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TITLE

Power relative to body mass best predicts change in core temperature during exercise-heat stress.

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Predicting change in core temperature during exercise-heat stress

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Abstract

Controlling internal temperature is crucial when prescribing exercise-heat stress, particularly during interventions designed to induce thermoregulatory adaptations. This study aimed to determine the relationship between the rate of rectal temperature (T_{rec}) increase, and various methods for prescribing exercise-heat stress, to identify the most efficient method of prescribing isothermic heat acclimation (HA) training.

Thirty-five males cycled in hot conditions (40°C, 39%R.H.) for 29±2 min. Subjects exercised at 60±9%$\dot{V}O_{2peak,}$ with methods for prescribing exercise retrospectively observed for each participant. Pearson product moment correlations were calculated for each prescriptive variable against the rate of change in T_{rec} (°C.hr^{-1}), with stepwise multiple regressions performed on statistically significant variables (p<0.05). Linear regression identified the predicted intensity required to increase T_{rec} by 1.0-2.0°C between 20-45 min periods, and the duration taken to increase T_{rec} by 1.5°C in response to incremental intensities to guide prescription.

Significant (p<0.05) relationships with the rate of change in T_{rec} were observed for prescriptions based upon relative power (W.kg^{-1}; r=0.764), power (%Power$_{max}$; r=0.679), RPE (r=0.577), $\dot{V}O_2$ (%$\dot{V}O_{2peak}$; r=0.562), HR (%HR$_{max}$; r=0.534), and TS (r=0.311). Stepwise multiple regressions observed relative power and RPE as variables to improve the model (r=0.791), with no improvement following inclusion of any anthropometric variable.

Prescription of exercise under heat stress utilizing power (W.kg^{-1} or %Power$_{max}$), has the strongest relationship with the rate of change in T_{rec} with no additional requirement to correct for body composition within a normal range. Practitioners should therefore prescribe exercise intensity using relative power during isothermic HA training to increase T_{rec} efficiently and maximize adaptation.

Key words

Heat adaptation, Acclimatization, Thermoregulation, Heat Production, Core temperature, Relative Power

INTRODUCTION

Heat illness is a potentially life threatening condition occurring in 1.2 per 100,000 high school athlete exposures across the US (37). In football, the risk increases to 4.4 per 100,000 athlete exposures (37). Heat acclimatization/acclimation (HA) has been identified as an important preventative measure that should be used prior to beginning work in a hot/humid environment to reduce the incidence of heat illness (4) and attenuate performance decrements (48). Whilst primarily used as a tool to mitigate negative responses to heat stress and heat illness (26,39), data also supports the use of HA as a potent training stimuli to elicit notable physiological adaptations in temperate (39,43), and hypoxic (27) conditions. Indeed, HA has been shown to improve endurance time trial performance in hot and cool conditions by 8%, and 6% respectively (39). Notwithstanding these benefits for health and performance, HA remains a time-consuming and practically challenging technique to implement, particularly should individualized exercise prescription preclude use with large groups of athletes or other populations who must perform work in hot environments. These challenges may dissuade its implementation, or reduce the potency of the intervention, and therefore it's efficacy from both athlete health and performance perspectives. Consequently, to optimize the use of HA, the most effective method to administer the intervention should be determined.

HA involves repeated bouts of training in the heat, conferring physiological adaptation. The fundamental potentiating stimuli for effective HA regimes are repeated, significant rises in core temperature leading to elevated skin temperature and profuse sweating in hot environments (50). Isothermic, or controlled hyperthermic HA, which targets core temperatures ≥38.5°C during training, has been identified as the optimal method to prepare individuals for training and competition in the heat (48). Isothermic methods are favorable for athletes (48), particularly those in the taper phase (26), as opposed to traditional fixed intensity training, as reduced training volume and lower sessional exercise intensities are agreeable with this phase of the training cycle (26). A typical isothermic session is ~90 min in duration and performed in hot, humid environmental conditions (ambient temperature ≥40°C, relative humidity ≥40%), where the environmental temperature exceeds that of the body, potentiating heat storage (7,53). Typically, there is a ~30 min initial, "active" phase of the session to attain the desired increase in core and skin temperature, and to stimulate profuse sweating (22,23,26,43,44). This rapid, yet controlled, increase in temperature affords the individual a further 60 min of exposure at or around the desired temperature to potentiate adaptation during the "maintenance" phase. The "active" phase requires moderate-to-high intensity exercise, whilst during the second "maintenance" phase, lower intensity exercise or rest can be implemented to "clamp" core temperature at the desired magnitude by maintaining heat balance. Reducing the duration of the active phase affords individuals a more economical prescription of HA training, while concurrently reducing the total exercise volume (26).

