International Journal of Sports Physiology and Performance, (Ahead of Print)
https://doi.org/10.1123/ijspp.2022-0043
First Published Online: Sept. 6, 2022

Human Kinetics
ORIGINAL INVESTIGATION

Continuous Thermoregulatory Responses to a Mass-Participation 89-km Ultramarathon Road Race

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Purpose: To continuously measure body core temperature (T_c) throughout a mass-participation ultramarathon in subelite recreational runners to quantify T_c magnitude and the influence of aerobic fitness and body fat. ***Methods:*** Twenty-three participants (19 men and 4 women; age 45 [9] y; body mass 72.0 [9.3] kg; body fat 26% [6%]; peak oxygen uptake 50 [6] $mL \cdot kg^{-1} \cdot min^{-1}$) had gastrointestinal temperature measured during an 89-km ultramarathon. Prerace-to-postrace changes in body mass, plasma sodium, and fluid and food recall quantified body water balance. ***Results:*** In maximal environmental conditions of 26.3 °C and 53% humidity, 21 of the 23 participants finished in 10:28 (01:10) h:min while replacing 49% (27%) of sweat losses, maintaining plasma sodium (140 [3] $mmol \cdot L^{-1}$), and dehydrating by 4.1% (1.3%). Mean maximum T_c was 39.0 (0.5) (range 38.2–40.1 °C) with 90% of race duration ≤39.0 °C. Mean maximum ΔT_c was 1.9 (0.9) (0.9–2.7 °C) with 95% of race duration ≤2.0 °C. Over 0 to 45 km, associations between ΔT_c and peak oxygen uptake (positive) and body fat (negative) were observed. Over 58 to 89 km, associations between T_c and peak oxygen uptake (negative) and body fat (positive) were observed. ***Conclusions:*** Modest T_c responses were observed in recreational ultramarathon runners. Runners with higher levels of aerobic fitness and lower levels of body fat demonstrated the greatest changes in T_c during the first half of the race. Conversely, runners with lower levels of aerobic fitness and higher levels of body fat demonstrated the greatest absolute T_c in the final third of the race.

Keywords: core temperature, hyperthermia, dehydration, aerobic fitness, body fat

Ultramarathons, defined as running events longer than the marathon distance of 42.195 km, are characterized by a diversity of distance, duration, topography, and environmental conditions.[1] A key consideration for the ultramarathon runner is the regulation of body core temperature (T_c), as the magnitude of T_c elevation during prolonged exercise has the potential to impact both performance and health.[2] T_c and sweat rate during running are primarily determined by metabolic heat production.[3,4] Postmarathon T_c typically averages 39 °C with sweat rates over 1 $L \cdot h^{-1}$ and dehydration of approximately 4% of body mass.[4,5] In marathon races, the fastest runners display the highest T_c and greatest dehydration,[5] subsequent to greater rates of heat production and required evaporative heat loss. However, few studies and limited data exist for the thermoregulatory responses to ultramarathon running.[6]

Mass-participation distance running is associated with the greatest risk of exertional heat illness in organized sports, with an estimated prevalence of 6.7%.[7] Exertional heat stroke is the rarest and most severe form of heat illness and is characterized by central nervous system dysfunction and T_c exceeding 40.5 °C.[7] Improved knowledge of thermoregulatory function during ultramarathon running will better inform athlete preparation and medical risk management. On the one hand, T_c elevation during ultramarathon running may be modest compared with shorter distance events as metabolic heat production (running speed) is lower with increasing distance.[8] This may explain the handful of ultramarathon studies reporting modest T_c responses (ie, 36.6 to 39.5 °C).[9–12] On the other hand, numerous factors specific to or exacerbated by ultramarathon running have the potential to elevate T_c via effects on increasing metabolic heat production and/or impairing body heat loss.[6] For example, heat production may increase for a given running speed due to the impaired running economy associated with peripheral muscle fatigue and muscle damage, resulting in a higher T_c if speed is maintained.[13,14] In addition, greater exposure to maximal daylight environmental conditions may increase skin temperature, reduce the core-to-skin temperature gradient, and necessitate an increase in T_c to reduce whole-body skin blood flow requirements for heat loss, if speed is maintained.[15] Furthermore, ultramarathon runners are a population with a wide range of aerobic fitness and body morphology attributes.[1] Higher aerobic fitness will be expected to lead to greater ΔT_c due to higher rates of metabolic heat production.[3] Alternatively, higher levels of body fat produce small but significant increases in T_c for a given level of heat production,[16] and this may be exacerbated by the prolonged nature of ultramarathon running.

This study aimed to advance knowledge of the thermoregulatory responses to ultramarathon running that is currently based

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upon single postrace T_c measures[9,10] or few intrarace serial T_c measures.[12] The objectives were to continuously measure T_c throughout an ultramarathon in a sample of recreational runners, to quantify the magnitude and pattern of response, to estimate body water balance, and to investigate the influence of aerobic fitness, body fat, and body water balance on the T_c response.

Methods

Participants, Design, and Setting

Twenty-three recreational distance runners (19 men and 4 women), who were registered entrants in an 89-km ultramarathon road race, volunteered with written informed consent to participate in this study. The study procedures were approved by the ethics committees of the School of Sport and Health Sciences at the University of Exeter, United Kingdom, and the Department of Exercise Science and Sports Medicine at the University of Cape Town, South Africa.

The study design represents an observational cross-sectional study of recreational ultramarathon runners employing convenience sampling. The design consisted of participants undertaking a single laboratory visit for physiological assessment followed by field-based physiological measurements during the Comrades Marathon on May 24, 2009. Twenty volunteers were recruited by responding to advertisements to Cape Town-based running clubs, and 3 were recruited by responding to advertisement at the prerace Expo in Durban. Comrades is an annual mass-participation ultramarathon road race of approximately 89 km (56 miles) distance between the cities of Pietermaritzburg and Durban in KwaZulu-Natal Province, South Africa. It is considered the world's oldest (first race in 1921) and largest (up to 20,000 participants) ultramarathon. Participants are required to complete the distance within 12 hours to receive an official finisher's medal. The start and finish of the race alternates annually between the 2 cities. The race under study, started at 05:30 hours in Pietermaritzburg (650-m altitude), finished in Durban (sea level), and is considered a "down run."

