Perceptual versus physiological heat strain during exercise-heat stress

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ABSTRACT

TIKUISIS, P., T. M. MCLELLAN, and G. SELKIRK. Perceptual versus physiological heat strain during exercise-heat stress. *Med. Sci. Sports Exerc.*, Vol. 34, No. 9, pp. 1454–1461, 2002. **Purpose:** The physiological strain index (PSI) has been proposed as a universally applicable measure of exercise-heat strain. Unknown is whether this index, based on normalized increases in core temperature and heart rate, is matched by its perceptual analog. **Methods:** By using a similar mathematical construct to the PSI, the perceptions of thermal sensation and perceived exertion were combined, and the resultant index, PeSI, was compared with its physiological counterpart, denoted as PhSI, for the exercise-heat stress specific to this study. Twenty-six young and healthy subjects wore semi-impermeable clothing and walked (3.5 km·h^{-1}) under hot conditions (40°C and 30% RH) until exhaustion or when their core temperature reached 39.5°C. Subjects were divided into two fitness groups [endurance trained (T) and untrained (U)] comprised of 10 men and 3 women each. U subjects had a higher level of body fatness (mean ± SD 18.1 ± 5.3 vs 12.6 ± 4.5%, $P = 0.010$) and a lower level of aerobic fitness ($\dot{V}O_{2max}$ = 43.6 ± 3.8 ± vs 59.0 ± 6.2 mL·min^{-1}·kg^{-1}, $P < 0.001$). **Results:** During the first hour of exposure, there was no group difference in PhSI, yet T perceived their physiological strain (PeSI) lower than U ($P = 0.002$). Further, the indices were not different for U whereas PhSI was higher than PeSI for T ($P = 0.008$). At the end of the exposure, T had a higher value of PhSI than U (8.23 ± 0.72 vs 6.74 ± 1.47, $P = 0.002$), but there was no group difference in PeSI. Although the indices were again not different for U, PhSI at the end was higher than PeSI for T (6.14 ± 1.68, $P < 0.001$). **Conclusion:** T underestimated and U consistently perceived their physiological strain, as defined by PhSI, in accordance with the measured increases in core temperature and heart rate throughout an exposure to uncompensable exercise-heat stress. **Key Words:** HEAT EXHAUSTION, HEAT INTOLERANCE, INDEX, MODELING, PREDICTION

Heat stress/strain indices have been in development and use over most of the last century as tools for predicting tolerance times for various activities in hot environments (9,15). Although exercise, environmental conditions, and clothing define the level of heat stress, heat strain defines the physiological consequence of the stress. Of interest in the present study is how well the perception of heat strain matches its physiological counterpart during exercise-heat stress. Belding (3) identified core temperature and heart rate as the two primary determinants of the physiological strain associated with heat stress. Relevant perceptual indices are thermal stress (7) and perceived exertion (4). Not readily obvious is the most appropriate physiological strain index for comparative purposes. This is because the above perceptual indices are bounded (usually on a scale from zero to maximal affect) in contrast to various measures of physiological strain that are usually unbounded.

Heat storage, for example, quantifies the increase in body heat content and can theoretically increase without a clearly defined upper bound. Other measures of heat strain that include various combinations of heart rate, core and skin temperatures, and/or their rates of change, and sweat production are also unbounded (13,14). Consequently, conventional measures such as heat storage and its variants cannot be easily normalized (i.e., expressed as a percentage of maximum strain) and are deemed inappropriate for statistical comparison with the perception of heat strain.

Robinson et al. (27) introduced a normalized physiological heat strain index that combined heart rate, core and skin temperatures, and sweat rate with equal weighting. Yaglou (33) argued that this arbitrary summation should not be considered as a true index of physiological strain because the variables involved are normally interrelated and their relative importance might vary quite considerably. Furthermore, the normalization of all four variables is complex and impractical for general application. A simpler heat strain index involving fewer variables with predictable or easily determined bounds is thus warranted.

Frank et al. (6) proposed a cumulative heat strain index that comprised core temperature and heart rate for the evaluation of heat tolerance tests, in concurrence with the original suggestion of Belding (3). This metric was further simplified by Moran et al. (20), who introduced the Physiological Strain Index (PSI) as an instantaneous measure of physiological strain. Despite the arbitrariness of the weighting factors assigned to core temperature and heart rate, Moran et al. have since demonstrated the applicability of PSI to exercise-heat stress under different hydration levels (21) and its invariance to gender (22).

