JOURNAL OF APPLIED PHYSIOLOGY

J Appl Physiol 131: 1543–1551, 2021.
First published October 7, 2021; doi:10.1152/japplphysiol.00253.2021

RESEARCH ARTICLE

The impact of elevated body core temperature on critical power as determined by a 3-min all-out test

Brendan W. Kaiser,[1] Ka'eo K. Kruse,[2] Brandon M. Gibson,[1] Kelsey J. Santisteban,[1] Emily A. Larson,[1] Brad W. Wilkins,[1,3] Andrew M. Jones,[4] John R. Halliwill,[1] and Christopher T. Minson[1]

[1]*Department of Human Physiology, University of Oregon, Eugene, Oregon;* [2]*Department of Human Evolutionary Biology, Harvard University, Cambridge, Massachusetts;* [3]*Department of Human Physiology, Gonzaga University, Spokane, Washington; and* [4]*Department of Sport and Health Sciences, University of Exeter, St. Luke's Campus, Exeter, United Kingdom*

Abstract

Critical power (CP) delineates the heavy and severe exercise intensity domains, and sustained work rates above CP result in an inexorable progression of oxygen uptake to a maximal value and, subsequently, the limit of exercise tolerance. The finite work capacity above CP, W′, is defined by the curvature constant of the power-duration relationship. Heavy or severe exercise in a hot environment generates additional challenges related to the rise in body core temperature (T_c) that may impact CP and W′. The purpose of this study was to determine the effect of elevated T_c on CP and W′. CP and W′ were estimated by end-test power (EP; mean of final 30 s) and work above end-test power (WEP), respectively, from 3-min "all-out" tests performed on a cycle ergometer. Volunteers (n = 8, 4 female) performed the 3-min tests during a familiarization visit and two experimental visits (thermoneutral vs. hot, randomized crossover design). Before experimental 3-min tests, the subjects were immersed in water (thermoneutral: 36°C for 30 min; hot: 40.5°C until T_c was ≥38.5°C). Mean T_c was significantly greater in the hot condition than in the thermoneutral condition (38.5 ± 0.0°C vs. 37.4 ± 0.2°C; means ± SD, $P < 0.01$). All 3-min tests were performed in an environmental chamber [thermoneutral: 18°C, 45% relative humidity (RH); hot: 38 °C, 40% RH]. EP was similar between thermoneutral (239 ± 57 W) and hot (234 ± 66 W; P = 0.55) conditions. WEP was similar between thermoneutral (10.9 ± 3.0 kJ) and hot conditions (9.3 ± 3.6; P = 0.19). These results suggest that elevated T_c has no significant impact on EP or WEP.

NEW & NOTEWORTHY The parameters of the power-duration relationship (critical power and W′) estimated by a 3-min all-out test were not altered by elevated body core temperature as compared with a thermoneutral condition.

blood lactate; exercise physiology; oxygen consumption; performance; thermoregulation

INTRODUCTION

Exercise intensity domains are described by oxygen uptake and blood [lactate] kinetics (1, 2), as well as intramuscular metabolic responses (3). The moderate-intensity domain is characterized by rapid (within 2–3 min) attainment of steady-state oxygen uptake kinetics in healthy individuals with no appreciable increase in blood lactate concentration (1). The transition from moderate to heavy exercise is delineated by increased blood [lactate] and the gas exchange threshold (4). Work rates within the heavy domain elicit a substantial slow component in oxygen uptake kinetics before a steady-state oxygen consumption, or $\dot{V}O_2$, and blood [lactate] is attained (5). Critical power (CP) defines the boundary between heavy and severe exercise domains, theoretically representing the highest external work rate at which $\dot{V}O_2$ and blood [lactate] will stabilize (1). Exercising at work rates above CP results in a progressive increase in $\dot{V}O_2$ until a maximal value is attained, and an inexorable increase in blood [lactate] with time until volitional exhaustion (6).

The finite amount of work that can be accomplished above CP, or W′, is represented in large part by the capacity of immediate and nonoxidative energy pathways available to perform work (7, 8). Following the complete depletion of W′, work can only be performed below CP (i.e., exercise that can be sustained by the aerobic energy system) (9, 10). Traditionally, CP and W′ are determined through a series (3–5) of constant work-rate exercise bouts or time trials performed to the limit of tolerance. The mean power output for each trial can then be plotted against 1/time (where time represents time to exhaustion in seconds), such that the slope of this relationship represents W′ and the y-intercept provides an estimate of CP (6, 8, 11). Alternatively, a 3-min all-out test may be used (12, 13). This approach uses cadence-dependent resistance to estimate the hyperbolic relationship between power output and time. The all-out nature of the 3-min test is sufficient to exhaust W′ after ~2.5 min (9, 12), such that the mean power output in the final 30 s of the 3-min test [termed end-test power (EP)] provides an estimate of CP, whereas the area under the curve provides an estimate of W′

Correspondence: C. T. Minson (minson@uoregon.edu).
Submitted 13 April 2021 / Revised 20 September 2021 / Accepted 5 October 2021

8750-7587/21 Copyright © 2021 the American Physiological Society.

Downloaded from journals.physiology.org/journal/jappl (045.149.228.100) on December 6, 2022.

or work above end-test power (WEP) (6, 8, 11, 13). CP, as determined through the 3-min test, is reduced following 2 h of heavy-intensity exercise (14–16) and is increased by training (17–19). Furthermore, previous work has shown CP to be reduced with moderate (14) as well as more severe (20) hypoxia. W′, as determined through the 3-min test, is not significantly impacted by endurance training (17), yet it is significantly reduced following 2 h of heavy-intensity exercise (15, 16). Moreover, previous research has demonstrated no changes in W′ with moderate hypoxia (14), yet others have shown that W′ is reduced with more severe hypoxia [fraction of inspired oxygen ($F_{I_{O_2}}$) = 0.123, simulated altitude = ~4,250 m] (20).

The cardiovascular challenges associated with heat stress are driven in large part by a repartitioning of cardiac output to increase cutaneous blood flow (21). Subsequent to this, reductions in central blood volume preclude increases in cardiac output and proportionally decrease transit time (22). Furthermore, these thermoregulatory adjustments to hyperthermia potentiate a decline in cardiac output and mean arterial pressure and negatively impact skeletal muscle oxygen delivery, thereby impacting CP (23). Systemically, heat stress is known to have a detrimental effect on aerobic exercise performance (24–29). The performance decrements associated with heat stress vary depending on the length of the bout of exercise and may be impacted by self-selected pacing strategies (27, 30, 31). Indeed, Périard and Racinais (31) have demonstrated that % peak oxygen consumption ($\dot{V}O_{2peak}$), while maintained within a narrow range, decreases to a greater extent in hot conditions during the latter portion of a prolonged time trial effort in trained cyclists. Importantly, CP has a variety of sport-specific applications (i.e., time trial efforts) (32–35) that may be impacted if performed in hyperthermic conditions. Recent data from Kuo et al. (36) have demonstrated that critical velocity assessed using the 3-min running test in a hot environment is well correlated with VT_1 but not VT_2. Furthermore, previous research indicates that hyperthermia may be associated with reductions in central motor drive (37–39), as well as reductions in $\dot{V}O_{2peak}$ during severe-intensity exercise (23, 40). Despite these well-established and multifaceted cardiovascular and thermoregulatory challenges, the impact of heat stress on CP and W′ has not been assessed. Therefore, the present study aimed to explore the potential impact of elevated body core temperature on the parameters of the power-duration relationship. We hypothesized that an elevated body core temperature, while performing a 3-min all-out test in a hot environment, would reduce EP with no change in peak power output, leading to an increase in the finite work capacity above EP, or WEP.

