12). In 1995, Sawka et al. (21) concluded in their review that if men and women were matched for aerobic fitness, they then have similar heat tolerances and body temperature responses during exercise in the heat. Nevertheless, Stephenson and Kolka (24) argued that most of the studies that compared responses of men and women were not controlled for menstrual cycle phase and, as a consequence, were limited in their conclusions.

Recently, Moran et al. (15) introduced a new physiological strain index (PSI) based on rectal temperature (Tre) and HR as representative of the combined strain reflected by the thermoregulatory and cardiovascular systems. This simple-to-use index scales the strain to a range of 0-10 and can be used online or during data analysis. It was shown that PSI can be applied at any time, including rest or recovery periods, whenever Tre and HR are measured (15). Furthermore, this index successfully rated and correctly discriminated between different clothing ensembles and climate conditions during heat stress and during different levels of hydration and exercise intensity (14).

The purpose of this study was to examine the ability of PSI as a tool to evaluate and assess gender heat strain differences at various exercise intensities and climatic conditions. In addition, we aimed to evaluate the interactions between PSI and msw or relative exercise intensity from these same experiments.

MATERIALS AND METHODS

Subjects. Two groups of eight men each and a group of nine women (W) participated in this study. The two groups of men were divided according to their maximal oxygen consumption (VO2max). The first group of men (M) was matched to the women of similar VO2max [46.1 ± 2.0 and 43.6 ± 2.9 ml·min⁻¹·kg⁻¹ (P < 0.001), respectively]. The second group of men (MF) was significantly (P < 0.001) more fit than either
M or W, with \( V_{2\text{max}} \) of 59.1 ± 1.8 ml·min\(^{-1}\)·kg\(^{-1}\). All subjects were young volunteers, and their physical characteristics are summarized in Table 1. Before experimentation, each subject underwent a medical examination that involved a complete medical history, electrocardiogram at rest, urine analysis, and sequential multichannel autoanalyzer-12 blood screening biochemistry. None of the participants had a history of medical disorders for at least 6 mo before the study. All subjects were informed as to the nature of the study and potential risks of exposure to exercise in a hot climate and signed a volunteer consent form.

Protocol. The study was conducted in the climatic chamber at the Heller Institute of Medical Research, Sheba Medical Center, Tel Hashomer, Israel. The experimental protocol was reviewed and approved by the Institution's Ethical Committee of Investigations Involving Human Subjects.

Before these experiments, the subjects underwent a thorough heat-acclimation procedure. The acclimation procedure consisted of exposure to 40°C, 40% relative humidity (RH) in a climatic chamber for 2 h daily for 10 consecutive days. During the exposure, the subjects exercised on a treadmill elevated by 3% \((V_{2\text{O2}} = 1.2 \text{l/min})\) at a speed of 1.34 m/s. They were dressed in only shorts and sport shoes (women with bras as well). Significantly lower \((P < 0.01)\) values of \( T_{re} \) and HR were found in all subjects at the end of the last acclimation exposure compared with the end of the first acclimation exposure. On the last day of the acclimation procedure, all subjects performed a \( V_{2\text{max}} \) test on a treadmill in a comfortable climate \((20^\circ\text{C}, 50\% \text{RH})\) (25).

After acclimation, all subjects were exposed to nine experimental exposures that consisted of different combinations of exercise intensity and climatic condition (Table 2). The combinations were assigned at random to the subjects but were controlled to eliminate order effects. The work consisted of exposure to 40°C, 40% RH in a climatic chamber for 2 h daily for 10 consecutive days. The study was conducted in the climatic chamber at the Heller Institute of Medical Research, Sheba Medical Center, Tel Hashomer, Israel. The experimental protocol was reviewed and approved by the Institution's Ethical Committee of Investigations Involving Human Subjects.

Each exercise intensity was combined with each climate, providing 9 experimental conditions. RH, relative humidity.

Table 2. Experimental combinations of climate and exercise intensity

<table>
<thead>
<tr>
<th>Exercise intensity</th>
<th>Low ((-300 \text{ W}))</th>
<th>Moderate ((-500 \text{ W}))</th>
<th>High ((-650 \text{ W}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Climate</td>
<td>Comfortable ([20^\circ\text{C}, 1.16 \text{kPa (50% RH)}])</td>
<td>Hot wet ([35^\circ\text{C}, 3.93 \text{kPa (70% RH)}])</td>
<td>Hot dry ([40^\circ\text{C}, 2.58 \text{kPa (35% RH)}])</td>
</tr>
</tbody>
</table>

Each exercise intensity was combined with each climate, providing 9 experimental conditions. The PSI was calculated from body weight differences with a precision electronic scale \((±0.5 \text{ g})\) at three locations (chest, arm, and leg), and mean weighted \( T_{sk} \) was calculated according to Burton (3).