Methodology

Laboratory Measurements. Twenty of the 23 participants attended the laboratory at the Department of Exercise Science and Sports Medicine at the University of Cape Town (Sports Science Institute of South Africa) on a single occasion 21 (10) (10–52) days before the race for assessment of their anthropometry, running economy, and peak oxygen uptake (VO_2peak). Three participants recruited at the prerace Expo did not attend the laboratory due to insufficient time before the race. Percentage of body fat was estimated from the sum of 4 skinfolds using the equations of Peterson et al.[17] Skinfold measurements were made in duplicate by one researcher with the mean of the 2 measurements accepted as the criterion for each site. An incremental treadmill run until volitional exhaustion was performed with VO_2 and heart rate (HR) measured continuously using a breath-by-breath metabolic cart (Jaeger Oxycon Pro 2, Erich Jaeger GmbH) and short-range telemetry (Suunto T6, Suunto), respectively.[18] Individual running speed–VO_2 regression equations were established from 30-second average VO_2 values (R^2 = .98 [.02]) for the prediction of VO_2 during the race when speed was known. Running economy was defined as the VO_2 at 10 $km \cdot h^{-1}$ and expressed in milliliters per kilogram per minute and milliliters per kilogram per kilometer. VO_2peak and maximal HR (HR_{max}) were defined as the highest 30-second average values observed during the test. Velocity at VO_2peak ($v VO_2$peak) was considered the functional expression of VO_2peak.[18] Peak treadmill velocity was defined as the highest running speed maintained for 60 seconds.

Field Measurements. Participants reported to a research station near the start line within 90 minutes of the official 05:30 hours race start time for prerace measurements and equipment fitting. Prerace hydration status was assessed by the osmolality of waking urine (Osmocheck, Vitech Scientific Ltd). Venous blood was sampled prerace and postrace for the analysis of plasma sodium using an automated analyzer (EasyLyte, Medica Corp). Prerace and postrace race body mass was measured in duplicate to the nearest 0.100 kg with participants in minimal attire (ie, shorts and vest) and having toweled dry. Participants ingested a telemetric temperature sensing capsule (VitalSense, Philips Respironics) prior to sleeping (approximately 7.5 h before race start) and during the race wore a 250-g data recorder for the continuous measurement of gastrointestinal temperature as an index of T_c.[19] Sensor ingestion timing aimed to ensure sensor transit beyond the stomach but not expulsion before data collection.[19] A HR telemetry system was fitted to 12 randomly selected participants (Polar Vantage, Polar Electro Oy), due to financial constraints limiting equipment availability. One participant was fitted with a global positioning system running computer (Garmin Forerunner 305, Garmin International Inc) for the measurement of race distance and elevation. Each runner wore the race organizers timing chip system (ChampionChip) on their shoes, which provided split times at 26.77, 44.97, 58.27, 70.97, 82.17, and 89.17 km (finish line). Upon crossing the finish line, participants walked approximately 100 m to the study research station in the race organizers medical tent for immediate postrace measurements. Finally, participants completed a fluid and food recall survey to estimate intake during the race. Environmental conditions for the race were provided by the South African Weather Service.

Data Processing. The T_c and HR data represent 60-second average values of data recorded at 15- and 5-second intervals, respectively. Complete T_c data were recorded in 19 of the 23 participants. Mean T_c during the 60 seconds prior to the race start represented baseline T_c. The loss of 4 T_c data sets was due to complete and unexplained T_c data recording failure in 2 data sets, data loss after 35% of race duration in 1 data set possibly due to excretion of the sensor, and the confounding effect of fluid intake affecting 66% of data in a further data set. Complete HR data were recorded in 9 of the 12 participants fitted. The 3 data sets were lost after 320, 380, and 380 minutes possibly due to battery failure. HR data were expressed relative to laboratory measured HR_{max}. Mean VO_2 per liter per minute was predicted from laboratory-derived speed–VO_2 relationships solved for mean 89-km race speed. Mean metabolic heat production was predicted from the product of mean VO_2, the energy equivalent of VO_2 (assuming a nonprotein respiratory exchange ratio of 0.85, ie, 20.375 $kJ \cdot VO_2$ $L \cdot min^{-1}$), and conversion factor 16.667; and expressed in absolute terms (in watts), relative to body mass (in watts per kilogram), and relative to body surface area (in watts per meter square). Dehydration was calculated in classic form as the prerace to postrace body mass change expressed as a percentage of the prerace mass. Dehydration was also calculated in contemporary form by correcting for respiratory and gas exchange losses as 0.20 $g \cdot kcal^{-1}$ of total energy expenditure and expressed as a percentage of the prerace mass.[20] Total energy expenditure (in kilocalories) was estimated as the product of mean VO_2, race duration, and the energy equivalent of VO_2 (assuming a nonprotein respiratory exchange ratio of 0.85, ie, 4.862 kcal·VO_2 L·min^{-1}). Whole-body sweat loss (in liters) was calculated as the sum of corrected body mass change and the mass of estimated food and fluid intake. Urine and fecal losses were not recorded or accounted for in the estimation of dehydration and sweat loss. Sweat rate (in liters per hour) was calculated as the sweat loss expressed relative to race duration.

Split times enabled the 89.17-km race and measured data to be split into 6 split sections (S1–S6): S1 = 0 to 26.77 km (26.77 km, 30.0% of total distance), 0.5% mean gradient, 2:52 (0:25) hours:minutes duration; S2 = 26.77 to 44.97 km (18.2 km, 20.4%), −0.5%, 2:04 (0:16) hours:minutes; S3 = 44.97 to 58.27 km (13.3 km, 14.9%), −0.5%, 1:41 (0:11) hours:minutes; S4 = 58.27 to 70.97 km (12.7 km, 14.2%), −2.2%, 1:33 (0:12) hours:minutes; S5 = 70.97 to 82.17 km (11.2 km, 12.6%), −2.0%, 1:28 (0:12); and S6 = 82.17 to 89.17 km (7.0 km, 7.9%), −1.5%, 0:52 (0:08) hours:minutes.