Efficient prescription is pertinent to ensure optimal adaptations and to facilitate adaptation across large numbers of individuals of varying anthropometric and biophysical characteristics, training status and under significant time constraints. To date, a number of different methods of monitoring/prescribing exercise to increase core temperature have been implemented. Robust mechanistic data determining core temperature responses has been obtained via exercise intensity prescriptions using absolute, or relative (to mass, or surface area) metabolic heat production (H_{prod}) (11,55), and evaporative heat loss (11,47), however these methods have limited practicality due to extensive equipment demands to monitor H_{prod}. More widely implemented measurements include peak oxygen uptake (%$\dot{V}O_{2peak}$) (39,46), power relative to body mass ($W.kg^{-1}$) (44), percentage of peak power (%$Power_{max}$) (8), relative (to maximum) heart rate (HR; %HR_{max}) (32), and subjective RPE (6,43,49). Whilst each of these methods may have potential applications for prescribing exercise-heat stress to increase core temperature, the variability of the increase is likely to differ between methods, and between individuals, resulting from established heat production differences at the same prescription (11,13,33,34,55). Within HA experimental work, Patterson et al., (44) implemented a fixed relative power prescription of 2.5 $W.kg^{-1}$ attaining a core temperature of 38.5°C in 30 min, whilst Garrett et al., (22,23) utilized absolute power to achieve the target core temperature of 38.5°C in 28-35 min. Neal et al., (43) have demonstrated that a target core temperature of 38.5°C can be attained in 25 min using a fixed rating of perceived exertion (RPE), whilst utilizing 65%$\dot{V}O_{2peak}$ has led to active phase durations ranging from 38 - 47 min (25–27,42). Differences between protocols of ~10-15 min may be trivial within a single session, however, given the necessity to perform exercise-heat stress on 5 to 10 consecutive days (58), a five- to ten-fold increase in the "inefficiency" is more impactful upon the individual. Moreover, some of these prescription techniques also necessitate an initial test to establish $\dot{V}O_{2peak}$ or appropriate power outputs. This may be beneficial if it improves the efficiency of the administration, however it is presently unknown whether relative (to aerobic capacity) prescriptions are indeed of benefit, with their implementation questioned (26). Should these preliminary tests not be required, then the efficiency of the intervention is improved further. Experimental data suggests that exercise heat stress prescribed relative to aerobic capacity is likely to demonstrate greater variability in core temperature than that prescribed based upon a method more closely representing relative heat production (12,33). For practitioners in the field, or those working with large groups of individuals, a simple prescription method that can be applied *a priori* to confidently increase core temperature by a desired amount, over a given time period is warranted.

This study investigated the relationship between the rate of core temperature increase during exercise-heat stress, and of the aforementioned prospective variables appropriate for prescribing exercise-heat stress, in order to identify the optimal approach for practitioners, coaches and athletes to use for HA training. It was hypothesized that relative power would demonstrate the strongest relationship with the rate of change in core temperature due to the linear relationship between power and $\dot{V}O_2$, and the large component of H_{prod} which is determined by $\dot{V}O_2$.

METHODS

Experimental approach to the problem

Data was analyzed from the first 30 min of fifty-four experimental trials whereby participants cycled in hot conditions part of an acute exercise-heat stress exposure, or first day of HA as published elsewhere (24–27,42). The data was subsequently analyzed to determine which exercise intensity methods (independent variables: relative power ($W.kg^{-1}$ and %max), $\%\dot{V}O_{2peak,}$ $\%HR_{max}$, RPE and thermal sensation (TS)) would most effectively predict the change in T_{rec} (dependent variable; ΔT_{rec}), and should therefore be used to prescribe HA. Once the most appropriate methods were identified and ranked, further analysis was then performed to guide practitioners in the use of each method.

Subjects

Thirty-five moderately trained (multisport cohort, mean performance level 2 (45)), unacclimated adult males (see Table 1 for descriptive characteristics) formed the experimental cohort. Nineteen of the participants performed two sessions which were included in the analysis; these were separated by a minimum of nine months. All participants were informed of the benefits and risks of the investigation and prior to participation each completed and signed medical questionnaires and institutionally approved informed consent following the principles outlined by the Declaration of Helsinki as revised in 2013 before commencing any trial. This study was approved by an Institutional Ethics Board with ethical limitations stating the experiment was to be terminated if T_{rec} ≥39.7°C. Confounding variables of smoking, caffeine, glutamine, alcohol, generic supplementation, prior thermal, hypoxic, and hyperbaric exposures were all controlled as described in the original manuscripts (24–27,42). Prior to any preliminary or experimental trial euhydration was set in accordance with established urine osmolality guidelines (<700 $mOsm \cdot Kg^{-1}$ H_2O (52)) and measured using a urine osmometer (Alago Vitech Scientific, Pocket PAL-OSMO, UK).

INSERT TABLE 1 APPROXIMATELY HERE

Procedures

Anthropometric data collection including stature and nude body mass (NBM) were recorded using a fixed stadiometer (Detecto Physicians Scales; Cranlea & Co., Birmingham, UK) and digital scales (ADAM GFK 150, USA; accuracy ± 0.01kg). Later, body fat (%) was estimated (54) from body density, derived from a four site skin fold calculation (15) using skinfold calipers (Harpenden, Burgess Hill, UK) with body surface area (BSA) also calculated retrospectively (1).

$\dot{V}O_{2peak}$ ($L.min^{-1}$) was determined from an incremental test on a cycle ergometer (Monark e724, Vansbro, Sweden) in temperate conditions (~20°C, ~40% RH). Saddle height was adjusted and remained unchanged for the subsequent experimental trials. Starting exercise intensity was set at 80 W with resistance applied to the flywheel eliciting 24 $W.min^{-1}$ increases at the constant cadence of 80 rpm. HR ($b.min^{-1}$) was monitored continually during all exercise tests by telemetry (Polar Electro Oyo, Kempele, Finland). The test was terminated when participants could not maintain cadence above 70 rpm after strong verbal encouragement. Expired metabolic gas was measured throughout the test using an online system (Metamax 3X or 3B, Cortex, Germany). $\dot{V}O_{2peak}$ was considered the highest volume of oxygen ($\dot{V}O_2$) obtained in any 10 s period with $\dot{V}O_{2peak}$ more appropriately describing the end point of the test due to an absence of $\dot{V}O_2$ plateau in all participants. Confirmation of $\dot{V}O_{2peak}$ was made via the attainment of a HR within 10 b.min^{-1} of age predicted maximum, and RER >1.1 in all participants.