METHODS

Subjects

Before participation, each volunteer gave written informed consent as set forth in the Declaration of Helsinki. All protocols were approved by the Institutional Review Board of the University of Oregon. Eight volunteers were recruited from local cycling and running communities. Subject characteristics obtained during the screening visit, including age, height, body mass, body mass index, and peak oxygen consumption, are shown in Table 1. All volunteers were actively training at least 4 days/wk and were familiar with high-intensity efforts and/or interval training. Data were collected between October 2019 and January 2020 such that none of the subjects was heat acclimated.

Study Design

The present study used a randomized crossover design. All bouts of exercise were separated by a minimum of 48 h and a maximum of 1 wk. Each subject completed an incremental exercise test to determine $\dot{V}O_{2peak}$, a familiarization 3-min all-out test, and two experimental 3-min all-out tests. Data from the familiarization 3-min all-out test were not included in the subsequent analysis, yet are reported in support of the ability of the subjects to adequately reproduce maximal efforts during the 3-min test. The order of the two experimental tests was randomized between two conditions —“thermoneutral” and “hot.”

Screening Visit

An initial screening visit was conducted to discuss testing procedures and equipment with the subjects and to obtain demographic and anthropometric information (age, height, and weight). All the subjects performed an incremental cycling $\dot{V}O_{2peak}$ test during the screening visit, as described below in *$\dot{V}O_{2peak}$ Test*.

Before the $\dot{V}O_{2peak}$ test, the subjects were asked to refrain from all alcohol, exercise, and over-the-counter medication for 24 h. Before each subsequent visit, the subjects reported to the laboratory euhydrated and having refrained from food for 3 h, caffeine for 6 h, alcohol for 12 h, and heavy exercise for 24 h.

Measurements

The incremental ramp test and all 3-min tests were performed on an electronically braked cycling ergometer (Excalibur Sport, Lode, Groningen, The Netherlands) for determination of $\dot{V}O_{2peak}$ and gas exchange threshold (GET). Seat height and handlebar position were noted and replicated for subsequent visits. Heart rate was continuously measured via telemetry (Model T31, Polar Electro, Lake Success, NY) throughout all exercise bouts. On both experimental days, body core temperature (T_c) was determined using either an ingestible temperature sensor (*n* = 4; HQ Inc., Palmetto, FL) or a rectal thermistor inserted 10 cm past the anal sphincter (*n* = 4; YSI Model 400, Yellow Springs

Table 1. *Summary of subject characteristics*

n	8, 4 female
Age, yr	32 ± 8
Height, cm	172 ± 14
Mass, kg	64 ± 11
BMI, kg·m^{-2}	21 ± 2
$\dot{V}O_{2peak}$, L·min^{-1}	3.55 ± 0.31
$\dot{V}O_{2peak}$, mL·kg^{-1}·min^{-1}	55 ± 2
Maximum heart rate, beats·min^{-1}	180 ± 7

Values are means ± SD. BMI, body mass index; $\dot{V}O_{2peak}$, peak oxygen consumption.

Downloaded from journals.physiology.org/journal/jappl (045.149.228.100) on December 6, 2022.

Instruments, Yellow Springs, OH). The subjects who were not comfortable with using a rectal thermistor were given the option of using an ingestible temperature sensor, and the same method was used between subjects for each experimental session.

$\dot{V}O_{2peak}$ Test

The subjects pedaled for 3 min during a warm-up period at a resistance of 60 W. The starting work rate was selected such that all subjects would reach the limit of tolerance within 8–12 min. Once the ramp test began, resistance increased by 0.5 $W \cdot s^{-1}$ and continued until volitional exhaustion. The test was terminated when the subjects were unable to maintain a cadence greater than 60 rpm despite strong verbal encouragement. Expired gases were analyzed for determination of $\dot{V}O_2$ and $\dot{V}CO_2$ (ParvoMedics, Salt Lake City, UT). GET was determined from *1*) the first disproportionate increase in $\dot{V}CO_2$ relative to $\dot{V}O_2$ and *2*) the first increase in $\dot{V}E/\dot{V}O_2$ without an increase in $\dot{V}E/\dot{V}CO_2$, as described previously (4). $\dot{V}O_{2peak}$ was determined as the highest 15-s average in the final 30 s of the ramp protocol. Additional criteria were as follows: RER $\geq$ 1.1, rating of perceived exertion $\geq$ 17 on the Borg scale, and a plateau in oxygen consumption with increasing work rate (41, 42).

3-Min Test

Vanhatalo et al. (13) demonstrated that the 3-min test can reliably estimate CP and W′ in a single bout of exercise. As such, *visits 2–4* each involved one 3-min all-out test. The first test was used for familiarization purposes, and the data generated were not used in subsequent analysis. The 3-min test involved a warm-up period of 3 min at 30 W. In the final 5 s before the start of the 3-min all-out test, resistance was lowered to 0 W, and the subjects were instructed to increase their cadence as high as possible. At exactly 3 min following the beginning of the warm-up, the Lode ergometer was changed to linear mode, creating cadence-dependent resistance proportional to a linear factor. The linear factor was determined for each subject based on their power midway between GET and $\dot{V}O_{2peak}$, divided by their preferred cadence squared, as derived from their $\dot{V}O_{2peak}$ test (13). Preferred cadence for each subject was calculated as the mean cadence during their incremental ramp $\dot{V}O_{2peak}$ test. During the 3-min test, the subjects were provided with no feedback other than current cadence in an effort to prevent pacing and ensure a maximal effort. Power profiles during the 3-min test were carefully scrutinized to ensure a smooth curvilinear decrease in power following early achievement of peak power output. $\dot{V}O_{2peak}$ during the 3-min test was calculated as the highest 15-s average $\dot{V}O_2$ value during the final 30 s of the test. Immediately following the conclusion of the 3-min test, resistance was lowered to 30 W, and the subjects were allowed to cool down at a self-selected cadence for 5 min. Blood [lactate] was determined 0, 3, and 5 min following the end of the 3-min test using a fingertip blood sample (Lactate Plus, Nova Biomedical, Waltham, MA).

Before all sessions, the subjects provided a urine sample to confirm euhydration (urine specific gravity < 1.02). If urine specific gravity was >1.02, the subjects drank 5 mL of water per kilogram of body mass before water immersion. The subjects were weighed nude before immersion. During both experimental sessions, the subjects were immersed in water to the level of the sternum, where they remained for the duration of water immersion leading up to the 3-min all-out test. For the thermoneutral condition, the subjects were immersed for 30 min in 36°C water. Previous research from our laboratory has indicated that this is an optimal temperature for minimizing core-to-skin temperature gradient and preventing changes in $T_c > 0.2°C$ for the duration of immersion (43). For the hot condition, the subjects were immersed in hot water (40.5°C) until $T_c \geq 38.5°C$. Previous research has demonstrated that aerobic exercise performance is reduced with modest ($T_c < 38.5°C$) hyperthermia (24). Water was provided ad libitum in both conditions.