Table 1 Physical and Physiological Characteristics of Study Participants (Mean [SD])

	Males (n = 19)	Females (n = 4)	Sample (N = 23)
Age, y	47 (8)	36 (11)	45 (9)
Stature, m	1.76 (0.07)	1.58 (0.04)	1.73 (0.1)
Body mass, kg	73.8 (7.2)	58.6 (9.2)	72.0 (9.3)
BMI, kg·m^{-2}	24.2 (3.2)	24.0 (3.2)	24.2 (3.1)
Body fat, %	24 (5)	32 (4)	26 (6)
VO_2peak, mL·kg^{-1}·min^{-1}	51 (6)	46 (4)	50 (6)
Running economy at 10 km·h^{-1}			
mL·kg^{-1}·min^{-1}	33 (3)	35 (2)	34 (3)
mL·kg^{-1}·km^{-1}	200 (17)	209 (12)	202 (16)
$v VO_2$peak, km·h^{-1}	15.3 (1.7)	13.8 (1.1)	15.0 (1.7)
Peak treadmill velocity, km·h^{-1}	15.8 (1.5)	13.8 (1.2)	15.4 (1.7)

Abbreviations: BMI, body mass index; $v VO_2$peak, velocity at VO_2peak; VO_2peak, peak oxygen uptake.

Statistical Analyses

Data were analyzed with SPSS IBM (version 26). Descriptive data are presented as mean (SD) (range). Statistical significance was accepted as $P < .05$ for all tests. Single-factor repeated-measures analysis of variance with Bonferroni follow-up tests investigated changes in variables (ie, running speed, pacing, %HR_{max}, mean T_c, maximum T_c, mean ΔT_c from baseline, maximum ΔT_c from baseline, within-split maximum positive ΔT_c, and within-split maximum negative ΔT_c) across the 6 split sections. Paired samples t tests analyzed prerace to postrace changes in means for body mass and plasma sodium. Identification of T_c responses classified as meaningful observations was achieved by converting individual maximum T_c data per split and within-split maximum positive and negative ΔT_c per split into z scores. An individual z score > 1.96 was considered a meaningful observation. Pearson correlation coefficient and the coefficient of determination (R^2) were employed to determine the relationship and strength of association between selected variables. Meaningful relationships were identified as those with a correlation coefficient of $r \geq .50$ ($R^2 \geq .25$), representing a large effect size.[21]

Results

Participant Characteristics, Course Profile, and Environmental Conditions

Table 1 illustrates the participant's physical and physiological characteristics. Total race distance was 89.17 km of undulating terrain (3208-m ascent and 3829-m descent) with a net descent of 621 m (Figure 1A). Dry bulb temperature and relative humidity ranged from a minimum of 11.7 °C and 95% at the start (05:30 h) to a maximum of 26.3 °C and 53% after 7.5 hours (13:00 h). Table 2 illustrates the sample demographics and distribution of finishing times in relation to the race population.

Performance, Pacing, and Exercise Intensity

Twenty of the 23 participants completed the distance within 12 hours, 1 participant completed the distance 3 minutes after the 12-hour cutoff, and 2 participants voluntarily withdrew after 08:01 and 11:21 hours:minutes, respectively. Table 3 illustrates mean finishing time, running speed, estimated intensity, and HR for the finishers. Figure 1B and 1C illustrates the running speed and pacing profile, respectively. Figure 1D illustrates %HR_{max} across the race.

Mean race speed demonstrated positive relationships with peak treadmill velocity ($R^2 = .51$, $P = .001$), $v VO_2$peak ($R^2 = .48$, $P = .001$), and VO_2peak ($R^2 = .43$, $P = .003$); and a negative relationship with body fat percentage ($R^2 = .35$, $P = .007$).

Thermoregulatory Responses

Body T_c. Figure 2A–2D illustrates the individual mean T_c and ΔT_c per hour. Table 4 provides a summary of T_c and ΔT_c variables and the proportion of race time in T_c and ΔT_c zones. All participants exhibited maximum T_c > 38.0 °C, 95% ≥38.5 °C, 47% ≥39.0 °C, 10.5% ≥39.5 °C, and a single participant exceeded 40.0 °C (ie, 40.1 °C). The 2 nonfinishers exhibited unremarkable T_c of 38.5 °C (ΔT_c = 1.0 °C) and 38.4 °C (ΔT_c = 0.9 °C) at withdrawal, having spent the majority of race time (≈75%) with T_c < 38.5 °C. Their peak T_c and ΔT_c during the race were 39.0 °C (ΔT_c = 1.6 °C) and 38.8 °C (ΔT_c = 1.6 °C).

Figure 3 illustrates box plots of peak T_c and ΔT_c data sets across the 6 split sections. Maximum T_c (Figure 3A) and maximum ΔT_c from prerace baseline (Figure 3B) were similar across split sections ($P = .429$). Within-split maximum positive ΔT_c (Figure 3C) was greater in S1 versus S2 to S6 ($P \leq .001$), and within-split maximum negative ΔT_c was greater in S1 and S3 versus S6 ($P \leq .014$; Figure 3D). Within S1, 81 (17) (50%–100%) of the maximum ΔT_c for the entire race was achieved in the first 60 minutes of running. The net change in T_c over S2 to S6 (27–89 km) was 0.04 (0.51) (−0.87 to 0.89 °C).

Maximum T_c responses identified as meaningful observations were observed in 3 runners. These were in 4 consecutive split sections for 1 runner (ie, S3 = 39.6 °C; S4 = 39.7 °C; S5 = 39.7 °C; and S6 = 40.1 °C); 2 split sections for a further runner (ie, S1 = 39.4 °C and S5 = 39.6 °C); and a single split section in another runner (ie, S2 = 39.3 °C). Within-split peak positive ΔT_c responses identified as meaningful were observed in 4 runners, including the 2 latter runners above. One runner experienced a 1.0 °C change in S2 in 17 minutes (0.058 °C·min^{-1}) to 39.3 and 0.9 °C in S3 in 19 minutes (0.047 °C·min^{-1}) to 39.2 °C. A further runner produced