All experimental trials were conducted in the morning (08:00±02:00 h) on a cycle ergometer located inside an environmental chamber whereby temperature (40.1±0.1°C) and humidity (39.0±1.3% RH) were thermostatically controlled (WatFlow control system; TISS, Hampshire, UK). Following provision of a urine sample and measurement of NBM, each participant was equipped with a rectal thermistor inserted 10 cm past the anal sphincter (Henleys Medical, UK, Meter logger Model 401, Yellow Springs Instruments, Yellow Springs, Missouri, USA), and a HR monitor affixed around the torso. A 10 min period of seated rest in temperate laboratory conditions (~20°C, ~40% RH) preceded entry to the environmental chamber. Upon entering the chamber, participants immediately commenced cycling at an external mechanical power output corresponding to either 50% (n = 22), 65% (n = 26), or 75% $\dot{V}O_{2peak}$ (n = 6). During the experimental session HR, T_{rec}, power (external work), RPE (2)) and TS (59)) were recorded every 5 min. Upon participants being unable to maintain the target cadence of 80 rpm, intensity was reduced by 5-10%$\dot{V}O_{2peak}$ to recover the target cadence (80 rpm). The rate of T_{rec} increase (°C.hr^{-1}) was calculated following completion of the ~30 min trial.

Following the 29 ± 2 min of exercise-heat stress, the relationship between each prescriptive parameter recorded, and the rate of T_{rec} increase for the given trial were calculated.

$$\text{EQ.3. Rate of change in } T_{rec}\ (°\text{C.hr}^{-1}) = (T_{rec}^{2} - T_{rec}^{1}/\text{time}^{2} - \text{time}^{1})*60$$

Note: T_{rec}^2 and time^2 are simultaneous measurements taken at the end of the exercise heat stress; and T_{rec}^1 and time^1 are the seated resting values in the chamber immediately prior to beginning the exercise protocol.

Power corresponding to the percentage of $\dot{V}O_{2peak}$ was calculated by plotting power against $\dot{V}O_2$ from the preliminary $\dot{V}O_{2peak}$ test, and using the linear regression equation to determine resistance required to elicit the desired power at a fixed cadence of 80 rpm. Mean relative power ($W.kg^{-1}$) was calculated by dividing observed mean power by NBM. Percentage of peak power (%$Power_{max}$) was calculated by dividing the mean power during the 30 min exposure by the power at $\dot{V}O_{2peak}$ during the preliminary trial ($Power_{max}$).

$$\text{EQ.4. } \%Power_{max} = (\text{mean Power (W)} / (Power_{max} \text{ (W)}))*100$$

Percentage of age predicted maximum HR (%HR_{max}) was calculated from the recorded mean HR and age predicted maximum HR (56).

$$\text{EQ.5. } \%HR_{max} = (\text{mean HR } (b.min^{-1}) / (208 - 0.7 \text{ x age (years)}))*100$$

RPE, and TS, were recorded at 5 min intervals throughout the exposure, with a mean calculated, and used for subsequent analysis.

Calculations

Using the significant linear relationship between rate of T_{rec} increase and each exercise intensity parameter, the slope and intercept were used to calculate the requirements to increase T_{rec} by 1.0°C, 1.5°C, and 2.0°C in 20, 25, 30, 35, 40 and 45 min periods, utilizing the equation below (see Table 2 for slope and intercept corresponding to each variable).

$$\text{EQ.1. Prescription} = ((\text{rate of change in } T_{rec} \text{ } (°C.hr^{-1})) * (60 / \text{desired duration for change in } T_{rec} \text{ (min)}) - \text{intercept } [°C.hr^{-1}]) / \text{slope } [°C.hr^{-1}]$$

Further to identifying the prescription required to achieve incremental changes in T_{rec} over incremental durations, an additional calculation to describe the duration to achieve a +1.5°C change in T_{rec} in response to smaller incremental changes in the prescription was calculated using the equation below (see Table 2 for slope and intercept corresponding to each variable).

$$\text{EQ.2. Time (min)} = (1.5°C) / ((\text{intensity} * \text{slope } [°C.min^{-1}]) + \text{intercept } [°C.min^{-1}])$$

The ranges in T_{rec} were implemented to account for variation in T_{rec} due to potential differences from the basal 37.0°C (57), with diurnal variation (+0.5°C, (61)), and with HA (-0.5°C, (27,39)). Time was also adjusted to make the active phase more efficient (~1:4 active:maintenance ratio), or more palatable for the individual (1:1 active:maintenance ratio). A +1.5°C change in T_{rec} represented the attainment of the isothermic threshold of 38.5°C from the basal T_{rec} (37.0°C).

INSERT TABLE 2 APPROXIMATELY HERE

Statistical Analyses

All statistical calculations were performed using SPSS software version 20.0 (SPSS, Chicago, IL, US) with all data reported as mean ± standard deviation. Significance level was set at $p < 0.05$. All outcome variables were assessed for normality of distribution and sphericity prior to further analysis. Pearson's correlations (R) were used to examine the relationships between the rate of T_{rec} increase and dependent variables describing parameters for prescribing exercise intensity. Stepwise multiple regression was later performed on all significant correlates for the rate of change in T_{rec} utilizing a forward selection entry method, with an acceptable Durbin-Watson (d) test score observed as d = 2.023, thus demonstrating a lack of autocorrelation between data at the 0.05 α level.

RESULTS

A mean rate of T_{rec} increase of $2.24 \pm 1.09°C.hr^{-1}$ (range $0.64 – 4.82°C.hr^{-1}$) was observed. This rate of T_{rec} increase correlated ($p<0.05$) with relative power ($W.kg^{-1}$; r=0.764), percentage of peak power (%$Power_{max}$; r=0.679), RPE (r=0.577), percentage of $\dot{V}O_{2peak}$ (%$\dot{V}O_{2peak}$; r=0.562), percentage of age predicted maximum HR (%HR_{max}; r=0.534), and TS (r=0.311). Anthropometric descriptive variables of age (r=0.368), mass (r=-0.327), body fat (r=-0.335) and BSA/mass (r=0.301) correlated with the rate of T_{rec} increase ($p<0.05$), with no correlation observed for BSA (r=-0.262) or stature (r=-0.020). Absolute $\dot{V}O_{2peak}$ (r=0.437) and relative $\dot{V}O_{2peak}$ (r=0.527) obtained during the preliminary trial were correlated with the rate of T_{rec} increase ($p<0.05$).