Calculations. The PSI was calculated as suggested by Moran et al. (15) as follows

\[
\text{PSI} = 5\left( T_{\text{ret}} - T_{\text{rel}} \right) \cdot \left( 39.5 - T_{\text{ret}} \right)^{-1} + 5\left( H_{\text{ret}} - T_{\text{ret}} \right) \cdot \left( 180 - H_{\text{ret}} \right)^{-1}
\]

where \( T_{\text{ret}} \) and \( H_{\text{ret}} \) are the initial \( T_{re} \) and HR, and \( T_{\text{ret}} \) and \( H_{\text{ret}} \) are simultaneous measurements taken at any time. The PSI was categorized (Table 3) as previously suggested (15).

The relative \( V_{2\text{max}} \) (%V\(2\text{max}\)) for each subject during each exercise intensity at the different climates was computed from the \( V_{2\text{max}} \) performed in a comfortable climate as \%V\(2\text{max}\) = 100(V\(2\text{o2}\)/V\(2\text{max}\)).

Statistical analysis. Statistical calculations were performed with SAS 6.04 software. Two-way ANOVA with repeated measures was used where appropriate to search for significant differences. One-way nonparametric ANOVA was used to search for significant differences between the parameters. Correlation coefficients were calculated from the means of select physiological values for the different exposures. All values are presented as means ± SE. Unless otherwise indicated, significant differences reported herein are at \( P < 0.05 \).

RESULTS

No significant differences \((P > 0.05)\) were observed between M and W for age, weight, height, body mass index, and \( V_{2\text{max}} \) (Table 1). However, \( V_{2\text{max}} \) was significantly higher \((P < 0.05)\) for MF than M or W, whereas age, weight, height, and body mass index did not differ between any of the groups. Therefore, the %V\(2\text{max}\) during these experiments was the same for M and W but significantly lower for MF. This experimental design allowed us to test the ability of PSI to discriminate apparent gender differences (MF vs. W) or when no differences should be found (M vs. W).

Table 1. Physical characteristics of subjects

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Age, yr</th>
<th>Wt, kg</th>
<th>Height, cm</th>
<th>( A_{b} ), m(^2)</th>
<th>( V_{2\text{max}} ), ml·min(^{-1})·kg(^{-1})</th>
<th>BMI, ( A_{b})/Wt</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>9</td>
<td>25 ± 1</td>
<td>62.7 ± 3.4</td>
<td>169 ± 1.6</td>
<td>1.71 ± 0.04</td>
<td>43.6 ± 2.9</td>
<td>0.028 ± 0.000</td>
</tr>
<tr>
<td>M</td>
<td>8</td>
<td>23 ± 1</td>
<td>71.5 ± 2.8</td>
<td>175 ± 2.5</td>
<td>1.86 ± 0.04*</td>
<td>46.1 ± 2.0</td>
<td>0.026 ± 0.001</td>
</tr>
<tr>
<td>MF</td>
<td>8</td>
<td>25 ± 1</td>
<td>65.9 ± 2.9</td>
<td>174 ± 3.4</td>
<td>1.79 ± 0.05</td>
<td>59.1 ± 1.8*</td>
<td>0.027 ± 0.000</td>
</tr>
</tbody>
</table>

Values are means ± SE. \( A_{b} \), body surface area; BMI, body mass index; M, men; W, women; MF, fit men; *Significant difference between W and M \((P < 0.03)\); †significant difference between MF and M or W \((P < 0.001)\).
Generally, $T_{re}$ was elevated in the three groups (W, M, and MF) in proportion to the magnitude of the exercise intensity and increased progressively during exercise (Fig. 1). Significantly higher $T_{re}$ values were observed in the hot climates (hot dry and hot wet) than for exposure to the comfortable climate ($P < 0.05$). $T_{re}$ dynamics, depicted as hyperthermic plateaus, were observed in the comfortable climate at each of the three exercise intensities. A very modest $T_{re}$ increase was measured under the hot climates (hot dry and hot wet) during the low exercise intensity, whereas a continuous $T_{re}$ increase was observed during the moderate and high intensities. The women's $T_{re}$ during exercise was significantly higher compared with values for M and MF groups ($P < 0.05$). Furthermore, the women's initial $T_{re}$ values were also the highest of the three groups in eight of nine experimental exposures ($P < 0.05$). Therefore, the overall $T_{re}$ changes during exercise between the three groups at the same matched exposures were not significant. Higher values of $T_{re}$ were measured in M than MF in all exposures. However, significant differences were found only in the hot-wet climate at moderate and high exercise intensities ($P < 0.05$).