Following immersion, the subjects toweled dry and entered the environmental chamber. To minimize the duration between exiting the hot tub and entering the chamber, most (7/8) subjects were immersed while wearing cycling clothing. This was done in an effort to attenuate reductions in T_c during this transition period, which lasted ~1 min. The 3-min all-out test was performed in an environmental chamber set to 18°C and 45% relative humidity for the thermoneutral condition and 38°C and 40% relative humidity for the hot condition. Immediately following the cool down from the 3-min test, the subjects toweled dry and provided a second nude body weight.

Data and Statistical Analysis

CP was estimated by EP, calculated from the mean power sustained over the final 30 s during the 3-min test. W′ was estimated as WEP, calculated from the area under the power curve above EP, as described previously (13). Statistical comparison of all variables between thermoneutral and hot conditions (EP, WEP, total work, peak power, $\dot{V}O_{2peak}$ achieved during the 3-min test, max heart rate achieved during the 3-min test, and mean core temperature during the warm-up and 3-min test) was performed using paired-samples *t* tests. Using the performance decrement in total work from previous research (24) examining time trial performance at similar core temperatures and environmental conditions as the present study, as well as a conventional α (0.05) and β (0.80), we determined that eight subjects would provide sufficient power to determine the impact of elevated core temperature on EP and WEP. Subject characteristics are presented as means ± SD, group means for each condition are presented as means ± SD, and differences between conditions are presented as %Δ ± 95% confidence interval of the difference. Effect size is reported where appropriate. Statistical analyses were performed using SPSS Statistics (version 27, Chicago, IL).

RESULTS

Subject characteristics, including anthropometric data as well as $\dot{V}O_{2peak}$ and heart rate$_{max}$ as determined during the ramp $\dot{V}O_{2peak}$ test, are provided in Table 1.

Figure 1 demonstrates the effectiveness of hot water immersion for elevating body core temperature to 38.5 ± 0.1°C before the 3-min test in the hot condition. Mean core

Downloaded from journals.physiology.org/journal/jappl (045.149.228.100) on December 6, 2022.

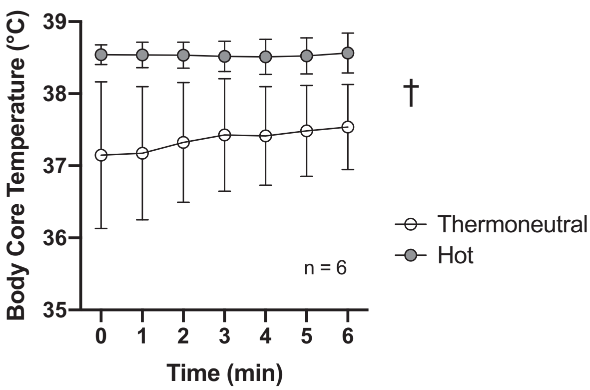

Figure 1. Body core temperature for both experimental conditions during the 3-min warm-up and the 3-min test. Time = 0 min at the beginning of 3-min test warm-up; time = 6 min at the conclusion of the 3-min test. Subjects were removed from water immersion when T_c was ≥38.5°C. Data were analyzed using a paired-samples *t* test. Mean core temperature was significantly greater in the hot condition. †$P < 0.01$ vs. the thermoneutral condition (n = 6 subjects).

temperature during the warm-up and 3-min test was significantly higher in the hot condition compared with the thermoneutral condition (38.5°C vs. 37.4 ± 0.2°C; $P < 0.01$; Fig. 1).

Figure 2 displays EP (Fig. 2*A*), WEP (Fig. 2*B*), total work done (Fig. 2*C*), and peak power (Fig. 2*D*) as derived from the 3-min all-out test under thermoneutral and hot conditions. Although the subjects had variable responses, in general, EP was similar between thermoneutral and hot conditions (−2.5 ± 7%; Cohen's d = 0.219). The coefficient of variation for EP in thermoneutral and hot conditions was 24% and 28%, respectively. Similarly, WEP (−12 ± 27%; d = 0.514), total work performed (−5 ± 6.5%; d = 0.543), and peak power (0.8 ± 8.2%; d = 0.022) were not statistically different between thermoneutral and hot conditions. The coefficient of variation for WEP in thermoneutral and hot conditions was 27% and 39%, respectively.

Data from the familiarization 3-min test are reported here in support of the reproducibility of a maximal effort during the 3-min test. EP during the familiarization 3-min test was 239 ± 56 W, compared with a thermoneutral EP of 239 ± 57 W. Furthermore, the mean slope of the final 30 s of the familiarization, thermoneutral, and hot 3-min tests was −0.432 ± 0.68, −0.15 + 0.3, and −0.0099 ± 0.42 $W{\cdot}s^{-1}$, respectively.

Figure 3 displays the metabolic and cardiovascular responses to the 3-min all-out test under thermoneutral and hot conditions. $\dot{V}O_{2peak}$ measured as the highest 15-s mean value during the final 30 s of the 3-min test was not significantly different between thermoneutral and hot conditions (6.6 ± 5.5%; P = 0.34, d = 0.257, Fig. 3*A*). $\dot{V}O_{2peak}$ values measured during the thermoneutral condition were 95 ± 5% of that achieved during the incremental ramp test, which represented a significantly lower value than the incremental ramp test ($P < 0.05$), whereas values measured during the hot condition were 98 ± 4% of those achieved during the incremental ramp test (P = 0.21). Peak heart rate during the 3-min test (n = 7) was increased in the hot compared with the thermoneutral condition (3.6 ± 3.5%; P = 0.041, d = 0.982, Fig. 3*B*). Blood [lactate] was similar at all time points in both conditions (Table 2).

DISCUSSION

To the best of our knowledge, this study is the first to examine the effects of hyperthermia on the parameters of the power-duration relationship (CP and W′) as estimated with the 3-min all-out test. Our findings demonstrate that hyperthermia with concurrent high environmental temperature does not affect peak power, total work performed, end-test power, or work performed above end-test power during a 3-min all-out test.