The PSI is comprised of the normalized increases in core temperature (TC) and heart rate (HR) with equal weight. On a scale of 0–10, PSI is calculated as (20):

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$$PSI = 5 \cdot \frac{(TC_t - TC_0)}{(39.5 - TC_0)} + 5 \cdot \frac{(HR_t - HR_0)}{(180 - HR_0)} \quad (1)$$

where the subscripts '0' and 't' refer to measurements taken at the start of the exposure and at some time after the start, respectively. When compared against the rating of perceived exertion, it has been proposed that PSI better represents the overall state of the physiological strain (21). Indeed, Baker et al. (2) found that PSI overestimated the perceived exertion (PE) during a short period (12 min) of moderate exercise under temperate conditions but that PSI correlated highly with PE for prolonged (60 min) exercise. However, no comparison of PSI has been conducted where the perceptions of thermal sensation and physical exertion have been combined. In this study, we combine these two perceptional measures in a mathematical construct similar to PSI and compare indices by using experimental data involving uncompensable exercise-heat stress. Such stress occurs when the individual's evaporative cooling requirement exceeds the ambient cooling power, as for example, during heat exposure while wearing vapor-impermeable clothing.

The PSI was developed with maximum limits on core temperature and heart rate (refer to 39.5°C and 180 bpm, respectively, in Equation 1) that were assumed representative for all individuals. It was further suggested that a given value of PSI represents the same strain for all individuals. Although a core temperature as high as ~ 40°C has been implicated in the fatigue of highly trained endurance athletes during exercise-heat stress (10,11,25,26), recent data have revealed that inactive sedentary individuals cannot tolerate the same high core temperature as their endurance-trained counterparts during uncompensable heat stress (5,31). It would thus appear that physiological strain is not perceived similarly by all individuals, and if not, this has implications on how long an individual would continue to tolerate exercise-heat stress (in a psychological sense), perhaps to the detriment of their health.

The hypothesis of this study is that highly trained endurance individuals that routinely experience high levels of physiological strain (as defined by the PSI) would perceive similar levels of such strain less than untrained individuals and consequently tolerate higher levels of PSI, thereby limiting the applicability of the PSI. This study should also reveal whether the physiologic and perception based indices are interchangeable for predictive purposes. It is emphasized that this is not a validation study of either index but an investigation on the relationship between these two indices.

METHODS

Subject selection and baseline measurements. Twenty-six young and healthy men ($N = 20$) and women ($N = 6$) were recruited to participate in an experiment involving level treadmill walking while wearing semipermeable protective clothing under hot conditions. Before participation, subjects were medically screened and a full explanation of procedures, discomforts, and risks were given before obtaining their written informed consent. The study was approved by the ethics committees on human experimentation at both DRDC and the University of Toronto. Testing was conducted from January to June to limit heat acclimation through casual exposure to hot ambient conditions.

The subjects' physical activities were profiled by an oral questionnaire to determine the presence or absence of regular aerobic activities. Body fatness was determined from underwater weighing using helium dilution to determine residual lung volume. Lean body mass (LBM) was determined by subtracting the calculated mass of body fat from the total body mass and was used to correct for aerobic capacity. Although the expression of maximal aerobic capacity relative to lean body mass has been challenged for its predictive value of physical fitness tests (8), recent findings have confirmed that the major influence of body mass on maximal aerobic capacity is explained by the fat-free mass (12). By removing the influence of fat mass on the expression of maximal aerobic capacity, our aim in this study was to allow for a more accurate classification of subjects as trained or untrained. Maximum aerobic capacity (VO_{2max}) was determined with an incremental running protocol on a motor-driven treadmill using open-circuit spirometry before the heat stress exposure. VO_{2max} was defined as the highest VO_2 observed during the incremental test. Heart rate was monitored throughout the incremental test from a telemetry unit (Polar Electro PE3000, Stanford, CT). The maximum heart rate, generally at the end of the exercise test, was recorded as the individual's HR_{max}.

Experimental protocol. Subjects refrained from hard exercise (e.g., running, swimming, cycling, and/or weight lifting), alcohol, nonsteroidal anti-inflammatories, and sleep medication for 24 h before, and avoided caffeine and/or nicotine for 12 h before the experimental session. All testing was conducted during the morning (between 0800 and 1200 h). Women were tested during the early follicular phase (days 2–5) of the menstrual cycle for nonusers of oral contraceptives and during days 3–6 of the week when no exogenous steroidal supplement was provided for the one female subject using oral contraceptives. Tengalia et al. (32) have shown that heat tolerance while wearing semipermeable protective clothing is similar for nonusers and users of oral contraceptives during the follicular phase of the menstrual cycle.