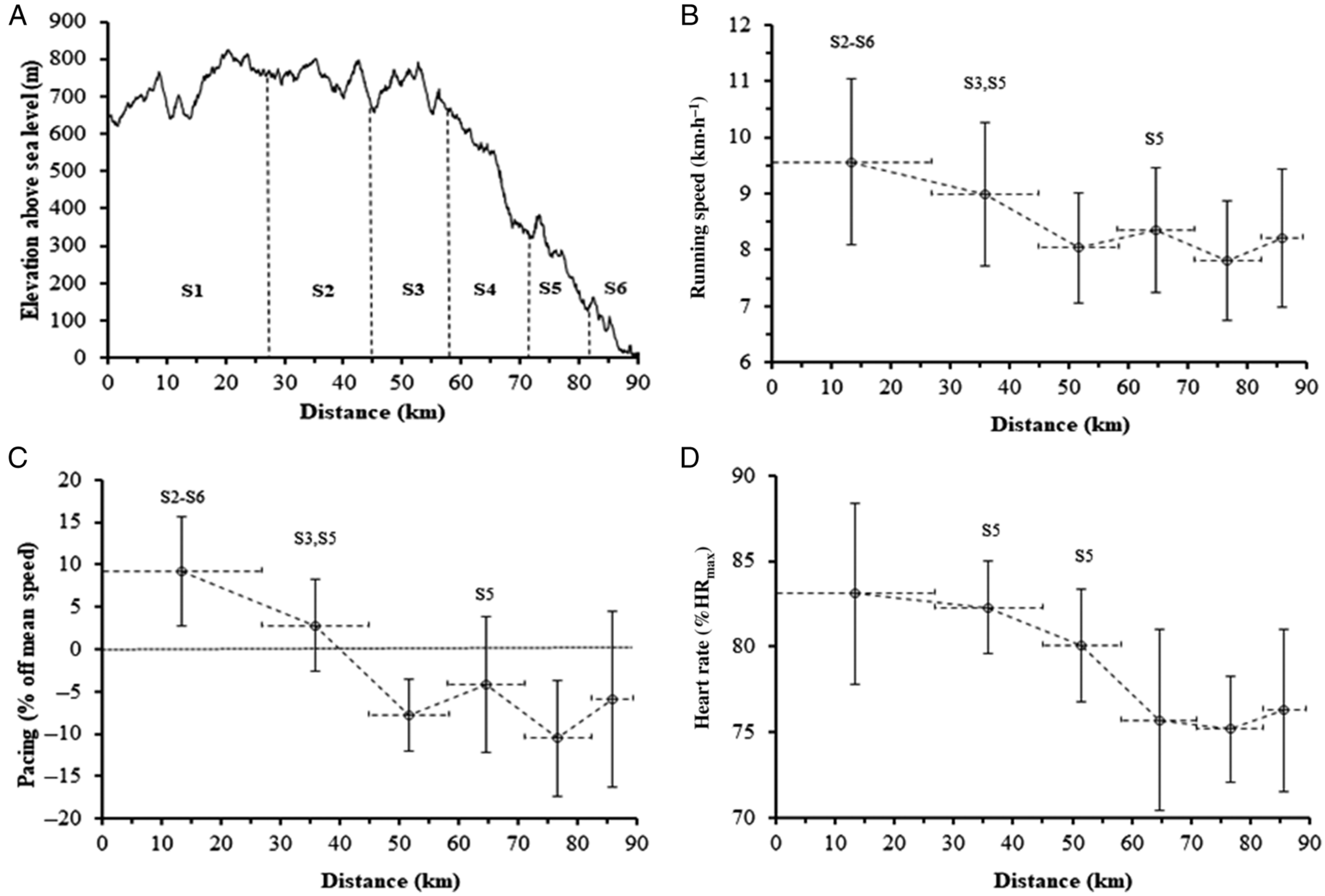

Figure 1 — Course profile illustrating distance versus elevation and the 6 (S1–S6) split sections (A); mean (SD) running speed for each split section (B, n = 21); mean (SD) pacing as percentage of mean 89-km speed for each split section (C, n = 21); and mean (SD) $\%HR_{max}$ for each split section (D, n = 8). HR_{max} indicates maximal heart rate; S, split section value. S is significantly greater than designated number split section(s), $P < .05$.

Table 2 Demographics of Study Participants and Total Comrades Marathon Race Entrants

	Study participants	Race entrants
Starters/finishers, n	23/20	11,345/10,005
Finishers, %	87.0	88.2
Finishers (male/female, n)	17/3	8256/1749
Finishers (male/female, %)	85.0/15.0	82.5/17.5
Finish time 05:23 < 07:30 h, %	0	5.8
Finish time 07:30 < 09:00 h, %	20.0	19.3
Finish time 09:00 < 11:00 h, %	50.0	47.0
Finish time 11:00 < 12:00 h, %	30.0	27.9

a change of 1.1 °C in S6 to 38.8 °C, with 0.8 °C of the 1.1 °C change occurring in the final 13 minutes of the race (0.062 $°C·min^{-1}$). In 2 further runners, similar magnitudes of change to the above (S4 = 0.96 °C and S5 = 0.81 °C), albeit at slower rates (S4 = 0.013 $°C·min^{-1}$ and S5 = 0.015 $°C·min^{-1}$), produced peak T_c of 39.3 and 39.0 °C, respectively.

Correlates of T_c. The ΔT_c in the first half of the race (ie, S1–S2) was positively related to measures of aerobic fitness and negatively related to body fat and baseline T_c. For example, S1 mean ΔT_c was positively related to VO_2peak ($R^2 = .29$, $P = .027$) and negatively related to % body fat ($R^2 = .37$, $P = .008$) and baseline T_c ($R^2 = .45$, $P = .002$). The proportion of race time with ΔT_c 1.0 to 2.0 °C was also positively related to measures of aerobic fitness (eg, peak treadmill velocity $R^2 = .31$, $P = .026$) and negatively related to baseline T_c ($R^2 = .60$, $P \leq .001$).

The T_c in the last third of the race (ie, S4–S6) demonstrated positive relationships with measures of body fat and baseline T_c and negative relationships with measures of aerobic fitness. For example, S6 peak T_c was positively related to body mass index ($R^2 = .43$, $P = .004$) and baseline T_c ($R^2 = .25$, $P = .041$) and negatively related to vVO_2peak ($R^2 = .52$, $P = .002$).