Tables 1 and 2 present the descriptive data for linear regression equation relating to each independent variable. Figure 1 presents a matrix of the scatterplots for each variable in relation to the rate of change in core temperature.

INSERT FIGURE 1 APPROXIMATELY HERE

Multiple regression observed acceptance of relative power (W.kg^{-1}; R^2 change=0.583, SE_E=0.712) and RPE (R^2 change=0.042) into the model for a final regression equation (see EQ.6. below) demonstrating an improvement predictive capability (r= 0.791, R^2=0.625, SE_E=0.682).

EQ.6. Rate of change in T_{rec} (°C.hr^{-1}) = -1.614+ (1.040*Power (W.kg^{-1}) + (0.114*RPE)

DISCUSSION

The aim of this study was to determine the strongest relationship between the rate of T_{rec} increase during exercise-heat stress replicating the active phase of an isothermic HA session, and a series of prospective variables appropriate for prescribing exercise-heat stress. As with any training stimuli, the efficient administration is congruous with its palatability and beneficial application. Our data identifies a potential optimal approach for practitioners to use to induce heat adaptation. In agreement with our hypothesis, power relative to mass (W.kg^{-1}) demonstrated the strongest relationship with the rate of T_{rec} increase during ~30 min of exercise-heat stress in uncompensable conditions. This parameter explained 58% of the variance of the increase, and can therefore be suggested as the most appropriate parameter for controlling the increase in T_{rec}, noticeably reducing the variability in the duration taken to achieve the target T_{rec} of 38.5°C during isothermic HA. Additionally, %Power$_{max}$ explained 46% of the variance of the increase in T_{rec}. RPE (33%), $\%\dot{V}O_{2peak}$ (32%), $\%HR_{max}$ (29%), and TS (10%) all demonstrated a significant but lesser explanation of the increase in T_{rec}. The variability of these prescription methods is likely due to an indirect, rather than direct relationship with the conceptual heat balance equation (35), whereby power (W.kg^{-1} or %Power$_{max}$) is directly represented as external work, and relates to H_{prod} due to the relationship between external work, and metabolic energy expenditure based upon established rates of mechanical efficiency (36). Relative physiological intensities demonstrate an indirect relationship with H_{prod} , thus a greater variability in the change in T_{rec} in occurs (19)."

Resting core temperature is routinely measured as 37.0°C at the rectum (57) representing a 1.5°C difference from the isothermic target proposed as optimal for heat adaptation (48,58). Utilizing linear regression, the described prescription to increase T_{rec} by 1.5°C in 30 min (17) within the participants used in the study is as follows: power = 2.7 $W.kg^{-1}$, power = 64 $\%Power_{max}$, RPE = 17 "Very Hard", HR = 95 $\%_{max}$, $\dot{V}O_2$ = 68 $\%_{peak}$, and TS = 8.0 (Table 3). The relationship between each predictive method and the intensity-duration to achieve a +1.5°C change in T_{rec} are presented in Table 4.

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The linear regression calculations are comparable to that published elsewhere, for example it has been observed that an RPE = 15 can be used to attain a T_{rec} of 38.5°C within ~25 min (43), and that a fixed relative power prescription of 2.5 $W.kg^{-1}$ attaining 38.5°C in 30 min (44). Both of these are lower than the calculated RPE = 17 and 2.7 $W.kg^{-1}$ in the present study, whereby in our cohort RPE = 15 would increase T_{rec} to 38.5°C in 37 min, and 2.5 $W.kg^{-1}$ would require 33 min (Table 4). This disparity can be explained by the higher $\dot{V}O_{2peak}$ of the participants whereby the greater aerobic capacities (63 and 54 $mL.kg^{-1}.min^{-1}$), mean that for the same relative intensity, a higher absolute intensity, $\dot{V}O_2$ and H_{prod} occurs. This data highlights that isothermic HA may be more efficient in more aerobically trained individuals in spite of increased capacities for heat loss via sweating in this population (7). Conversely, the linear regression observed a prescription of 68% $\dot{V}O_{2peak}$ as being required, further reinforcing this mechanism for the delayed attainment in the experiments which have utilized a 65% $\dot{V}O_{2peak}$ prescription (25–27,42). This identifies that in these experiments (25–27,42), that the work intensity was too low to achieve a T_{rec} = 38.5°C in 30 mins, and that the reduced predictive capacity of this variable means it is inferior to relative power and RPE. Practitioners adopting the relative power prediction can derive confidence from the linear relationship between external work and $\dot{V}O_2$, and the consistency of gross efficiency within absolute work and external temperatures (18,60,62). The finding that external power relative to body mass in W.kg^{-1} is the best predictor of the rate of change of T_{rec} supports the notion that heat production per unit mass is the primary determinant (11,13,33,34,55), because mechanistically (and biophysically) this is most likely the reason for the observed relationships. There is little mechanistic justification for external workload per unit mass as an independent determinant of the rate of change in T_{rec}, rather this is the most effective surrogate for the impractical measurement of H_{prod}. Little attention has been given to the required intensity for exercise during the maintenance phase of the isothermic HA in published literature. Table 4 proposes that to elicit minimal increases in T_{rec} during this ~60 min phase the following prescriptions are appropriate power ≤1.25 W.kg^{-1}, power ≤30 %Power$_{max}$, RPE ≤10 "Very Light - Light", $\dot{V}O_2$ ≤40 %$_{peak}$, HR ≤60 %$_{max}$, and TS ≤5.0.