All subjects performed a familiarization and treatment exposure to the hot-dry environmental chamber (40°C, 30% RH, wind speed $< 0.1\ m \cdot s^{-1}$) while wearing a semipermeable protective clothing ensemble that had a thermal resistance of $0.29°C \cdot m^{-2} \cdot W^{-1}$ and a Woodcock water vapor permeability coefficient of 0.33. The clothing ensemble consisted of underwear, T-shirt, socks, light-weight cotton combat jacket and pants, semipermeable overgarment, jogging shoes, impermeable overboots and gloves, and a respirator and cannister. Further details regarding subject preparation have been described elsewhere (31). Upon entering the chamber, the subject's physiological monitoring sensors were connected to a computerized data acquisition system (Hewlett-Packard 3497A control unit, 236-9000 computer and 2934A printer, Los Angeles, CA) that recorded and displayed values every minute.

During the exposure to heat, subjects walked on a level treadmill at 3.5 km·h^{-1} (0.97 m·s^{-1}) and were provided with 200 mL of water at approximately 37°C before entering the chamber and every 15 min during the exercise. Subjects rated their thermal sensation (TS) and perceived exertion (PE) every 15 min (these scales are described further below). The session continued until either core temperature (TC, as measured by a rectal thermistor 15 cm past the anal sphincter) reached 39.5°C, heart rate remained at or above 95% of HR_{max} for 3 min, nausea or dizziness precluded further exercise, or the subject was removed from the chamber by his or her own request or by the investigator's discretion. Tolerance time was defined as the elapsed time from the beginning of the exercise to the attainment of any of the endpoint criteria that resulted in the subject's removal from the chamber.

Subject characteristics. A preliminary comparison of the physical characteristics between all men and women indicated that height (mean ± SD, 176 ± 8 vs 165 ± 8 cm) and weight (76.0 ± 12.2 vs 57.4 ± 8.3 kg) were the only measured gender differences. Neither of these differences should preclude combining men and women for the purpose of testing the hypothesis of this study. Sawka et al. (30) concluded that male and female subjects have similar tolerance to exercise in dry and humid heat if matched for aerobic fitness (or relative exercise intensity). Further, Moran et al. (22) found no difference in the PSI between male and female subjects matched for aerobic fitness and exposed to the same exercise-heat stress. Henceforth, all subject comparisons will be based on fitness/training status.

The subjects were divided into two groups comprised of 10 men and 3 women each but distinguished by their level of endurance training denoted as untrained (U) or trained (T). Training status was established by whether the subject participated at least 3 d·wk^{-1} in aerobic activities such as running, cycling, and/or rowing, and the attainment of a VO_{2max} in excess of 60 and 55 mL·min^{-1}·kg$^{-1}_{LBM}$ for men and women, respectively. The U subjects were either inactive or participated in recreational sporting activities infrequently, were marginally younger ($P = 0.050$), and had a higher level of body fatness ($P = 0.010$) and lower level of aerobic fitness ($P < 0.001$); otherwise, there were no group differences in height, weight, and maximum heart rate (see Table 1).

Heat strain indices. The physiologic-based heat strain index used herein is defined by a modified version of the PSI (Equation 1) necessitated by the data. First, a true resting HR was not obtained because the subjects experienced elevated heart rates at the start of the trial due to the encumbrance of the protective garment. Thus, HR_0 was arbitrarily assigned a value of 60 bpm (analysis to be discussed later indicates that PSI is not sensitive to this value). Second, the heart rate during the trials sometimes exceeded the maximum value of 180 bpm designated by Equation 1; therefore, this limit was replaced by the subject's actual HR_{max}. The modified PSI used herein is defined as

$$PhSI = 5 \cdot \frac{(TC_t - TC_0)}{(39.5 - TC_0)} + 5 \cdot \frac{(HR_t - 60)}{(HR_{max} - 60)} \quad (2)$$

where the additional 'h' distinguishes the *ph*ysiologic state from the perceptual state defined below.

By direct analogy, the perception-based heat strain index is defined by:

$$PeSI = 5 \cdot \frac{(TS_t - 7)}{6} + 5 \cdot \frac{PE_t}{10} \quad (3)$$

where the additional 'e' refers to the p*e*rceptual state, TS is a modified version of the Gagge et al. (7) rating of thermal sensation from comfortable to intolerably hot (on a scale from 7 to 13, respectively), and PE is a modified version of the Borg (4) rating of physical exertion (on a scale from 0 to 10).