Implications of Hyperthermia and Environmental Heat Stress on Endurance Performance

Rowell et al. (22) demonstrated that reductions in cardiac output mediated by significant reductions in stroke volume

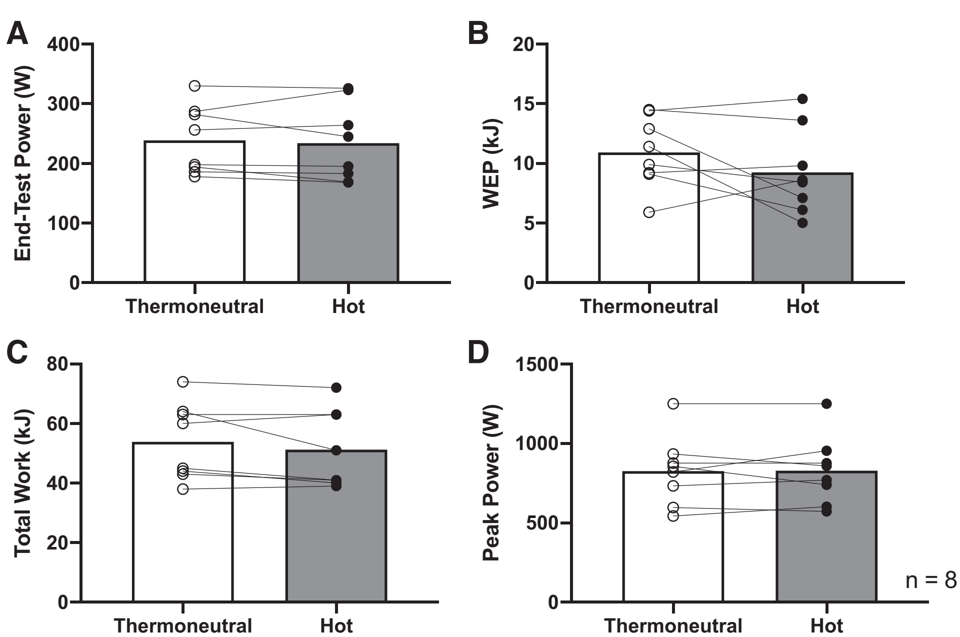

Figure 2. Estimated parameters of the power-duration relationship and total work in both experimental conditions. *A*: end-test power. *B*: work above end-test power (WEP). *C*: total work. *D*: peak power. Data are presented as mean as well as individual values (n = 8 subjects). Data were analyzed using a paired-samples *t* test.

Downloaded from journals.physiology.org/journal/jappl (045.149.228.100) on December 6, 2022.

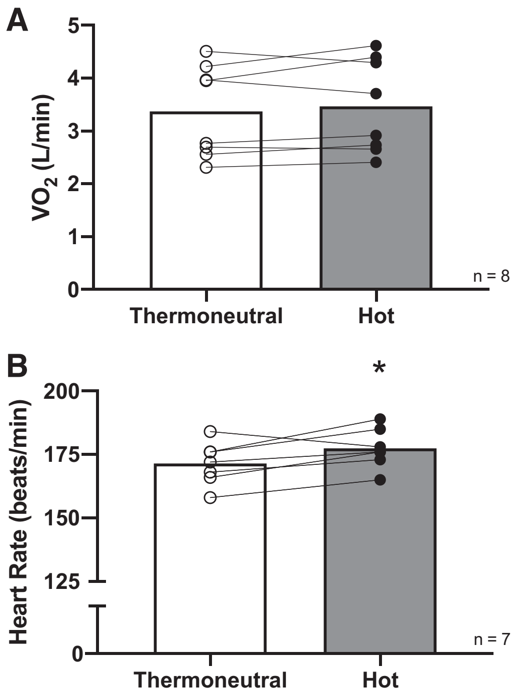

Figure 3. Absolute oxygen uptake and heart rate during final 30 s of the 3-min test in both experimental conditions. Data are presented as mean as well as individual values. Data were analyzed using a paired-samples *t* test. *A*: group mean data for highest 15-s mean oxygen uptake during the final 30 s of the 3-min test for both thermoneutral and hot conditions. Data represent ∼95% and ∼98%, respectively, of peak oxygen uptake achieved during the incremental ramp test. *B*: mean heart rate during final 30 s of the 3-min test in thermoneutral and hot conditions. Heart rate in the hot condition greater than in the thermoneutral condition (n = 7 subjects, $*P < 0.05$). $\dot{V}O_2$, oxygen consumption.

underpin the cardiovascular limitations to exercise in hyperthermic conditions. More recent studies support these findings, demonstrating that $\dot{V}O_{2peak}$ is reduced during exhaustive exercise with hyperthermia, consequent to an inability to meet skeletal muscle oxygen delivery requirements (23, 40). As CP represents the maximal steady-state oxidative metabolic rate (44), it would be expected that CP would be reduced in the face of combined hyperthermia and high environmental temperatures. However, the results of the present study did not demonstrate a reduction in $\dot{V}O_{2peak}$, nor an altered power-duration relationship, in the hot condition compared with the thermoneutral condition. In agreement with Nybo et al. (40), we found that heart rate was higher in the hot condition compared with the thermoneutral condition, yet we found no significant difference in whole body $\dot{V}O_{2peak}$ between conditions. However, Nybo et al. (40) had subjects perform 2 h of submaximal cycling (∼50% $\dot{V}O_{2peak}$) at 37°C before their hyperthermic maximal test, whereas the present study used hot water immersion. Accordingly, the present study aimed to induce hyperthermia in the absence of an exercise stimulus to explore the effect of high body temperature per se on CP and W′ as estimated by a 3-min all-out test.

Recently, Chou et al. (45) demonstrated that elevating skin temperature and narrowing the core-to-skin temperature gradient resulted in an increase in skin blood flow in the initial minutes of exercise. This increase in cutaneous blood flow and cutaneous venous volume plateaued at a core temperature of ∼38°C, whereafter increases in heart rate were due to increases in skin and esophageal temperature, rather than increases in peripheral vascular volume and a decrease in ventricular filling pressure (45). This may partially explain our finding that heart rate was significantly higher in the hot condition (Table 2), such that an increase in heart rate offsets a decrease in stroke volume to maintain cardiac output. Specifically, Chou et al. (45) suggested that the increases in heart rate (and subsequent reductions in stroke volume) are due to concurrent increases in core and skin temperature. In the present study, passive increases in core temperature were mediated through hot water immersion, undoubtedly increasing skin temperature. It is possible that increases in heart rate in the hot condition occur through the same mechanisms as those described by Chou et al. (45). Furthermore, Fritzsche et al. demonstrated that the decline in stroke volume during exercise is mediated by an increase in heart rate, rather than an increase in cutaneous blood flow (46). Indeed, previous research indicates that increases in body core temperature may independently increase heart rate via increases in sympathetic nervous system activity (47–49). It is possible that these mechanisms, in concert with increases in cutaneous blood flow, may explain the increased heart rate seen in the hot condition.

The nature of the 3-min test (severe domain exercise of short duration) may have minimized the performance disadvantages of hyperthermia reported by others (27, 30, 39). That is, since the subjects started the trial euhydrated, the skin blood flow and sweat rate responses may not be sufficient or of long enough duration to elicit a significant cardiovascular challenge. In addition, the onset of exercise is met with cutaneous vasoconstriction, as demonstrated by Johnson and Park (50). Given the maximal nature of the 3-min test and subsequent cutaneous vasoconstriction, it is unlikely that blood flow to the skeletal muscle was sacrificed in favor of cutaneous blood flow to aid in heat loss. Rather, our findings are in line with those of Rowell et al. (51), who reported that maximal oxygen consumption ($\dot{V}O_{2max}$) may be preserved despite preheating and high environmental temperature, in sufficiently short (3–5min) bouts of exercise. It is, therefore, difficult to directly compare our results with those from studies where the cardiovascular system may

Table 2. *Results from experimental 3-min tests*

	Thermoneutral	Hot
Critical power, W	239 ± 57	234 ± 66
W′, kJ	10.9 ± 3	9.3 ± 3.6
Peak power, W	826 ± 219	828 ± 215
Total work, kJ	54 ± 13	51 ± 13
$\dot{V}O_{2peak}$ during 3-min test, L·min^{-1}	3.37 ± 0.87	3.46 ± 0.89
Heart rate peak during 3-min test, beats·min^{-1}, n = 7	171 ± 11	179 ± 8*
Blood [lactate], mmol·L^{-1}		
0 min	13.6 ± 2.4	12.9 ± 3.8
3 min	11.5 ± 2.7	11.8 ± 3.3
5 min	10.9 ± 2.4	10.6 ± 3.6
Mean core temperature during warm-up and 3-min test, °C	37.4 ± 0.2	38.5†

Values are means ± SD. Blood [lactate] data were collected following the 3-min test at the time points indicated. $\dot{V}O_{2peak}$, peak oxygen consumption. $*P < 0.05$ compared with the thermoneutral condition. $†P < 0.01$ compared with the thermoneutral condition.