The significant relationship, but lower predictive capacity for the rate of change in T_{rec} of %$\dot{V}O_{2peak}$ and %HR_{max} is explained by the nature of their implementation, notably the disparity in absolute intensity observed between individuals for the same relative prescription (40). It has been observed that aerobically trained individuals can produce a higher power for equal relative intensities when compared to untrained equivalents in both temperate and hot conditions (46). For individuals who demonstrate a greater absolute aerobic capacity (i.e. $\dot{V}O_{2peak}$) and consequently exercise at a greater absolute $\dot{V}O_2$, and therefore greater absolute H_{prod} for the same relative prescription, a greater rate of change in T_{rec} likely occurs (11,33,34,55). This highlights previous observations that isothermic HA may be more efficient in individuals with a high *vs.* a low aerobic capacity (26). The implementation of %$\dot{V}O_{2peak}$, %HR_{max} for training administration has been proposed as appropriate for moderate intensity prescriptions (<60% $\dot{V}O_{2peak}$) between individuals (40), however under heat stress, significant cardiovascular drift occurs reducing absolute $\dot{V}O_{2peak}$ (38), further reducing the effectiveness of these relative intensity prescriptions. These uncertainties make identification of this "moderate" intensity domain unclear. The %$\dot{V}O_{2peak}$ (or %HR_{max}) approach is often preferred for prescribing training as it is known that each participant, irrespective of absolute aerobic capacity, will be able to complete the exercise bout. In a varied cohort of individuals commencing isothermic HA, where the intention is to provide a potent exercise load to rapidly increase heat storage, $\%\dot{V}O_{2peak}$, $\%HR_{max}$ are however inferior measurements in comparison to that of power relative to body mass.

The predictive capacity of the RPE scale is appealing for practitioners due to the simplicity of its application, and the present analysis further reinforces the effective implementation of the scale as a viable method for prescribing exercise heat-stress (6). In addition to being effective at predicting the rate of T_{rec} increase (Figure 1), RPE has shown consistency between days for administration variables such as mean power, and time until $T_{rec} \geq 38.5°C$ in trained individuals (43). An additional benefit of the RPE method is that it is less susceptible to decreases in the adaptation stimuli with ongoing HA (58) or the increases in aerobic capacity known to occur with heat adaptation (39). This notion furthers mitigates the use of $\%\dot{V}O_{2peak}$ and $\%HR_{max}$. Even with increased aerobic capacity and improved TS during heat adaptation (39), RPE is subjectively interpreted by an individual based upon cardiovascular and thermoregulatory afferent feedback (16). Consequently, even with increased aerobic capacity, clamping RPE will likely result in increased exercise performance/work. This concurrently increases H_{prod} following elevated absolute $\dot{V}O_2$. Although heat storage will decrease with adaptation throughout HA, an increased time to attain the isothermic target is less likely to occur as the self-regulation of work at a higher intensity appears to maintain the potency of this prescription at least through short term timescales (43). Though RPE is a complex multifactorial construct, it provides an effective method for prescribing work in the heat, with a targeted prescription of 17 being predictive of an increase in T_{rec} of 1.5°C within 30 min when the monitoring of power at $2.7\ W.kg^{-1}$ is not possible.

Multiple regressions observed a 4.2% improvement to the simple linear regression equation could be made by adding RPE to the relative power ($W.kg^{-1}$). This generated a total prediction of 62.5%. Whilst this may offer a mathematical improvement to the model, within the experimental conditions imposed, RPE was not manipulated, nor is manipulation of RPE able to directly modulate the physiology responsible for H_{prod} i.e. $\dot{V}O_2$ and respiratory exchange ratio (RER). Instead RPE is a reflection of the perception of the afferent feedback pertaining to the physiological responses of the external work being performed, and potentially the external environment where it is occurring (16). In light of this, and considering the aim of this analysis (to predict changes in T_{rec}, thus optimize isothermic HA), the small improvements in determining the rate of change in T_{rec} via multiple regression is deemed unhelpful in this instance, particularly regarding the sensitivity of the RPE scale and the variability in RPE at any given power between individuals as demonstrated by Figure 1. The rejection of participant descriptive characteristics into the multiple regression models in favor of power ($W.kg^{-1}$) and RPE is noteworthy. Had participant descriptive variables been included in an improved regression model, practitioners may have needed to adjust prescriptions of exercise intensity to account for individual variation in fitness/fatness (12). Based on our data, and recent work dissuading the use of power relative to lean body mass (14), this is not necessary.

It has been stated that after 60 min of exercise in compensable conditions, H_{prod} ($W.kg^{-1}$) is the best predictor (49.6%) of the rate of change in T_{rec} (12), with anthropometric characteristics of surface area to mass ratio (4.3%), and body fat percentage (2.3%) improving the model. This reaffirms the importance of H_{prod} in modulating changes in core temperature during accurate prescription of exercise heat stress. A limitation of the proposed optimal implementation via the H_{prod} method is that, whilst setting the initial intensity prescription can be achieved based upon preliminary data, to effectively control and monitor the training, continual measurement of metabolic gas exchange is also required (11). This is neither feasible, nor practical for those in the field or when working with large groups due to requirements for specialized equipment and individual pre intervention testing. Previous studies have demonstrated that core temperature increase has a positive relationship with absolute or relative H_{prod} (30,33) and negatively correlates with body mass (9,28–31). Data in the present study highlights a correlation between the rate of change in T_{rec} and some anthropometric variables (mass, mass/BSA, and body fat (%)). The predictive ability of the anthropometric variables was less than the exercise intensity parameters, and did not further improve the multiple regression equation. This is in agreement with recent data highlighting the most important characteristic determining core temperature during compensable exercise-heat stress to be relative H_{prod} (12), which is a byproduct of absolute $\dot{V}O_2$ even when considering independent participant groups demonstrate large differences in absolute H_{prod} (11), and body composition (14) at the same relative intensity. The dynamics of internal heat distribution may differ greatly between individuals and environments accounting for unexplained variation in T_{rec} increase (12); this is an important area of future research particularly regarding heat illness.