Statistical analyses. Data were analyzed according to the period of exposure common to all subjects and to the endpoint results at the end of each subject's exposure. The common period was defined by the start of the exposure and the latest time that data were obtained for all subjects. The endpoint data were constrained by the measures of TS and PE that were recorded every 15 min. Thus, endpoint will refer to the end of the last 15 min interval of the exposure where all variables for a particular subject were recorded and TEND will refer to the time at this endpoint. In addition to these variables, the analyses included TC, HR, PhSI, PeSI, and two additional variables that define the fractional contribution of HR to PhSI and PE to PeSI, i.e.

$$fHR = \frac{5}{PhSI} \cdot \frac{(HR_t - 60)}{(HR_{max} - 60)} \quad (4)$$

and

$$fPE = \frac{5}{PeSI} \cdot \frac{PE_t}{10} \quad (5)$$

It is conceivable that although the indices may not differ, the contributions of the various components toward these indices might differ, to be ascertained by an analysis of fHR and fPE.

An analysis of variance (Statistica, www.statsoft.com) was conducted on these variables as a mixed 2 (FITNESS) × 4 (TIME) factors design on the common period of exposure with significance at the 0.05 level. FITNESS is the descriptor used to distinguish U and T subjects. Contrast analyses between U and T were conducted wherever an interaction was found. Additional analyses of variance were conducted to test whether the indices (PhSI vs PeSI) and fractional contributions of exertion to the indices (fHR vs

TABLE 1. Mean ± SD of the untrained (U) and trained (T) subjects' physical characteristics.

Characteristic	U	T
Age (yr)	21.8 ± 1.8*	24.7 ± 4.6
Height (cm)	175 ± 9	172 ± 10
Weight (kg)	75.9 ± 13.9	67.5 ± 12.9
Body Fat (%)	18.1 ± 5.3*	12.6 ± 4.5
VO_{2max} (mL·min^{-1}·kg^{-1})	43.6 ± 3.8*	59.0 ± 6.2
VO_{2max} (mL·min^{-1}·kg$^{-1}_{LBM}$)	53.4 ± 3.9*	67.1 ± 5.7
HR_{max} (bpm)	198 ± 7	196 ± 8

* Significant difference between groups.

fPE) were different within each group as a completely within 4 (TIME) × 2 (INDEX) and 4 (TIME) × 2 (FRACTION) factors design, respectively.

The endpoint data including TEND were analyzed for significant differences as a t-test comparison (at the 0.05 level) for independent groups (U vs T). Dependent t-test comparisons were also conducted within each group to determine whether PhSI versus PeSI and fHR versus fPE were different at the end of the exposure.

RESULTS

Early response. All subjects lasted at least 60 min, and this defined the common period of exposure for the analysis of variance. Not surprisingly, there was a main effect of TIME for all variables and these increased in value except for fHR and fPE, which decreased in value (see Fig. 1). TC, PhSI, fHR, and fPE were not different between groups, whereas higher values of HR, TS, PE, and PeSI were found for U compared with T. Further, there was a significant interaction of FITNESS with TIME for these latter variables except HR.

No difference was found between PhSI and PeSI for U during the first 60 min of exposure (Fig. 2). However, PhSI was higher than PeSI for T and there was a significant interaction of INDEX with TIME over this period. The fractional contribution of HR to PhSI (fHR) was significantly higher than the fractional contribution of PE to PeSI (fHR) at all times during the first 60 min of exposure for both U and T (Fig. 2), but there were no significant interactions of FRACTION with TIME.

Endpoint response. No significant differences in HR, TS, PE, PeSI, and fPE were found between U and T at the end of the exposure (see Table 2). U ended the exposure sooner than T (69 vs 95 min) with lower values of TC and PhSI, and a higher value of fHR. Although there was no difference between the endpoint PhSI and PeSI for U, PeSI was lower than PhSI for T. There were no differences between the endpoint fHR and fPE for both U and T.

DISCUSSION

The observation that both subject groups had nearly identical increases in core temperature during the first hour of exposure (Fig. 1a) can be attributed to the experimental condition of uncompensable heat stress. Had the subjects worn vapor-permeable or minimal clothing, we would have expected a slower rate of change of TC for T due to an adaptive increase in evaporative cooling (24), and consequently differences in PhSI would have likely occurred with an even greater separation in PeSI. Semi-impermeable protective clothing has been previously reported to limit sweat loss to approximately 300 g·h^{-1} (1,5). Thus, the rate of heat storage and consequent rise in core temperature is primarily governed by the clothing properties and rate of heat production (17). Yet, the indistinguishable increase in TC was clearly contrasted by the subjects' assessment of thermal sensation, which tended to be higher and divergent for U versus T (Fig. 1b), indicating a lower perceived heat tolerance of the U subjects. Further, we believe that these results are not overly sensitive to where core temperature was measured as changes in alternate core sites (e.g., arterial blood, esophageal, or tympanic) should correspond proportionally to rectal temperature changes during heat stress.