Baseline T_c was a consistent correlate of both ΔT_c (negative) and T_c (positive) responses. In turn, baseline T_c was positively related to measures of body fat (eg, body mass index $R^2 = .56$,

Table 3 Environmental Conditions, Finishing Time, Running Speed, and Exercise Intensity During the 89-km Ultramarathon

	Mean (SD)	Range
Dry bulb temperature, °C	19.9 (5.5)	11.7 to 26.3
Relative humidity, %	70 (19)	53 to 95
Finish time, h:min	10:28 (01:10)	08:25 to 12:03
Running speed, $km \cdot h^{-1}$	8.6 (1.0)	7.4 to 10.6
VO_2, $mL \cdot kg^{-1} \cdot min^{-1}$	30 (4)	23 to 37
%VO_2peak	60 (9)	46 to 77
%Peak treadmill velocity	56 (5)	46 to 65
Metabolic heat production		
W	717 (129)	472 to 961
$W \cdot kg^{-1}$	10.2 (1.2)	7.9 to 12.5
$W \cdot m^{-2}$	392 (51)	301 to 484
HR		
$Beats \cdot min^{-1}$	148 (9)	133 to 158
%HR_{max}	79 (3)	76 to 84
Race time in %HR_{max} zone, %		
40% < 55%	0.4 (0.8)	0 to 2.5
55% < 70%	6.7 (8.8)	0.2 to 26.0
70% < 80%	39.2 (13.8)	22.0 to 56.0
80% < 90%	48.2 (14.1)	32.5 to 72.1
≥90%	5.2 (7.2)	0 to 19.4

Abbreviations: HR, heart rate; HR_{max}, maximal HR; VO_2, oxygen uptake; VO_2peak, peak VO_2. Note: Values represent n = 21 for finish time and running speed; n = 18 for VO_2, %VO_2peak, %peak treadmill velocity, and heat production; and n = 8 for HR and %HR_{max}.

$P \leq .001$; %fat $R^2 = .54$, $P \leq .001$) and negatively related to measures of aerobic fitness (eg, VO_2peak $R^2 = .47$, $P = .001$; $v$$VO_2$peak $R^2 = .39$, $P = .005$).

Body Water Balance

Table 5 illustrates body water balance variables in response to the race. Body mass was reduced postrace ($P \leq .001$). Plasma sodium was unchanged ($P = .988$), with individual changes ranging from −8 to 7 $mmol \cdot L^{-1}$. The proportion of the sample with dehydration < 2%, 2% < 3%, 3% < 4%, and >4% was 5%, 15%, 30%, and 50%, respectively. The proportion of the sample with corrected dehydration <2%, 2% < 3%, 3% < 4%, and >4% was 45%, 15%, 25%, and 15%, respectively. One participant who withdrew at 11:21 hours: minutes demonstrated unremarkable values for corrected body mass loss (1.8 kg), corrected dehydration (1.4%), postplasma sodium (143 $mmol \cdot L^{-1}$), plasma sodium change (−0.6 $mmol \cdot L^{-1}$), sweat rate (0.7 $L \cdot h^{-1}$), and sweat replaced (73%).

Corrected dehydration was positively related to plasma sodium change ($R^2 = .47$, $P = .002$), VO_2peak ($R^2 = .39$, $P = .006$), and mean race speed ($R^2 = .25$, $P = .023$). Corrected dehydration was negatively related to baseline T_c ($R^2 = .27$, $P = .019$), S4 peak T_c ($R^2 = .28$, $P = .024$), and S5 mean and peak T_c ($R^2 = .30$, $P = .023$; $R^2 = .35$, $P = .013$).

Discussion

Our main finding is that recreational runners in a mass participation 89-km road-based ultramarathon lasting up to 12 hours in mild environmental heat, display thermoregulatory responses within normal limits. The incidence of marked hyperthermia (ie, $T_c \geq 40$ °C)[22] in this subelite population appears low as evidenced by a single observation (ie, $T_c = 40.1$ °C) in the current study.

The novel feature of the current study was the continuous measurement of T_c throughout an 89-km ultramarathon. Our data are in general agreement with Dancaster and Whereat[9] who provide the only comparative T_c data for the Comrades marathon and reported postrace (5–10 min) rectal temperatures in the range 38.3 to 38.9 °C in 9 runners following an "up run." We observed mean final T_c of 38.6 (0.6 °C) and 59% of final T_c values and 72% of race time was spent within the T_c range 38.0 to 38.9 °C. However, we did observe a greater upper range of final T_c (21% ≥39.0 °C) and maximum T_c (47% ≥39.0 °C). Taken together, both studies suggest the majority of Comrades runners experience a modest level of hyperthermia. Our observations are also consistent with the modest levels of hyperthermia reported in the existent ultramarathon evidence base. For example, postrace T_c ranged from 38.7 to 39.2 °C following 56 km (3 h 48 min to 5 h 24 min) of road running,[10] 37.2 to 39.4 °C during 161 km (26 h 48 min) of trail running,[12] and peaked at 39.0 to 39.5 °C during 217 km (36 h) of desert running.[11]

A novel observation was that baseline T_c was inversely related to ΔT_c and directly related to measures of T_c. This apparent paradox (ie, higher baseline T_c not only associated with lower ΔT_c but also higher T_c) is explained by the interaction of baseline T_c, aerobic fitness, body fat, and the parts of the race when these relationships were significant (ie, 0–45 km for baseline T_c: ΔT_c relationship; and 58–89 km for baseline T_c: absolute T_c relationship). Baseline T_c,