Limitations

Our data is in partial agreement with the recent observation that experiments should adopt a H_{prod} ($W.kg^{-1}$) prescription of intensity (12), to compare changes in core temperature effectively. A primary limitation of this retrospective analysis is the absence of real time, online measurement of expired metabolic gases during the exercise-heat stress that would facilitate data analysis on actual H_{prod} and $\dot{V}O_2$. Data presented in elegant experiments isolating the effectiveness of H_{prod} derived prescriptions have shown consistent changes in core temperature inferring this method to be optimal in compensable conditions (11,33,34,55), at present no data is available to extend this to uncompensable conditions in which isothermic HA is performed. Whilst experimentally beneficial the impracticalities of implementing these techniques discourage their use by practitioners for the prescription of exercise intensity when training individuals and teams in the heat.

The disparity between the environmental conditions for the determination of $\%\dot{V}O_{2peak}$ and $\%Power_{max}$, and that in which the exercise-heat stress was performed is an additionally plausible contributing factor for the individual variation in the rate of change in T_{rec} using a $\%\dot{V}O_{2peak}$ (or $\%Power_{max}$) method (25–27,42). A greater contributing factor may be systematic differences in H_{prod}, in addition to other physiological responses, notably sweating, when utilizing this method (10,19,33). Finally, this data assumes all individuals tolerate cycling exercise to the same extent as the participants within this study, and would not find the requisite prescriptions intolerable due to localized fatigue. It remains unknown whether the $W.kg^{-1}$ prescription is effective in other exercise modalities where measurement of power is achievable, this should be experimentally elucidated. This observation also extends to protocols where power isn't able to be monitored or cycling exercise cannot be performed, e.g. when the exercise modality is treadmill running. At the current time the optimal approach to administering HA may be via prescriptive RPE as implemented recently elsewhere (6). Confidence in the use of the prescribed RPE when running from this cycling data can be drawn from the equality of submaximal $\dot{V}O_2$ and RPE between exercise modes at submaximal intensities (3).

Although the data presented in Table 3 and Table 4 presents the requirements of the described intensity prescription, some data have been excluded from the tables at the upper extremes of the prescriptions representing a large increase in T_{rec} over short durations. The exclusion criteria were made when the regression equation calculated a prescription that was unattainable within the confines of the implementation tool (RPE>20, TS>8) or impractical (>100% of $\%HR_{max}$). These tables offer an effective guide for practitioners who are designing HA strategies. Caution should be drawn from data where the prescription appears unsustainable for extended periods (>100% of $\%Power_{max}$, >100% of $\%\dot{V}O_{2peak}$).

It should be noted the present data is based upon only male participants. Future work should therefore aim to predict core temperature responses to exercise in the heat in female participants, with some caution applied when implementing these workloads in females whom demonstrate different baseline heat tolerance to males (42), in particular at differing times of the menstrual cycle and in response to contraceptive medication (7).

Future directions

Future experiments may consider the efficacy of this analysis utilizing running, or arm cranking models of HA, and cycle models in combination with prohibited evaporation (41), under imposed hypohydration (22,43), or using an acclimatization, rather than acclimation model. Additionally, this analysis should be used to address the paucity of experimental HA data considering participants at the extremes of anthropometric norms known to be susceptible to extreme internal heat load (13), in addition to the assessment of female responses (42), and those with thermoregulatory impairment e.g. spinal cord lesion or multiple sclerosis patients (5,51). Optimizing the administration is desirable to improve the ecological validity and effective implementation of the intervention in the aforementioned populations. This present data has highlighted that the observations regarding methods for effective control of core temperature change in compensable conditions are also relevant in uncompensable conditions (12,34), although this should be experimentally tested utilizing an explicit experimental design specific to that research question.

PRACTICAL APPLICATIONS

This data provides precise guidelines to allow practitioners to accurately implement isothermic HA to improve aerobic capacity and mitigate heat illness in athletes (48). Given the greatest predictive capacity, and equal or greater simplification of administration of using power (W.kg^{-1} or %Power$_{max}$) or RPE methods these are the preferred methods. The use of %$\dot{V}O_{2peak}$, %HR$_{max}$ or TS demonstrate reduced efficacy when the aim is to minimize the duration to achieve a given increase in core temperature. There is no necessity to adjust the administration to account for differences in body composition within a normal range, in part due to the relative (to body mass) predictive recommendations. A further benefit of the power (W.kg^{-1}) or RPE based prescription is the opportunity to forgo a pre HA intervention assessment of $\dot{V}O_{2peak}$ or $\dot{V}O_{2max}$, which may be of greatest relevance within the time-limited environment of professional sport, or during large scale occupational or military deployments. Practitioners should therefore implement a relative power based (21,22,44) prescription when administering training sessions in the heat (i.e. HA). If monitoring of power is unavailable RPE provides an effective alternative (43). Inexpensive and portable equipment allows easy monitoring of the physiological responses, notably the change in core temperature (20), during the exposure to ensure participant safety, and to observe maintenance of the stimuli for adaptation for an individual between sessions.

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FIGURE LEGEND

Figure 1. Relationships between the rate of change in T_{rec} and exercise intensity parameters Power (A; W.kg^{-1}), Power (B; %$_{max}$), RPE (C), $\dot{V}O_{2peak}$ (D; %), HR (E; %$_{max}$), TS (F).