Heart rate was higher for U (Fig. 1c), consistent with this group's rating of perceived exertion that was increasingly higher with time during the first hour compared with T (Fig. 1d). Despite the higher HR for U, PhSI was not significantly different between groups (Fig. 1e). According to the categorization of PSI (20), both groups should have experienced a moderate level of physiological strain by the end of the first hour of the exposure. Yet U had a higher and divergent perception of heat strain during the first hour of exposure (Fig. 1f). These results indicate that during the first hour of exposure, the untrained subjects rated a similar level of PhSI higher than their endurance-trained counterparts. Further, there was no difference between the two indices for U during this period, whereas PeSI was significantly lower than PhSI for T, indicating that the endurance-trained subjects underestimated their physiological strain, as defined herein by the increases in TC and HR.

The above results during the first 60 min of exposure were complemented by the endpoint results, however, in a reverse sense. In the earlier period, PhSI was not different between groups whereas PeSI was lower for T, and at the endpoint, PeSI was not different between groups whereas PhSI was higher for T. These results point to the same conclusion that T underestimated their physiological strain. According to the categorization of PSI (20), U ended at a physiological strain between moderate and high whereas T ended between high and very high.

It is doubtful whether the above findings would have been altered if the original form of PSI (i.e., Equation 1) could have been used. An indication of this stemmed from a complete reanalysis of the data by using an alternate definition of the upper limit of heart rate. Accordingly, HR_{max} was replaced by "220 − age" as a predictor of the upper limit in Equation 2, and in no instance was this limit exceeded by the measured HR. Further, no differences emerged from the statistical comparisons already presented using this definition. It is also doubtful whether knowledge of the subjects' actual resting heart rates would have altered the findings as a small adjustment of HR_0 has little impact on the value of PhSI (Equation 2). For example, assuming HR_0 = 54 bpm for T (representing a 10% decrease from the arbitrarily assumed value of 60 bpm), then the mean endpoint PhSI would increase from 8.23 (Table 2) to 8.28, or by only 0.6%.

Another issue is whether the endpoint findings reflect a true level of heat tolerance. Indeed, U and T subjects respectively reached 67 and 82% of the maximum possible value of PhSI. Although none of the subjects reached their termination heart rate (95% of HR_{max}) at the endpoint, several subjects (3 and 6 in U and T, respectively) reached a core temperature of 39.5°C and the experiment was terminated. These subjects would likely have registered higher