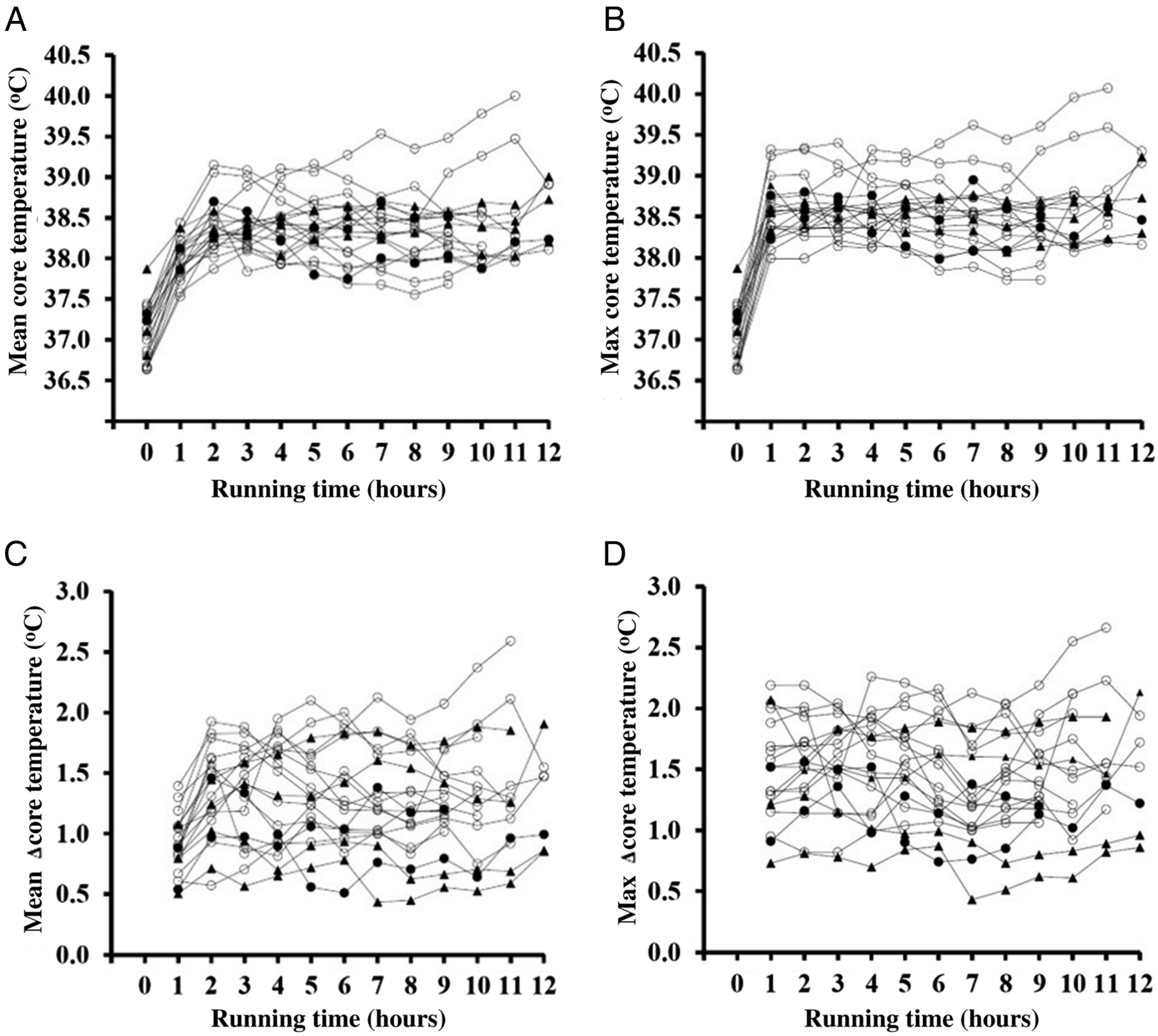

Figure 2 — Individual baseline and mean T_c (A), individual baseline and peak Tc (B), mean ΔT_c from baseline (C), and peak ΔT_c from baseline (D) per hour of running for 17 finishers (n = 13 males ○ and n = 4 females ▲) and 2 nonfinishers (n = 2 males •). T_c indicates core temperature.

measured at 05:30 hour when air temperature was a cool 11.7 °C, was directly related to measures of body fat and inversely related to measures of aerobic fitness. Two independent or interacting factors could potentially explain these relationships: (1) the role of subcutaneous fat and muscle tissue providing thermal insulation and limiting heat loss and T_c decline during cold air exposure before the race[23] and (2) lower resting T_c representing a biomarker of enhanced heat adaptation and endurance training status.[24,25] The lack of standardization in baseline T_c measurement means that prerace physical activity and clothing are potential confounding influences. However, the relationships were robust, linear, uninfluenced by outliers, and warrant confirmation from future well-controlled field or laboratory studies.

Our data indicate that individuals with lower baseline T_c had lower levels of body fat, higher levels of aerobic fitness, and displayed higher changes in T_c from baseline in the first 45 km of the race. However, due to their lower baseline $T_{c,}$ the leaner fitter runner's absolute T_c responses were not elevated above the fatter, less fit runner's absolute T_c responses. Conversely, individuals with a higher baseline T_c had higher levels of body fat, lower levels of aerobic fitness, and displayed higher absolute levels of T_c in the 58 to 89 km part of the race. However, due to their higher baseline $T_{c,}$ the fatter-less fit runner's ΔT_c responses were not elevated above the leaner-fitter runner's ΔT_c responses. These latter relationships were evident during a part of the race characterized by downhill running (Figure 1A, S4–S6). It is possible that the consequences of downhill running on heat production and subsequent T_c were greater for the fatter-less fit runners than the leaner-fitter runners.

Marked hyperthermia (ie, $T_c \geq 40$ °C) was observed in a single participant for the final 8 minutes (1.3%) of their 10-hour 14-minute race. This runner exhibited $T_c \geq 39$ °C for the final 7 hours 19 minutes (71.5%) of their race resulting in the highest final and peak T_c (40.1 °C) and ΔT_c (2.7 °C) of the sample. Notable features from this

Table 4 Overview of T_c Responses During the 89-km Ultramarathon Race

	Mean (SD)	Range
Baseline T_c, °C	37.1 (0.3)	36.6 to 37.9
T_c rate of rise in 30 min, °C·min^{-1}	0.05 (0.01)	0.01 to 0.07
Mean T_c, °C	38.4 (0.3)	37.8 to 39.1
Maximum T_c, °C	39.0 (0.5)	38.2 to 40.1
Final T_c, °C	38.6 (0.6)	37.7 to 40.1
Mean ΔT_c, °C	1.3 (0.3)	0.6 to 1.7
Maximum ΔT_c, °C	1.9 (0.9)	0.9 to 2.7
Final ΔT_c, °C	1.5 (0.5)	0.8 to 2.7
Race time in T_c zone, %		
<38.0 °C	18.5 (21.2)	1.5 to 82.0
>38.0 ≤ 38.5 °C	47.4 (20.3)	7.3 to 73.1
>38.5 ≤ 39.0 °C	24.5 (19.6)	0 to 66.6
>39.0 ≤ 39.5 °C	8.1 (15.4)	0 to 48.2
>39.5 < 40.0 °C	1.3 (5.4)	0 to 22.3
≥40.0 °C	0.1 (0.3)	0 to 1.3
Race time in ΔT_c zone, %		
≤0.5 °C	4.1 (6.0)	1.4 to 26.7
>0.5 ≤ 1.0 °C	20.8 (28.1)	1.0 to 82.3
>1.0 ≤ 1.5 °C	39.5 (20.9)	0 to 67.9
>1.5 ≤ 2.0 °C	31.0 (26.0)	0 to 82.7
>2.0 ≤ 2.5 °C	4.2 (8.0)	0 to 28.0
≥2.5 °C	0.2 (1.0)	0 to 4.2