Downloaded from journals.physiology.org/journal/jappl (045.149.228.100) on December 6, 2022.

reach its regulatory limit and curtail exercise. Furthermore, although increases in core temperature of ~1.5°C represent a substantial increase from resting values, it is possible that greater increases, similar to those reported during competition (52), would accentuate the cardiovascular and thermoregulatory challenges of exercise in a hot environment. Future research should explore this potential dose-response relationship between increases in body core temperature and CP. The major finding of the present study is that hyperthermia per se during exercise in a hot environment does not alter the parameters of the power-duration relationship as estimated by the 3-min all-out test. More prolonged constant work-rate (or time trial) exercise in the heat may evince cardiovascular and thermoregulatory limitations, due to elevated skin blood flow and sweating responses, sufficient to impact the parameters of the power-duration relationship. It is possible that traditional determinations of CP, involving three to five bouts of constant work-rate exercise lasting between 2 and 15 min, may more robustly challenge the cardiovascular system and negatively impact the power-duration relationship and exercise performance.

The Power-Duration Relationship under Physiological Stress

The 3-min all-out test relies upon the hyperbolic nature of the power-duration relationship to estimate both CP and W′ (6, 11). CP describes the maximal metabolic intensity below which $\dot{V}O_2$, [blood lactate] (1, 2), and intramuscular phosphocreatine [PCr] and pH remain in a steady state over time (3, 53). Exercise performed above CP depletes W′ and elicits a substantial $\dot{V}O_2$ slow component (1, 2), a continuous rise in [blood lactate] (6), a precipitous decrease in intramuscular [PCr] and pH, and a continuous rise in intramuscular [Pi] until exhaustion (3, 53). Exercise under the stress of hypoxia has been reported to reduce CP due to a reduction in the contribution of oxidative metabolism (14, 20, 54). Moderate hypoxia has been shown to have no impact on W′ (14), yet W′ is shown to be decreased at higher (4,250 m) simulated altitudes (20). Furthermore, blood flow occlusion during forearm exercise abolished CP (55) and factors related to oxygen delivery may mediate interindividual differences in CP (56). Combined, these reports demonstrate the dependence of the power-duration relationship parameters on adequate oxygen supply to match demand through oxidative metabolic pathways. A significant cardiovascular challenge during exercise under hyperthermic conditions (23, 40, 47) may begin to limit oxygen delivery to exercising muscle. To that end, traditional determinations of critical power (3–5 bouts of constant work-rate exercise) in the presence of hyperthermia would likely present a combined cardiovascular and thermoregulatory challenge sufficient to limit exercise performance. However, the results from the present study suggest that a rise in core body temperature of ~1.5°C per se was not sufficient to alter CP or W′ estimated from the 3-min all-out test. Although the cardiovascular challenges of prolonged exercise in the heat have been explored, their impact on CP and W′ has yet to be fully characterized.

Along these lines, Clark et al. (15) reported a substantial reduction in both EP and WEP following 2 h of heavy-intensity exercise. The experiments were performed under thermoneutral environmental conditions; however, core body temperature changes and other thermoregulatory responses (e.g., increased skin blood flow) may have presented a significant cardiovascular challenge and could potentially explain part of the observed reduction in CP. Based on the results of the present study, hyperthermia per se cannot explain the reduction in CP reported by Clark et al. (15); however, it cannot be excluded that greater cardiovascular strain arising from alterations in thermoregulation contributed to the lowering of CP following the 2-h exercise bout. The need exists to explore the impact of hyperthermia and high environmental temperature on CP and W′ as determined through separate, continuous bouts of constant work-rate exercise.

Recent research examined the validity and reliability of the 3-min running test for estimating critical velocity in a hot environment (36). Kuo et al. (36) demonstrated moderate-to-high test-retest reliability with the 3-min running test and a correlation between critical velocity and VT_1, yet they also found that the 3-min running test underestimated critical velocity at high temperatures. Of note, Kuo et al. (36) did not directly compare performance between thermoneutral and hyperthermic conditions, yet they established the influence that heat stress might have on the power-duration relationship during the 3-min running test.

An important consideration is that increases in muscle temperature are associated with improvements in muscle force production and power output during short-duration exercise (57, 58). Although we may expect a reduction in oxygen delivery and exercise performance due to the increased thermoregulatory and cardiovascular strain, especially during longer endurance activities (23, 26, 40, 47), high body temperatures may have positively influenced power output during the 3-min test. That is, due to the cadence-dependent nature of ergometer resistance in the 3-min test, it is possible that prior heating confers performance benefit for this relatively short-duration, severe-intensity exercise task. A benefit of hyperthermia on peak power would counteract any potential performance decrement from a reduced CP.

Experimental Considerations and Limitations

The present study did not validate estimates of CP from the 3-min test against constant work-rate trials above and below the estimated CP values. Vanhatalo et al. (13) reported that the 3-min test was capable of determining CP and W′ in a single bout of exercise, which was subsequently supported in hypoxia by Parker-Simpson et al. (14). Conversely, some reports suggest that the 3-min test overestimates CP (59–62) and underestimates W′ (59), possibly due to subject pacing. In the present study, there was no evidence to suggest that pacing occurred during the 3-min tests in either experimental condition. Specifically, EP represents a stable power output during the final 30 s of the 3-min test. The slope of the power curve during the 3-min test in familiarization, thermoneutral, and hot conditions was -0.432 ± 0.68, -0.15 ± 0.3, and -0.0099 ± 0.42 W·s^{-1}, respectively. Taken together with the identical EP between familiarization and thermoneutral conditions, as well as the similar EP between thermoneutral and hot conditions, this

Downloaded from journals.physiology.org/journal/jappl (045.149.228.100) on December 6, 2022.

finding suggests that the subjects were able to adequately reproduce a maximal effort without pacing during the 3-min tests in the present study.

Body core temperature was assessed through two different means in the present study. In four subjects, body core temperature was assessed using an ingestible temperature-sensing pill, whereas in the other four subjects, core temperature was assessed using a rectal thermistor. The same method was used between subjects during each experimental visit. Previous literature has reported acceptable agreement between rectal thermistors and ingestible core temperature pills (63–65). However, others have indicated systemic bias of $>0.1°C$ when comparing between these methods (66). To maximize the accuracy of the telemetric temperature pill system, the subjects were instructed to ingest the pill ∼6 h before arriving at the laboratory. Previous research has found that this is sufficient time for the pill to exit the stomach, after which ingestible pills are within the limits of accuracy when comparing with rectal temperature (64).