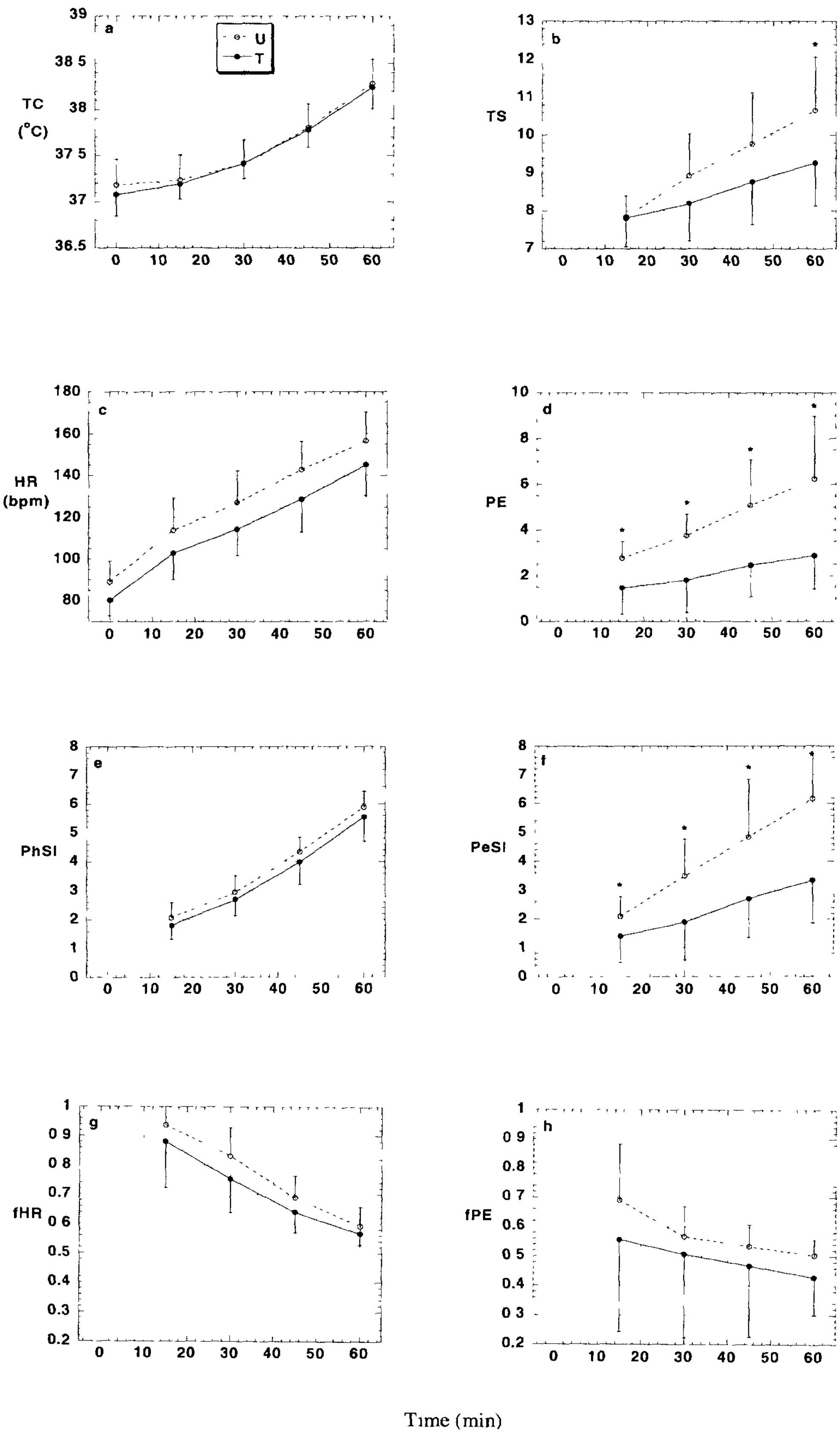

FIGURE 1—Mean ± SD of a) core temperature, b) thermal sensation, c) heart rate, d) perceived exertion, e) modified physiological heat strain index, f) perception-based heat strain index, g) fractional contribution of heart rate to PhSI, and h) fractional contribution of perceived exertion to PeSI during the first 60 min of exposure; * indicates a significant difference between the untrained (U) and trained (T) groups for TS, PE, and PeSI where a FITNESS × TIME interaction was found.