TABLE LEGENDS

Table 1. Participant descriptive characteristics prior to the commencement of each experimental trial and the respective relationship to the rate of T_{rec} increase within each experimental trial

Table 2. Summary of data describing relationships between exercise intensity prescription parameters and the rate of T_{rec} increase [expressed as °C.hr^{-1} (used in EQ 1 for calculations in Table 3) or °C.min^{-1} (used in EQ 2 for calculations in Table 4)] within each experimental trial

Table 3 Relative power (W.kg^{-1} and %Power$_{max}$), RPE, oxygen uptake (%$\dot{V}O_{2peak}$), HR (%HR$_{max}$) and TS requirements to achieve incremental changes in T_{rec} over incremental durations. Note Shaded areas represent intensities where prescription exceeds physiological capacity/perceptual scale.

Table 4 Duration to achieve a +1.5°C change in T_{rec} in response to incremental changes in relative power (W.kg^{-1} and %Power$_{max}$), RPE, oxygen uptake (%$\dot{V}O_{2peak}$), HR (%HR$_{max}$) and TS.

Table 1. Participant descriptive characteristics prior to the commencement of each experimental trial and the respective relationship to the rate of T_{rec} increase within each experimental trial

	Mean ± SD	Min	Max	R^2	P
Age (years)	23 ± 4	18	36	0.14	0.006
Height (cm)	180 ± 6	168	190	0.00	0.885
Mass (kg)	76.3 ± 10.1	58.6	107.6	0.11	0.016
BSA (m^2)	1.95 ± 0.13	1.72	2.29	0.07	0.055
BSA/Mass (cm^2/kg)	258 ± 17	204	296	0.09	0.027
Fat (%)	13.8 ± 4.1	7.8	31.0	0.11	0.013
$\dot{V}O_{2peak}$ ($L.min^{-1}$)	3.82 ± 0.66	2.23	5.41	0.19	0.001
$\dot{V}O_{2peak}$ ($mL.kg^{-1}.min^{-1}$)	51 ± 11	21	87	0.28	<0.001

Table 2. Summary of data describing relationships between exercise intensity prescription parameters and the rate of T_{rec} increase [expressed as °C.hr^{-1} (used in EQ 1 for calculations in Table 3) or °C.min^{-1} (used in EQ 2 for calculations in Table 4)] within each experimental trial

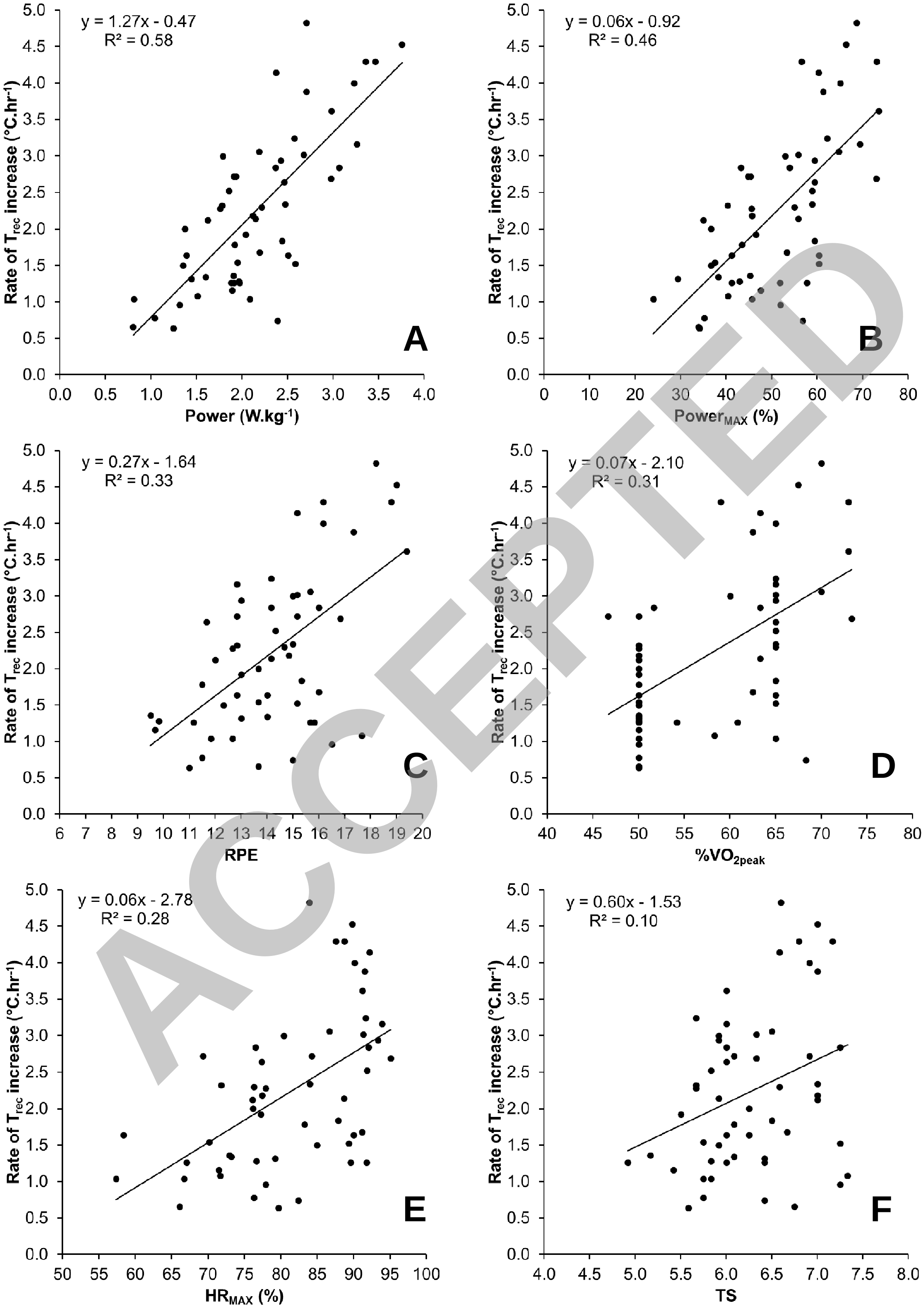
	Mean ± SD	Min	Max	R^2	P	Slope (°C.hr^{-1})	Intercept (°C.hr^{-1})	Slope (°C.min^{-1})	Intercept (°C.min^{-1})
Power (W.kg^{-1})	2.1 ± 0.1	0.8	3.8	0.58	<0.001	1.2650	-0.4704	0.02108	-0.00784
Power (%max)	51 ± 12	24	78	0.46	<0.001	0.0619	-0.9576	0.00103	-0.01596
RPE (A.U.)	14 ± 2	9	19	0.33	<0.001	0.2725	-1.6769	0.00454	-0.02795
Oxygen Uptake (%$\dot{V}O_{2peak}$)	51 ± 11	47	73	0.32	<0.001	0.0745	-2.1042	0.00124	-0.03507
HR (%HR_{max})	83 ± 10	58	96	0.29	<0.001	0.0616	-2.7794	0.00103	-0.04632
TS (A.U.)	6.3 ± 0.6	4.9	7.3	0.10	0.022	0.6004	-1.5797	0.01001	-0.02633