Finally, this study used hot and thermoneutral water immersion to either increase or maintain core temperature, respectively. The aim of thermoneutral water immersion was not to elicit a specific core temperature but rather to prevent changes in core temperature. Thermoneutral water immersion was standardized at 30 min, whereas hot water immersion lasted until core temperature was $\geq 38.5°C$. As such, the duration of hot water immersion required to elicit a core temperature of 38.5°C varied between the subjects. Data presented in Fig. 1 begin at the onset of the 3-min warm-up before the 3-min test (time = 0 min) and conclude at the end of the 3-min test (time = 6 min). During this period, mean core temperature was greater in the hot condition as compared with the thermoneutral condition ($P < 0.01$). Despite this, it is possible that a greater increase in core temperature would elicit a reduction in CP. Future studies should address this potential dose-response relationship between increases in body core temperature and reductions in CP.

Conclusions

The results presented here have implications for sports performance in a range of disciplines (32–34, 67). Prolonged submaximal efforts in the heat notwithstanding, the data reported here indicate a negligible impact of elevated body core temperature on the parameters of the power-duration relationship as estimated from a short, high-intensity exercise bout. The impact of prolonged exercise in heat on the parameters of the power-duration relationship remains to be explored.

ACKNOWLEDGMENTS

We thank all volunteers for participation in the study and also thank undergraduate research assistants Rima Pandit, Emma Whittman, and Angela Tan for assistance in data collection.

GRANTS

The study was funded through the Kenneth and Kenda Singer Endowed Professorship (C.T.M.). K.K.K. was supported by the Summer Program for Undergraduate Research at the University of Oregon.

DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

B.W.K., K.K.K., B.W.W., J.R.H., and C.T.M. conceived and designed research; B.W.K., K.K.K., B.M.G., K.J.S., and E.A.L. performed experiments; B.W.K. analyzed data; B.W.K., K.K.K., B.W.W., A.M.J., J.R.H., and C.T.M. interpreted results of experiments; B.W.K., J.R.H., and C.T.M. prepared figures; B.W.K., J.R.H., and C.T.M. drafted manuscript; B.W.K., K.K.K., B.M.G., K.J.S., E.A.L., B.W.W., A.M.J., J.R.H., and C.T.M. edited and revised manuscript; B.W.K., K.K.K., B.M.G., K.J.S., E.A.L., B.W.W., A.M.J., J.R.H., and C.T.M. approved final version of manuscript.

REFERENCES

1. **Gaesser GA**, **Poole DC.** The slow component of oxygen uptake kinetics in humans. *Exerc Sport Sci Rev* 24: 35–71, 1996.
2. **Whipp BJ.** The slow component of O_2 uptake kinetics during heavy exercise. *Med Sci Sports Exerc* 26: 1319–1326, 1994 [Erratum in *Med Sci Sports Exerc* 27: 298, 1995].
3. **Jones AM**, **Wilkerson DP**, **DiMenna F**, **Fulford J**, **Poole DC.** Muscle metabolic responses to exercise above and below the "critical power" assessed using ^{31}P-MRS. *Am J Physiol Regul Integr Comp Physiol* 294: R585–R593, 2008. doi:10.1152/ajpregu.00731.2007.
4. **Beaver WL**, **Wasserman K**, **Whipp BJ.** A new method for detecting anaerobic threshold by gas exchange. *J Appl Physiol (1985)* 60: 2020–2027, 1986. doi:10.1152/jappl.1986.60.6.2020.
5. **Whipp BJ**, **Wasserman K.** Oxygen uptake kinetics for various intensities of constant-load work. *J Appl Physiol* 33: 351–356, 1972. doi:10.1152/jappl.1972.33.3.351.
6. **Poole DC**, **Ward SA**, **Gardner GW**, **Whipp BJ.** Metabolic and respiratory profile of the upper limit for prolonged exercise in man. *Ergonomics* 31: 1265–1279, 1988. doi:10.1080/00140138808966766.
7. **Miura A**, **Sato H**, **Sato H**, **Whipp BJW**, **Fukuba Y.** The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle ergometry. *Ergonomics* 43: 133–141, 2000. doi:10.1080/001401300184693.
8. **Moritani T**, **Ata AN**, **Devries HA**, **Muro M.** Critical power as a measure of physical work capacity and anaerobic threshold. *Ergonomics* 24: 339–350, 1981. doi:10.1080/00140138108924856.
9. **Coats EM**, **Rossiter HB**, **Day JR**, **Miura A**, **Fukuba Y**, **Whipp BJ.** Intensity-dependent tolerance to exercise after attaining $\dot{V}o_{2max}$ in humans. *J Appl Physiol (1985)* 95: 483–490, 2003. doi:10.1152/japplphysiol.01142.2002.
10. **Chidnok W**, **Fulford J**, **Bailey SJ**, **Dimenna FJ**, **Skiba PF**, **Vanhatalo A**, **Jones AM.** Muscle metabolic determinants of exercise tolerance following exhaustion: relationship to the "critical power." *J Appl Physiol* 115: 243–250, 2013. doi:10.1152/japplphysiol.00334.2013.
11. **Monod H**, **Scherrer J.** The work capacity of a synergic muscular group. *Ergonomics* 8: 329–338, 1965. doi:10.1080/00140136508930810.
12. **Burnley M**, **Doust JH**, **Vanhatalo A.** A 3-min all-out test to determine peak oxygen uptake and the maximal steady state. *Med Sci Sports Exerc* 38: 1995–2003, 2006. doi:10.1249/01.mss.0000232024.06114.a6.
13. **Vanhatalo A**, **Doust JH**, **Burnley M.** Determination of critical power using a 3-min all-out cycling test. *Med Sci Sports Exerc* 39: 548–555, 2007. doi:10.1249/mss.0b013e31802dd3e6.
14. **Parker Simpson L**, **Jones AM**, **Skiba PF**, **Vanhatalo A**, **Wilkerson D.** Influence of hypoxia on the power-duration relationship during high-intensity exercise. *Int J Sports Med* 36: 113–119, 2015. doi:10.1055/s-0034-1389943.
15. **Clark IE**, **Vanhatalo A**, **Bailey SJ**, **Wylie LJ**, **Kirby BS**, **Wilkins BW**, **Jones AM.** Effects of two hours of heavy-intensity exercise on the power-duration relationship. *Med Sci Sports Exerc* 50: 1658–1668, 2018. doi:10.1249/MSS.0000000000001601.
16. **Clark IE**, **Vanhatalo A**, **Thompson C**, **Joseph C**, **Black MI**, **Blackwell JR**, **Wylie LJ**, **Tan R**, **Bailey SJ**, **Wilkins BW**, **Kirby BS**, **Jones AM.** Dynamics of the power-duration relationship during prolonged

Downloaded from journals.physiology.org/journal/jappl (045.149.228.100) on December 6, 2022.

endurance exercise and influence of carbohydrate ingestion. *J Appl Physiol* 127: 726–736, 2019. doi:10.1152/japplphysiol.00207.2019.