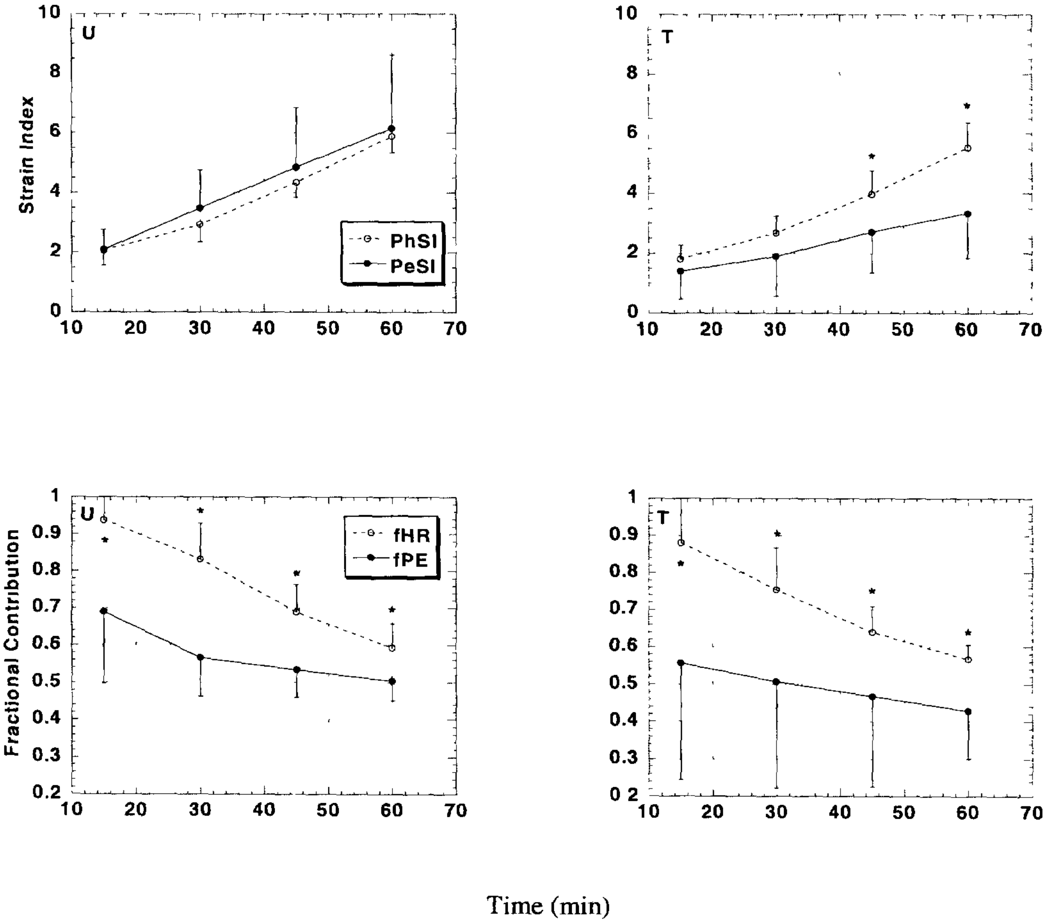

FIGURE 2—Mean ± SD of the modified physiological heat strain index (PhSI) vs the perception-based heat strain index (PeSI), and the fractional contribution of heart rate to PhSI (fHR) vs the fractional contribution of perceived exertion to PeSI (fPE) for U and T during the first 60 min of exposure; * indicates a significant difference between the indices/fractions where an interaction was found.

PhSI and PeSI values had they been allowed to continue. In addition, several other subjects (7 and 5 in U and T, respectively) continued beyond the TEND values used herein because the perceptual scores of TS and PE were only recorded every 15 min. Actual termination times were 74.0 ± 11.0 and 99.6 ± 19.4 for U and T, respectively, with termination TC of 38.71 ± 0.55 and 39.35 ± 0.18°C (both group comparisons were significantly different at $P < 0.001$). Although speculative, it would be fair to extrapolate the endpoint findings presented earlier to suggest that group differences would be preserved at true heat intolerance because all differences in TS, PE, and PeSI between the groups were divergent when compared on the same time scale (Fig. 1).

The fractional contribution of HR to PhSI (fHR) was initially quite high (Fig. 1g) because the relative rate of rise in heart rate exceeded the initial rate of rise in core temperature. Further, fHR was significantly lower than fPE during the first 60 min of exposure (Fig. 2), probably due to the confounding effects of heat stress and the neglect of skin temperature. That is, whereas PhSI was primarily governed by the rise in HR and less by the rise in TC during the early phase of the exposure, thermal sensation was likely appreciably influenced by a rise in skin temperature that contributed to PeSI but is not accounted for by PhSI. Skin temperature was purposely excluded from the definition of PhSI because it does not appear in the original physiological strain index, PSI (20). By the end of the exposure, fHR and fPE were not different for both U and T, indicating that the perception of the separate components of heat strain corresponded to their physiological analogs. It is noteworthy that this occurred with T because this group underestimated PhSI throughout the exposure, yet their weighting of each

TABLE 2. Mean ± SD of the untrained (U) and trained (T) subjects' responses at the endpoint (i.e., at the end of the last 15-min interval that all data for a subject were available).

Variable	U	T
TEND (min)	69.2 ± 11.5*	94.6 ± 17.7
TC (°C)	38.58 ± 0.52*	39.21 ± 0.16
HR (bpm)	162.1 ± 16.9	163.9 ± 13.4
TS	11.15 ± 1.25	11.19 ± 1.16
PE	6.96 ± 2.40	5.42 ± 2.42
PhSI	6.74 ± 1.47*	8.23 ± 0.72
PeSI	6.94 ± 2.09	6.14 ± 1.68
fHR	0.56 ± 0.08*	0.50 ± 0.06
fPE	0.47 ± 0.03	0.44 ± 0.12

* Significant difference between groups. TEND is the endpoint time. TC is core temperature, HR is heart rate. TS is thermal sensation, PE is perceived exertion, PhSI and PeSI are the physiological and perceptual heat strain indices, and fHR and fPE are the fractional contributions of HR and PE to PhSI and PeSI, respectively.

component of heat strain toward PeSI was not skewed during the latter part of the exposure.