Table 3 Relative power ($W.kg^{-1}$ and $\%Power_{max}$), RPE, oxygen uptake ($\%\dot{V}O_{2peak}$), HR ($\%HR_{max}$) and TS requirements to achieve incremental changes in T_{rec} over incremental durations. Note Shaded areas represent intensities where prescription exceeds physiological capacity/perceptual scale.

	+1.0°C						+1.5°C						+2.0°C					
Time (min) -	20	25	30	35	40	45	20	25	30	35	40	45	20	25	30	35	40	45
Power ($W.kg^{-1}$)	2.7	2.3	1.9	1.7	1.5	1.4	4.0	3.2	2.7	2.4	2.1	1.9	5.2	4.2	3.6	3.1	2.7	2.5
Power ($\%Power_{max}$)	64	54	48	43	40	37	88	74	64	57	52	48	112	93	80	71	64	59
RPE (A.U.)	17	15	13	12	12	11	20+	19	17	16	14	13	20+	20+	20+	19	17	16
Oxygen Uptake ($\%\dot{V}O_{2peak}$)	68	60	55	51	48	46	89	77	68	63	58	55	100+	93	82	74	68	64
HR ($\%HR_{peak}$)	95	85	79	74	70	68	100+	100+	95	88	83	79	100+	100+	100+	100+	95	90
TS (A.U.)	7.6	6.6	6.0	5.5	5.1	4.9	8.0+	8.0+	7.6	6.9	6.4	6.0	8.0+	8.0+	8.0+	8.0+	7.6	7.1

Table 4 Duration to achieve a +1.5°C change in T_{rec} in response to incremental changes in relative power ($W.kg^{-1}$ and $\%Power_{max}$), RPE, oxygen uptake ($\%\dot{V}O_{2peak}$), HR ($\%HR_{max}$) and TS. Note Shaded areas represent intensities where prescription exceeds physiological capacity/perceptual scale, italics indicate data calculated outside of the upper and lower bounds of the experimental data (see Table 2).

Power	Time to T_{rec} = +1.5°C	Power	Time to T_{rec} = +1.5°C	RPE	Time to T_{rec} = +1.5°C	Oxygen Uptake	Time to T_{rec} = +1.5°C	HR	Time to T_{rec} = +1.5°C	TS	Time to T_{rec} = +1.5°C
($W.kg^{-1}$)	(min)	($\%Power_{max}$)	(min)	(A.U.)	(min)	($\%\dot{V}O_{2peak}$)	(min)	($\%HR_{peak}$)	(min)	(A.U.)	(min)
1.00	113	20	*322*	7	*390*	30	*680*	50	*298*	3.0	*406*
1.25	81	25	153	8	*179*	35	*178*	55	*147*	3.5	*172*
1.50	63	30	100	9	116	40	*103*	60	98	4.0	*109*
1.75	52	35	75	10	86	45	72	65	73	4.5	*80*
2.00	44	40	59	11	68	50	55	70	59	5.0	63
2.25	38	45	49	12	56	55	45	75	49	5.5	52
2.50	33	50	42	13	48	60	38	80	42	6.0	44
2.75	30	55	37	14	42	65	33	85	37	6.5	39
3.00	27	60	33	15	37	70	29	90	33	7.0	34
3.25	25	65	29	16	34	75	26	95	29	7.5	31
3.50	23	70	27	17	30	80	*23*	100	*27*	8.0	*28*
3.75	21	75	24	18	28	85	*21*				
4.00	*20*	80	*23*	19	26	90	*20*				
4.25	*18*	85	*21*	20	*24*	95	*18*				
4.50	*17*	90	*20*			100	*17*				
4.75	*16*	95	*18*								
5.00	*15*	100	*17*								



y = 1.27x - 0.47
R² = 0.58
A
Rate of T_{rec} increase (°C.hr^{-1})
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
Power (W.kg^{-1})
y = 0.06x - 0.92
R² = 0.46
B
Rate of T_{rec} increase (°C.hr^{-1})
0
10
20
30
40
50
60
70
80
$Power_{MAX}$ (%)
y = 0.27x - 1.64
R² = 0.33
C
Rate of T_{rec} increase (°C.hr^{-1})
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
RPE
y = 0.07x - 2.10
R² = 0.31
D
Rate of T_{rec} increase (°C.hr^{-1})
40
45
50
55
60
65
70
75
80
$\%VO_{2peak}$
y = 0.06x - 2.78
R² = 0.28
E
Rate of T_{rec} increase (°C.hr^{-1})
50
55
60
65
70
75
80
85
90
95
100
HR_{MAX} (%)
y = 0.60x - 1.53
R² = 0.10
F
Rate of T_{rec} increase (°C.hr^{-1})
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
8.0
TS