Compared with $T_{re}$, similar HR dynamics were observed (Fig. 2). However, HR reached a plateau for the three groups in six of nine total exposures, including all exposures at the low exercise intensity and all exposures during the comfortable climate. Highest absolute HR values were observed for W. However, no significant differences were found between W and M, whereas significant ($P < 0.05$) HR differences were found between W and MF at all exercise intensities under hot-dry and hot-wet climates and at the high exercise intensity for the comfortable climate. Significantly higher ($P < 0.05$) HR values were measured for M compared with MF. However, these differences were not significant during the low exercise intensity at the three climates or during the moderate exercise intensity at the comfortable climate.

$T_{sk}$ was significantly lower during the comfortable climate than in hot climates ($P < 0.0001$). $T_{sk}$ values were significantly lower in MF than in W ($P < 0.005$), but no differences were found between W and M.

Generally, PSI values progressively increased with exercise intensity and environmental heat load (Fig. 3). Significantly lower values ($P < 0.05$) for PSI were observed in the comfortable climate than either the hot-dry or hot-wet climates; however, differences between climates were not significant at the low exercise intensity. Higher absolute PSI values [not significant ($P > 0.05$)] were observed for the hot-wet than for the

**Table 3. Evaluation and categorization of different heat strains by PSI**

<table>
<thead>
<tr>
<th>Strain</th>
<th>PSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>No/little</td>
<td>0</td>
</tr>
<tr>
<td>Low</td>
<td>1</td>
</tr>
<tr>
<td>Moderate</td>
<td>3</td>
</tr>
<tr>
<td>High</td>
<td>5</td>
</tr>
<tr>
<td>Very high</td>
<td>7</td>
</tr>
</tbody>
</table>

See Ref. 15 for more information on physiological strain index (PSI).
hot-dry climate. The PSI evaluated the W group with the highest values, but significant differences ($P < 0.05$) were found only between W and MF at the high exercise intensity for the three climatic conditions and at the moderate exercise intensity for the two hot climates. No significant differences for PSI were found for the matched exposures between W and M groups. Higher absolute PSI values were found in M than MF for all exposures. However, significant differences between M and MF ($P < 0.05$) were as follows: 1) moderate exercise intensity for 60 min at the hot-wet climate and from 45 min to the end of the exposure at the hot-dry climate; and 2) high exercise intensity from 45 min to the end of the comfortable climate, from 35 min at the hot-wet climate, and the last 10 min of the hot-dry exposure.
The PSI rated the strain in rank order according to the combined exercise intensity and the climate condition. Applying PSI from the beginning to the end of exercise across the three climate conditions revealed that the low exercise intensity was ranked as little to low strain with values of 2–4, whereas the moderate exercise intensity was ranked as little to moderate strain with values of 2–6. The high exercise intensity was ranked from low to very high strain with values of 2–9.

$m˙_{sw}$ and the calculated PSI for the subjects for the different exposures are shown in Fig. 4. In general, $m˙_{sw}$ correlated with exercise intensity and environmental heat load. The higher the workload, the higher the observed $m˙_{sw}$. In addition, for the hot climates $m˙_{sw}$ was about twice that during the comfortable climate for the same exercise intensity. The highest $m˙_{sw}$ values were measured for the MF, whereas significantly different ($P < 0.05$) values were found between MF and W at the high exercise intensity in the two hot climates. No significant differences were found between M and W for $m˙_{sw}$. As depicted in Fig. 4, there is a high correlation ($r = 0.97$) between $m˙_{sw}$ and PSI for the same climatic condition at the different exercise intensities. However, there is an inverse correlation ($r = -0.95$) between $m˙_{sw}$ and PSI when analyzed for the different groups at the same exposure (climate and exercise intensity). Thus higher $m˙_{sw}$ is reflected as lower physiological strain when compared among these three groups.

The %$V_{O2\text{max}}$ and the simultaneously calculated PSI are depicted in Fig. 5. Generally, significant differences ($P < 0.01$) were found in %$V_{O2\text{max}}$ between the different exercise intensities. However, no significant differences were found between the same exercise intensities for the different climatic conditions. In all experimental exposures, the lowest %$V_{O2\text{max}}$ values were calculated for MF and were found to be significantly ($P < 0.05$) different from W or M. However, no significant differences were found in %$V_{O2\text{max}}$ between W and M. High correlations were found between %$V_{O2\text{max}}$ and PSI in two different statistical analyses: first, for the different exercise intensities under the same climatic conditions ($r = 0.99$) and, second, when compared between the different groups for the same exercise intensity and climatic condition ($r = 0.96$).