17. **Vanhatalo A**, **Doust JH**, **Burnley M.** A 3-min all-out cycling test is sensitive to a change in critical power. *Med Sci Sports Exerc* 40: 1693–1699, 2008. doi:10.1249/MSS.0b013e318177871a.
18. **Gaesser GA**, **Wilson LA.** Effects of continuous and interval training on the parameters of the power-endurance time relationship for high-intensity exercise. *Int J Sports Med* 9: 417–421, 1988. doi:10.1055/s-2007-1025043.
19. **Jenkins DG**, **Quigley BM.** Endurance training enhances critical power. *Med Sci Sports Exerc* 24: 1283–1289, 1992. doi:10.1249/00005768-199211000-00014.
20. **Townsend NE**, **Nichols DS**, **Skiba PF**, **Racinais S**, **Périard JD.** Prediction of critical power and W' in hypoxia: application to work-balance modelling. *Front Physiol* 8, 2017. doi:10.3389/fphys.2017.00180.
21. **Rowell LB.** Human cardiovascular adjustments to exercise and thermal stress. *Physiol Rev* 54: 75–159, 1974. doi:10.1152/physrev.1974.54.1.75.
22. **Rowell LB**, **Marx HJ**, **Bruce RA**, **Conn RD**, **Kusumi F.** Reductions in cardiac output, central blood volume, and stroke volume with thermal stress in normal men during exercise. *J Clin Invest* 45: 1801–1816, 1966. doi:10.1172/JCI105484.
23. **González-Alonso J**, **Calbet JAL.** Reductions in systemic and skeletal muscle blood flow and oxygen delivery limit maximal aerobic capacity in humans. *Circulation* 107: 824–830, 2003. doi:10.1161/01.CIR.0000049746.29175.3F.
24. **Ely BR**, **Cheuvront SN**, **Kenefick RW**, **Sawka MN.** Aerobic performance is degraded, despite modest hyperthermia, in hot environments. *Med Sci Sports Exerc* 42: 135–141, 2010. doi:10.1249/MSS.0b013e3181adb9fb.
25. **Altareki N**, **Drust B**, **Atkinson G**, **Cable T**, **Gregson W.** Effects of environmental heat stress (35°C) with simulated air movement on the thermoregulatory responses during a 4-km cycling time trial. *Int J Sports Med* 30: 9–15, 2009. doi:10.1055/s-2008-1038768.
26. **Tatterson AJ**, **Hahn AG**, **Martini DT**, **Febbraio MA.** Effects of heat stress on physiological responses and exercise performance in elite cyclists. *J Sci Med Sport* 3: 186–193, 2000. doi:10.1016/S1440-2440(00)80080-8.
27. **Peiffer JJ**, **Abbiss CR.** Influence of environmental temperature on 40 km cycling time-trial performance. *Int J Sports Physiol Perform* 6: 208–220, 2011. doi:10.1123/ijspp.6.2.208.
28. **Racinais S**, **Périard JD**, **Karlsen A**, **Nybo L.** Effect of heat and heat acclimatization on cycling time trial performance and pacing. *Med Sci Sports Exerc* 47: 601–606, 2015. doi:10.1249/MSS.0000000000000428.
29. **González-Alonso J**, **Teller C**, **Andersen SL**, **Jensen FB**, **Hyldig T**, **Nielsen B.** Influence of body temperature on the development of fatigue during prolonged exercise in the heat. *J Appl Physiol (1985)* 86: 1032–1039, 1999. doi:10.1152/jappl.1999.86.3.1032.
30. **Guy JH**, **Deakin GB**, **Edwards AM**, **Miller CM**, **Pyne DB.** Adaptation to hot environmental conditions: an exploration of the performance basis, procedures and future directions to optimise opportunities for elite athletes. *Sports Med* 45: 303–311, 2015. doi:10.1007/s40279-014-0277-4.
31. **Périard JD**, **Racinais S.** Self-paced exercise in hot and cool conditions is associated with the maintenance of $\%\dot{V}O_{2peak}$ within a narrow range. *J Appl Physiol (1985)* 118: 1258–1265, 2015. doi:10.1152/japplphysiol.00084.2015.
32. **Kolbe T**, **Dennis SC**, **Selley E**, **Noakes TD**, **Lambert MI.** The relationship between critical power and running performance. *J Sports Sci* 13: 265–269, 1995. doi:10.1080/02640419508732236.
33. **Kennedy MDJ**, **Bell GJ.** A comparison of critical velocity estimates to actual velocities in predicting simulated rowing performance. *Can J Appl Physiol* 25: 223–235, 2000. doi:10.1139/h00-017.
34. **Smith JC**, **Dangelmaier BS**, **Hill DW.** Critical power is related to cycling time trial performance. *Int J Sports Med* 20: 374–378, 1999. doi:10.1055/s-2007-971147.
35. **Vanhatalo A**, **Jones AM**, **Burnley M.** Application of critical power in sport. *Int J Sports Physiol Perform* 6: 128–136, 2011. doi:10.1123/ijspp.6.1.128.
36. **Kuo YH**, **Cheng CF**, **Hsu WC**, **Wong DP.** Validity and reliability of the 3-min all-out running test to measure critical velocity in hot environments. *Res Sport Med* 25: 470–479, 2017. doi:10.1080/15438627.2017.1365293.
37. **Tucker R**, **Rauch L**, **Harley YXR**, **Noakes TD.** Impaired exercise performance in the heat is associated with an anticipatoiy reduction in skeletal muscle recruitment. *Pflugers Arch Eur J Physiol* 448: 422–430, 2004. doi:10.1007/s00424-004-1267-4.
38. **Nybo L**, **Nielsen B.** Hyperthermia and central fatigue during prolonged exercise in humans. *J Appl Physiol (1985)* 91: 1055–1060, 2001. doi:10.1152/jappl.2001.91.3.1055.
39. **Tucker R**, **Marle T**, **Lambert EV** , **Noakes TD.** The rate of heat storage mediates an anticipatory reduction in exercise intensity during cycling at a fixed rating of perceived exertion. *J Physiol* 574: 905–915, 2006. doi:10.1113/jphysiol.2005.101733.
40. **Nybo L**, **Jensen T**, **Nielsen B**, **González-Alonso J.** Effects of marked hyperthermia with and without dehydration on $\dot{V}O_2$ kinetics during intense exercise. *J Appl Physiol (1985)* 90: 1057–1064, 2001. doi:10.1152/jappl.2001.90.3.1057.
41. **Taylor HL**, **Buskirk E**, **Henschel A.** Maximal oxygen intake as an objective measure of cardio-respiratory performance. *J Appl Physiol* 8: 73–80, 1955. doi:10.1152/jappl.1955.8.1.73.
42. **Howley ET**, **Bassett DR**, **Welch HG.** Criteria for maximal oxygen uptake: review and commentary. *Med Sci Sports Exerc* 27: 1292–1301, 1995. doi:10.1249/00005768-199509000-00009.
43. **Brunt VE**, **Howard MJ**, **Francisco MA**, **Ely BR**, **Minson CT.** Passive heat therapy improves endothelial function, arterial stiffness and blood pressure in sedentary humans. *J Physiol* 594: 5329–5342, 2016. doi:10.1113/JP272453.
44. **Jones AM**, **Burnley M**, **Black MI**, **Poole DC**, **Vanhatalo A.** The maximal metabolic steady state: redefining the 'gold standard'. *Physiol Rep* 7: e14098, 2019. doi:10.14814/phy2.14098.
45. **Chou TH**, **Allen JR**, **Hahn D**, **Leary BK**, **Coyle EF.** Cardiovascular responses to exercise when increasing skin temperature with narrowing of the core-to-skin temperature gradient. *J Appl Physiol (1985)* 125: 697–705, 2018. doi:10.1152/japplphysiol.00965.2017.
46. **Fritzsche RG**, **Switzer TW**, **Hodgkinson BJ**, **Coyle EF.** Stroke volume decline during prolonged exercise is influenced by the increase in heart rate. *J Appl Physiol (1985)* 86: 799–805, 1999. doi:10.1152/jappl.1999.86.3.799.
47. **González-Alonso J**, **Mora-Rodríguez R**, **Below PR**, **Coyle EF.** Dehydration markedly impairs cardiovascular function in hyperthermic endurance athletes during exercise. *J Appl Physiol (1985)* 82: 1229–1236, 1997. doi:10.1152/jappl.1997.82.4.1229.
48. **Jose AD**, **Stitt F**, **Collison D.** The effects of exercise and changes in body temperature on the intrinsic heart rate in man. *Am Heart J* 79: 488–498, 1970. doi:10.1016/0002-8703(70)90254-1.
49. **Coyle EF**, **González-Alonso J.** Cardiovascular drift during prolonged exercise: new perspectives. *Exerc Sport Sci Rev* 29: 88–92, 2001. doi:10.1097/00003677-200104000-00009.
50. **Johnson JM**, **Park MK.** Effect of heat stress on cutaneous vascular responses to the initiation of exercise. *J Appl Physiol Respir Environ Exerc Physiol* 53: 744–749, 1982. doi:10.1152/jappl.1982.53.3.744.
51. **Rowell LB**, **Brengelmann GL**, **Murray JA**, **Kraning KK**, **Kusumi F.** Human metabolic responses to hyperthermia during mild to maximal exercise. *J Appl Physiol* 26: 395–402, 1969. doi:10.1152/jappl.1969.26.4.395.
52. **Racinais S**, **Moussay S**, **Nichols D**, **Travers G**, **Belfekih T**, **Schumacher YO**, **Periard JD.** Core temperature up to 41.5°C during the UCI Road Cycling World Championships in the heat. *Br J Sports Med* 53: 426–429, 2019. doi:10.1136/bjsports-2018-099881.
53. **Vanhatalo A**, **Fulford J**, **Dimenna FJ**, **Jones AM.** Influence of hyperoxia on muscle metabolic responses and the power-duration relationship during severe-intensity exercise in humans: a 31P magnetic resonance spectroscopy study. *Exp Physiol* 95: 528–540, 2010. doi:10.1113/expphysiol.2009.050500.
54. **Dekerle J**, **Mucci P**, **Carter H.** Influence of moderate hypoxia on tolerance to high-intensity exercise. *Eur J Appl Physiol* 112: 327–335, 2012. doi:10.1007/s00421-011-1979-z.
55. **Broxterman RM**, **Ade CJ**, **Craig JC**, **Wilcox SL**, **Schlup SJ**, **Barstow TJ.** Influence of blood flow occlusion on muscle oxygenation characteristics and the parameters of the power-duration relationship. *J Appl Physiol (1985)* 118: 880–889, 2015. doi:10.1152/japplphysiol.00875.2014.