That T underestimated PhSI could simply be attributed to the maximum core temperature constraint (TC_{max}) of this index. It is conceivable that 39.5°C does not represent the true maximum for this group as a whole, indeed, 6 of the 13 subjects in this group would have exceeded this limit if allowed to continue. Of the remaining 7 subjects (herein denoted as T7) who ended the exposure before reaching the termination criterion, TC was 39.25 ± 0.21°C and their exposure time was 89.3 ± 15.7 min. These values were significantly higher than the respective values of 38.5 ± 0.40°C and 70.5 ± 10.1 min for the 10 U subjects (U10) who also did not reach the termination criterion of TC = 39.5°C. Yet, HR at exhaustion (158 ± 17 and 162 ± 11 for U10 and T7, respectively) was not different. Montain et al. (19) observed that HR at exhaustion from uncompensable exercise-heat stress varied depending on whether moderate- or high-intensity exercise was involved and on whether subjects were exposed to dry versus humid conditions, but no analysis with regard to subject fitness was conducted. Sawka et al. (29) found that the core temperature at exercise-heat exhaustion was invariant to the level of aerobic fitness. This was confirmed in the present study where regression analyses of the final TC against VO_{2max} indicated no statistical correlation for either U10 or T7.

Returning to the possibility that the core temperature constraint of PhSI is too low for T, limits greater than 39.5°C were substituted for TC_{max} in Equation 2 and the resultant PhSI values for T were reanalyzed. The significant difference in PhSI between U and T at exhaustion was eliminated when $TC_{max} > 39.8$°C for T, and no difference between PhSI and PeSI for T emerged when $TC_{max} >$ 40.1°C. In essence, the differences between fitness groups and between indices for T were eliminated by increasing TC_{max} to approximately 40°C. The implication of this result is that PhSI with fixed constraints might not be generally applicable if one-to-one correspondence with the perceptual index is sought. If so, consideration should be given to the calibration of PhSI on the basis of an individual's physical characteristics/fitness level.

It is also noteworthy that a recent series of studies has shown that fatigue during exertional heat stress in endurance-trained subjects is associated with the attainment of TC between 39.7 and 40.2°C (10,11,25,26). This range of maximal core temperature is consistent with the renormalization of PhSI using a higher TC_{max} for the trained subjects in the present study. In addition, Cheung and McLellan (5) and more recently Selkirk and McLellan (31) reported that untrained subjects could not tolerate the same increases in core temperature as their trained counterparts during uncompensable heat stress. And, the range in core temperature that can be psychologically tolerated during exercise with protective clothing in a hot environment has been shown to vary from 38.0°C to 39.7°C for individuals with varying fitness levels (16,18). Such differences in TC at exhaustion have also been previously reported by Sawka et al. (29). Thus, the PhSI in its current form (Equation 2) may not equate to the perception of physiological strain for all individuals because of differences in core temperatures that can be tolerated at exhaustion.

In conclusion, endurance-trained individuals underestimated PhSI (with a fixed TC_{max} of 39.5°C) throughout an exposure to uncompensable exercise-heat stress whereas the untrained individuals perceived this definition of physiological strain in accordance with the measured values of heart rate and core temperature. The implication of this finding, at least for uncompensable exercise-heat stress, is that an unambiguous measure of physiological strain might be ascertained for untrained individuals directly by inquiry. In contrast, trained individuals are likely to underestimate PhSI (with TC_{max} = 39.5°C) in accordance with the hypothesis. Whether this underestimation places them potentially at greater risk of heat strain injury if allowed to continue exercising in the heat according to their perception is not known.

Two possibilities exist if we accept that PeSI and PhSI represent the actual perceptual and physiological indices of strain, respectively. One is that if all individuals are susceptible to heat strain injury at the same critical core temperature, then the trained individuals are at greater risk than their untrained counterparts because they are likely to underestimate PhSI. Even if the maximum core temperature limit were raised to 40°C, thus lowering the PhSI for the trained individuals to match their PeSI, the risk of heat strain injury would not be eliminated because the perception of the strain is not affected. The alternative possibility is that trained individuals might be better prepared to tolerate a higher physiological strain due to a defensive adaptation to heat stress (23,28). If so, then adjusting TC_{max} to match individual characteristics might achieve a more realistic and reliable correspondence between the PeSI and PhSI. In this case, the prediction of PhSI based on core temperature and heart rate could also simply be ascertained by direct inquiry, as already surmised for the untrained individuals.

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