**DISCUSSION**

The PSI for the three groups (W, M, and MF) under investigation correctly described the relative heat strain while these subjects were exposed for 60 min to a matrix of three exercise intensities (300, 500, 650 W) and three different climate conditions (20°C, 50% RH; 40°C, 35% RH; 35°C, 70% RH). The PSI rated each one of these exposures on a universal scale of 0–10. Despite the variability in HR and $T_{re}$, the PSI, which is constructed from these two parameters, successfully categorized the physiological strain for the three experimental groups in the expected order. The focus of this paper was to determine the ability of PSI to discriminate between W, M, or MF during these exposures and to study the relationships between PSI and $m˙_{sw}$ or relative exercise intensity as a function of $V_{O2\text{max}}$ for gender during these same experiments.

$T_{re}$ values during all nine experimental exposures for the W group were markedly higher than for M and MF. Because we did not control for menstrual cycle phase in these experiments, our findings cannot be directly
related to the reported impact of menstrual cycle phase (9, 13, 22). Other investigators showed about a 0.4°C higher core body temperature in the luteal phase than the follicular phase (19). However, despite the higher $T_{re}$ values observed during the W exposures, PSI successfully categorized the W heat strain. The latter is attributed to the PSI construction, which normalizes each physiological parameter ($T_{re}$ and HR) for its initial value. In view of the fact that this procedure alters the span of the index, PSI was constructed to be scaled to a simple range of 0–10 without affecting its predictive accuracy, as shown in this and other studies (14, 15). Thus, although Figs. 1 and 2 depict higher $T_{re}$ and HR values for women, the PSI indicated the relative changes in the actual heat strain of the three groups and correctly discriminated between the nine exposures, consisting of three exercise intensities and three different climates (Fig. 3).

The $m_{sw}$ correlated highly with exercise intensity (6) and also with PSI. These findings are in accordance with earlier observations found between local $m_{sw}$ and PSI (14). However, analysis of our three groups at the same workload revealed an inverse correlation between $m_{sw}$ and PSI, as depicted in Fig. 4. The $m_{sw}$ for W was not different from M, which agreed with the nonsignificant differences in aerobic fitness between these two groups. Some investigators have claimed that women are more efficient sweaters than men in a hot-wet climate (2, 5, 22). In our study, there were no significant gender differences in $m_{sw}$ for the hot-wet and hot-dry climates.

In a previous study (15), PSI assessed higher strain under a hot-dry than hot-wet climate. However, in this study our hot-wet climate assessed the higher strain. The best explanation for the contradiction in these assessments is probably because of the subjects' different clothing. In the previous study, subjects exercised wearing protective garments, whereas in this study subjects dressed only in shorts (women with bras as well). Protective garments create a microclimate different from the environment, which does not necessarily reflect the same environmental stress while wearing only shorts or standard cotton clothing (8, 10). Moreover, the principle behind PSI is evaluation of the physiological strain resulting from the cardiovascular and the thermoregulatory systems. Therefore, various combinations of climate and clothing can result in different PSI assessments. The strength of this index is its ability to rate quantitatively and to compare the strain between different exposures at any time point.

In our study, matching between genders (M and W) was mainly done according to $V_{O2max}$. In addition, all three groups (M, W, MF) did not differ ($P > 0.05$) for age, height, weight, and body mass index (Table 1). However, $%V_{O2max}$ values during all of the different exposures were still slightly higher for W than for M (Fig. 5). The only significant physiological parameter that was different between these groups (MF vs. M or W) was $V_{O2max}$, and PSI accounted for these differences between genders when evaluated as a $%V_{O2max}$. Therefore, the aerobic fitness of these individuals was the most important variable for matching genders when exposed to exercise-heat stress. These findings also support those of previous investigations (2, 5), which reported that when men and women were matched for $V_{O2max}$ and select physical characteristics, their physiological performance postacclimation was essentially the same in both hot-dry and hot-wet environments.

![Fig. 5. PSI and relative rate of maximum O2 consumption (%$V_{O2max}$; $V_{O2}/V_{O2max}$; means ± SE) after 60 min for 3 groups in these 9 experimental exposures.](image-url)
In conclusion, the PSI successfully evaluated heat stress in men and women who exercised at different intensities in different climates. We have also extended the applicability of PSI in the present study to consider \( m_{ew} \) and relative exercise intensity as a function of climate. Therefore, PSI applicability was further extended for exercise-heat stress and gender at different combinations of exercise intensity and climate and continues to show the potential to be widely accepted.

This work was conducted at Heller Institute and analyzed at US Army Research Institute of Environmental Medicine, Natick, while the first author was a National Research Council Post-Doctoral Associate. The views, opinions, and/or findings contained in this report are those of the authors and should not be construed as an official Department of the Army position, policy, or decision unless so designated by other official documentation. Approved for public release; distribution is unlimited.

Address for reprint requests and other correspondence: D. S. Moran, USARIEM, 42 Kansas St., Natick, MA 01760-5007.

Received 14 December 1998; accepted in final form 11 March 1999.

REFERENCES