Downloaded from journals.physiology.org/journal/jappl (045.149.228.100) on December 6, 2022.

56. **Kellawan JM**, **Bentley RF**, **Bravo MF**, **Moynes JS**, **Tschakovsky ME.** Does oxygen delivery explain interindividual variation in forearm critical impulse? *Physiol Rep* 2: e12203, 2014. doi:10.14814/phy2.12203.
57. **Sargeant AJ.** Effect of muscle temperature on leg extension force and short-term power output in humans. *Eur J Appl Physiol Occup Physiol* 56: 693–698, 1987. doi:10.1007/BF00424812.
58. **Rodrigues P**, **Trajano GS**, **Wharton L**, **Orssatto LBR**, **Minett , GM.** A passive increase in muscle temperature enhances rapid force production and neuromuscular function in healthy adults. *J Sci Med Sport* 24: 818–823, 2021. doi:10.1016/j.jsams.2021.01.003.
59. **Bergstrom HC**, **Housh TJ**, **Zuniga JM**, **Traylor DA**, **Lewis RW**, **Camic CL**, **Schmidt RJ**, **Johnson GO.** Differences among estimates of critical power and anaerobic work capacity derived from five mathematical models and the three-minute all-out test. *J Strength Cond Res* 28: 592–600, 2014. doi:10.1519/JSC.0b013e31829b576d.
60. **Bergstrom HC**, **Housh TJ**, **Zuniga JM**, **Traylor DA**, **Lewis RW**, **Camic CL**, **Schmidt RJ**, **Johnson GO.** Mechanomyographic and metabolic responses during continuous cycle ergometry at critical power from the 3-min all-out test. *J Electromyogr Kinesiol* 23: 349–355, 2013. doi:10.1016/j.jelekin.2012.11.001.
61. **Bartram JC**, **Thewlis D**, **Martin DT**, **Norton KI.** Predicting critical power in elite cyclists: questioning the validity of the 3-minute all-out test. *Int J Sports Physiol Perform* 12: 783–787, 2017. doi:10.1123/ijspp.2016-0376.
62. **McClave SA**, **Leblanc M**, **Hawkins SA.** Sustainability of critical power determined by a 3-minute all-out test in elite cyclists. *J Strength Cond Res* 25: 3093–3098, 2011. doi:10.1519/JSC.0b013e318212dafc.
63. **Easton C**, **Fudge BW**, **Pitsiladis YP.** Rectal, telemetry pill and tympanic membrane thermometry during exercise heat stress. *J Therm Biol* 32: 78–86, 2007. doi:10.1016/j.jtherbio.2006.10.004.
64. **McKenzie JE**, **Osgood DW.** Validation of a new telemetric core temperature monitor. *J Therm Biol* 29: 605–611, 2004. doi:10.1016/j.jtherbio.2004.08.020.
65. **Mündel T**, **Carter JM**, **Wilkinson DM**, **Jones DA.** A comparison of rectal, oesophageal and gastro-intestinal tract temperatures during moderate-intensity cycling in temperate and hot conditions. *Clin Physiol Funct Imaging* 36: 11–16, 2016. doi:10.1111/cpf.12187.
66. **Byrne C**, **Lim CL.** The ingestible telemetric body core temperature sensor: a review of validity and exercise applications. *Br J Sports Med* 41: 126–133, 2007. doi:10.1136/bjsm.2006.026344.
67. **Hughson RL**, **Orok CJ**, **Staudt LE.** A high velocity treadmill running test to assess endurance running potential. *Int J Sports Med* 5: 23–25, 1984. doi:10.1055/s-2008-1025875.

Downloaded from journals.physiology.org/journal/jappl (045.149.228.100) on December 6, 2022.