Abbreviation: T_c, body core temperature. Note: Values represent n = 17 for race finishers T_c.

male runner's physical and physiological profile in comparison with the sample (Tables 1 and 3) include a high baseline T_c (37.4 °C), high level of adiposity (body mass index 28.0; %fat 29.1), low aerobic fitness parameters (VO_2peak 45 mL·kg^{-1}·min^{-1}; running economy 236 mL·kg^{-1}·km^{-1}; and $v$$VO_2$peak 11.6 km·h^{-1}), and high estimated race VO_2 (35 mL·kg^{-1}·min^{-1}), relative intensity (77 % VO_2peak), and metabolic heat production (12 W·kg^{-1}), despite a modest race speed (8.7 km·h^{-1}). The role of poor running economy in elevating heat production and ΔT_c for a given running speed[3] and higher levels of body fat producing small but significant increases in ΔT_c for a given heat production[16] have been demonstrated. The complex interaction between metabolic heat production, body morphology, and the physical properties of the skin and environment determining heat loss are considered the principal components determining T_c responses to exercise[26] and are likely determinants of the individual variability in T_c responses observed in the current study (Figures 2 and 3).

Our estimated body water balance responses (ie, body mass loss = 4.1% [1.3%] [1.9%–7.1%]) were in general agreement with previous Comrades studies.[9,27] We did not record or account for urine and fecal losses, and therefore, a slight overestimation of dehydration and sweat loss will be inherent in our results. Dancaster and Whereat[9] observed body mass losses of 5.2% (1.7%) (0.7%–8.2%) and Kelly and Godlonton[27] observed body mass losses of 3.6% (maximum 7.1%). The sweat losses and fluid replacement data of Dancaster and Whereat[9] (ie, sweat rate = 0.88 [0.24] [0.51–1.49] L·h^{-1}; fluid intake rate = 0.48 [0.30] [0.03–1.37] L·h^{-1}; and sweat loss replaced = 53% [20%] [5%–93%]) were also similar to our observations (ie, sweat rate = 0.6 [0.3] [0.2–1.1] L·h^{-1}; fluid intake rate = 0.3 [0.3] [0–1.0] L·h^{-1}; and sweat loss replaced = 49% [27%] [3%–93%]). In addition, plasma sodium was well regulated within the 135 to 145 mmol·L^{-1} normal range in all participants (ie, postrace plasma sodium = 140 [3] [135–145] mmol·L^{-1}). This indicator of euhydration was in the presence of 95% of participants exhibiting body mass loss ≥ 2.0% with 50% ≥4.0%. This supports the view that maintaining body mass loss < 2% for body water homeostasis during ultra-endurance exercise is not warranted.[28] Moreover, dehydration did not appear to negatively impact T_c or performance. Indeed, dehydration demonstrated inverse relationships with S4 and S5 T_c and was positively related to mean race speed ($R^2 = .25$, $P = .023$). The latter finding supports previous observations on 100-km ultramarathon[29] and 42.2-km marathon[30] races, that faster runners exhibit the greatest levels of dehydration, suggesting their performance is not impaired by their greater dehydration.

The physiological correlates of performance in the current study (ie, peak treadmill velocity, $v$$VO_2$peak, VO_2peak, and %fat) are in good agreement with previous studies.[31] The negative impact of body fat on marathon and ultramarathon[32] performance was confirmed by our observation of an inverse relationship between %fat and mean speed. The observed progressive reduction in speed, representing a positive pacing pattern, is consistent with previous pacing observations on marathon and ultramarathon races ranging from 100 to 161 km.[33,34] While the mechanisms underlying this pacing pattern were not the focus of this study, it appears that marked hyperthermia is not a contributing factor.

Practical Applications

Our study revealed that 89-km ultramarathon running in temperatures up to 26 °C is not associated with high body temperatures, suggesting that specific heat mitigation strategies (eg, precooling, per-cooling, aggressive hydration) may have limited effectiveness compared to warmer environmental conditions. Nevertheless, we revealed that modifiable internal factors such as high body fat and lower aerobic fitness were associated with higher body temperatures later in the race. Indeed, these same internal factors were associated with poorer ultramarathon running performance, just as they are with distance running over shorter distances. This suggests that dual benefits on performance and body temperature regulation are likely to result from preparation strategies that produce positive adaptations in body fat and markers of aerobic fitness. Runners who withdrew from the race appeared to run at an intensity lower than runners who completed the race and exhibited unremarkable body temperature and hydration responses suggesting their performance limitation was not of a thermoregulatory origin. Due to ultramarathons being characterized by a diversity of distance, duration, topography, and environmental conditions, our study findings are generalizable to the specific demands of the Comrades Marathon event. Our results should be viewed in the context of the modest distance (89.17 km), duration (≤12 h), topography (tarmacadam running surface, 3208-m ascent, and 621-m net descent), and environmental heat (≤26.3 °C) of the Comrades event versus the more extreme ultramarathon running races.[1,6] Our small sample size was representative of the subelite recreational male and female Comrades runner. Future research focusing on the thermoregulatory responses of elite and subelite male and female runners across the full spectrum of ultramarathon events is warranted.

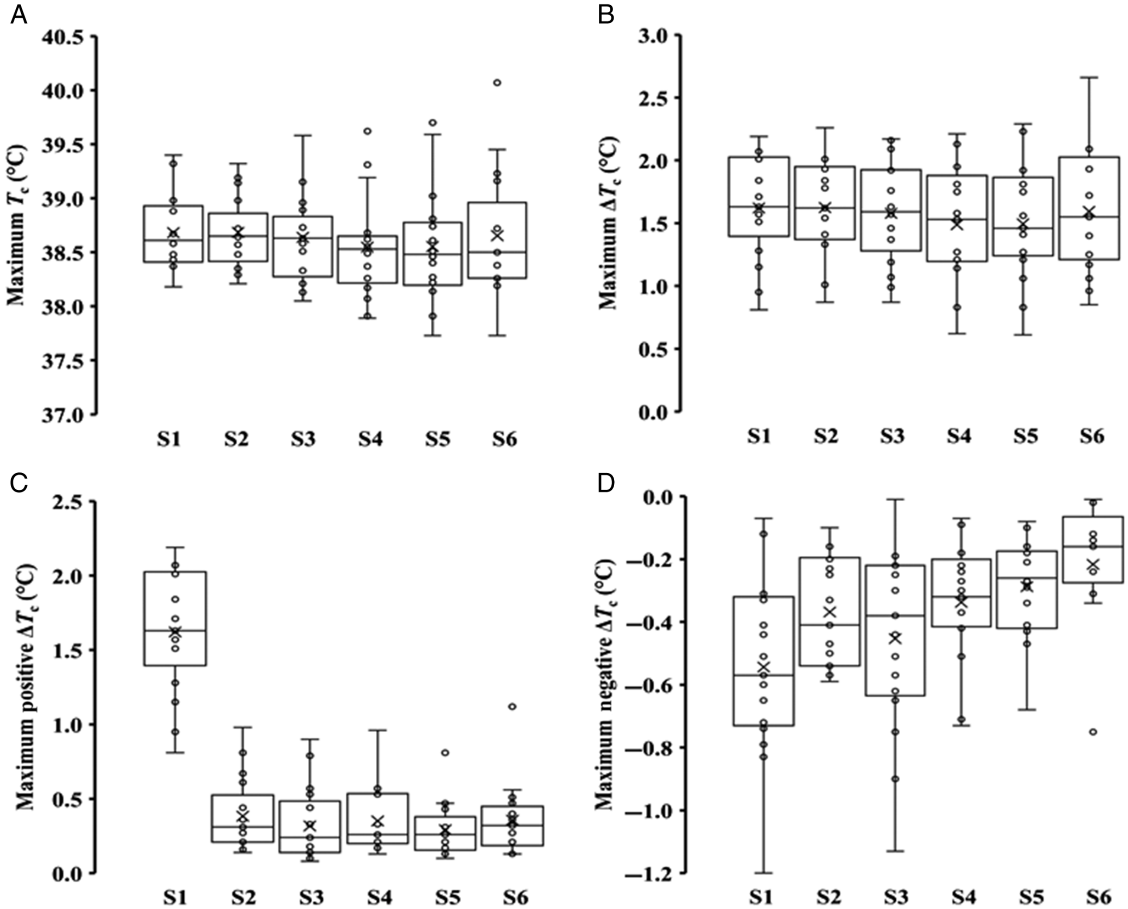

Figure 3 — Box plots of data sets for peak T_c (A), peak ΔT_c from baseline Tc (B), peak positive ΔT_c within each split (C), and peak negative ΔT_c within each split (D) across the 6 split sections for 17 finishers. Box plots represent minimum and maximum values (whiskers); 25th percentile, median (line), mean (×), 75th percentile, and interquartile range (box). Data points that exceed 1.5 times the interquartile range are considered outliers and are illustrated outside the whiskers.

Table 5 Body Water Variables in Response to the 89-km Ultramarathon Race

	Mean (SD)	Range
Prerace urine osmolality, mOsmol·kg^{-1}	588 (223)	250 to 1090
Prerace plasma sodium, mmol·L^{-1}	140 (3)	133 to 145
Postrace plasma sodium, mmol·L^{-1}	140 (3)	135 to 145
Change in plasma sodium, mmol·L^{-1}	0 (4)	−8 to + 7
Body mass loss, kg	2.9 (1.0)	1.5 to 5.4
Dehydration, %	4.1 (1.3)	1.9 to 7.1
Corrected body mass loss, kg	1.7 (1.0)	0.2 to 4.0
Corrected dehydration, %	2.3 (1.3)	0.3 to 5.3
Food intake, kg	0.6 (1.0)	0.1 to 4.0
Fluid intake, L	3.3 (2.9)	0.1 to 10.6
Fluid intake rate, L·h^{-1}	0.3 (0.3)	0 to 1.0
Sweat loss, L	5.8 (3.0)	2.0 to 11.4
Sweat rate, L·h^{-1}	0.6 (0.3)	0.2 to 1.1
Sweat loss replaced, %	49 (27)	3 to 93

Note: Values represent n = 21 for urine osmolality, body mass loss, and dehydration; n = 18 for serum sodium; and n = 15 for food, fluid, and sweat loss variables.

Conclusions

By measuring T_c continuously throughout an 89-km mass-participation ultramarathon, we revealed thermoregulatory responses within normal limits in a representative sample of subelite runners. The greatest and most consistent changes in T_c occurred during the first hour of running. While evidence of heat storage and meaningful changes in T_c were revealed thereafter, this typically did not manifest in marked hyperthermia except in a single case of 40.1 °C. Runners with lower body fat and higher aerobic fitness demonstrated the greatest changes in T_c during the first half of the race. These faster runners demonstrated the greatest degree of dehydration. Conversely, runners with higher body fat and lower aerobic fitness demonstrated the greatest T_c in the final third of the race and demonstrated lower levels of dehydration. In this study, faster runners did exhibit greater dehydration, but did not display greater absolute T_c responses due in part to a lower starting T_c, which appeared to reflect lower body fat and higher aerobic fitness and/or heat adaptation status.

Acknowledgments

The authors would like to thank Theresa Mann, Elske Schabort, and Nicholas Tam for their help with data collection, and Dr Jeremy Boulter and the Comrades Marathon medical team for accommodating our research stations. Jason Lee was supported by the National Research Foundation, Prime Minister's Office, Singapore, under its Campus for Research Excellence and Technological Enterprise (CREATE) program.

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