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ORIGINAL ARTICLE

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# Advantages of smaller body mass during distance running in warm, humid environments

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**Abstract** The purpose of this study was to examine the extent to which lighter runners might be more advantaged than larger, heavier runners during prolonged running in warm humid conditions. Sixteen highly trained runners with a range of body masses (55–90 kg) ran on a motorised treadmill on three separate occasions at 15, 25 or 35°C, 60% relative humidity and 15 km·h$^{-1}$ wind speed. The protocol consisted of a 30-min run at 70% peak treadmill running speed (sub-max) followed by a self-paced 8-km performance run. At the end of the sub-max and 8-km run, rectal temperature was higher at 35°C (39.5±0.4°C, $P$<0.05) compared with 15°C (38.6±0.4°C) and 25°C (39.1±0.4°C) conditions. Time to complete the 8-km run at 35°C was 30.4±2.9 min ($P$<0.05) compared with 27.0±1.5 min at 15°C and 27.4±1.5 min at 25°C. Heat storage determined from rectal and mean skin temperatures was positively correlated with body mass ($r$=0.74, $P$<0.0008) at 35°C but only moderately correlated at 25°C ($r$=0.50, $P$<0.04), whereas no correlation was evident at 15°C. Potential evaporation estimated from sweat rates was positively associated with body mass ($r$=0.71, $P$<0.002) at 35°C. In addition, the decreased rate of heat production and mean running speed during the 8-km performance run were significantly correlated with body mass ($r$=–0.61, $P$<0.02 and $r$=–0.77, $P$<0.0004, respectively). It is concluded that, compared to heavier runners, those with a lower body mass have a distinct thermal advantage when running in conditions in which heat-dissipation mechanisms are at their limit. Lighter runners produce and store less heat at the same running speed; hence they can run faster or further before reaching a limiting rectal temperature.

**Keywords** Endurance · Exercise · Heat stress · Temperature

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## Introduction

When prolonged exercise is performed at high ambient temperatures ($T_a$) and high relative humidity (rh) performance is significantly impaired [25]. The time to exhaustion during prolonged exercise at 70% of maximal aerobic power ($\dot{V}O_{2\,max}$) was found to vary under different environmental conditions, although the exercise terminated at the same rectal temperature ($T_{re}$) [22]. Performance decrement during exercise-induced hyperthermia has been linked to a reduction in oxygen consumption ($\dot{V}O_2$), increased skin blood flow and cardiovascular demands for a given workload [3, 30, 31, 36]. It is apparent, however, that an athletes' tolerance to increased body temperatures during exercise is not influenced by training [32], heat acclimation [26] or exercise intensity [24].

Little attention has been given to the possibility that athletes competing in hot environments might be either advantaged or disadvantaged by their individual physical characteristics. This is somewhat surprising given the common observation that distance runners are smaller than sprinters or middle distance competitors and that marathons run at a $T_a$ of 20–25°C are 6–10% slower than races run at a $T_a$ of 10–12°C [6, 12]. There is also evidence that characteristics such as the ratio between body surface area ($A_D$) and mass ($m$, in kg) ($A_D/m$) are important determinants of heat gain and loss when exercising in hot environments [11]. For example, a large $A_D/m$ ratio is advantageous for heat loss while a small $A_D/m$ ratio facilitates heat gain from the environment [11]. These observations suggest that a greater degree of heat retention in larger heavier runners may be a major factor limiting the performance of bigger athletes in distance events.

More than half a century ago Robinson [29] noted that, during moderate exercise in warm conditions (31–33°C and 68–74% rh), a large man (99 kg) was unable to maintain thermal balance compared with a smaller man (61 kg), even though the surface area of the larger man allowed for potentially greater evaporation of sweat. Similarly, Hayward et al. [17] observed that the rate of increase in $T_{re}$ was greater for subjects with a high mesomorphy component whilst subjects walked at 7 km·h$^{-1}$ at a $T_a$ of 30°C and 80% rh.

In contrast, Havenith et al. [15] found that the increase in $T_{re}$ and heat storage ($S$) while cycling at 60 W for 1 h (35°C and 60% rh) were inversely related to body mass ($r$=–0.70). This is to be expected as smaller subjects would probably be working at a higher relative $\dot{V}O_2$, when all exercised at the same absolute workload. However, the exercise protocol used in that study rarely invoked a thermoregulatory strain, with the end of exercise $T_{re}$ reaching only ≅38.1°C. The authors concluded, however, that exercise intensity is not the only determinant of core temperature, and that other individual characteristics such as surface area and volume also contribute to the core temperature response.

Recently Dennis and Noakes [8], using marathon runners as an example, examined the extent to which lighter runners might be more advantaged than heavier runners in races conducted in warm humid (35°C, 60% rh) conditions. Their calculations clearly indicate that heavier runners are unable to maintain thermal balance in such conditions. Furthermore, in order to maintain thermal balance, maximum running speed for a 75-kg runner was estimated to be 12.2 km·h$^{-1}$ under these extreme conditions, whereas a 45-kg runner could maintain thermal balance at a running speed of 19.1 km·h$^{-1}$. These calculations, therefore, implicate that a large body size is a major disadvantage in competitive endurance races conducted in warm humid conditions. To date there are no studies that have specifically tested this hypothesis using highly trained runners with a range of body mass.

Therefore, the purpose of this investigation was to examine to what extent lighter runners might be more advantaged than larger, heavier competitors during prolonged running performance in warm humid conditions.

## Materials and methods

### Subjects

Sixteen highly trained male endurance runners were recruited for the study. It was assumed that subjects were not naturally heat acclimatized, as the experiments were conducted during the months of September and October at which time the daily temperature ranged from 8 to 25°C. All experimentation was carried out in a climate chamber (Scientific Technology, South Africa). Table 1 shows the physical characteristics of each runner. On average the subjects maintained a training volume of 60–80 km·week$^{-1}$ for at least 3 months before the study. Subjects also competed in national and local running events on a regular basis. All participants maintained a regular diet during the study period and were asked to refrain from alcohol and caffeine ingestion for at least 24 h prior to testing. The study was approved by the Research and Ethics Committee of the University and each subject signed a letter of consent after being informed of the risks associated with the experiment.

### Descriptive measurements

Stature (cm) and body mass (kg) were determined using a precision stadiometer and balance (Model 770, Seca, Bonn, Germany). All measurements were recorded with the subject fully instrumented and wearing light running shorts. Skinfolds were measured in duplicate with skinfold calipers (Holtain, Crymych, UK) to the nearest mm at nine sites (bicep, tricep, subscapular, pectoral, mid-axilla, mid-abdominal, supra-iliac, mid-thigh and medial calf). Percentage body fat (%BF) was estimated as previously described [19]. Fat mass (FM) was estimated from %BF/100·body mass, while lean body mass (LBM) was estimated from body mass minus fat mass. Body surface area ($A_D$) was calculated from mass and height as described by DuBois and DuBois [10].

**Table 1** Physical characteristics of each subject. ($A_D$ Body surface area in m$^2$, $A_D/m$ body-surface-area-to-mass ratio, *ΣSF* sum of nine skinfold sites in mm, *%BF* percent body fat, *FM* fat mass, *LBM* lean body mass, *PTRS* peak treadmill running speed determined during the incremental tests)

| Subject number | Mass (kg) | Height (cm) | $A_D$ (m$^2$) | $A_D/m$ | ΣSF (mm) | %BF | FM (kg) | LBM (kg) | PTRS (km·h$^{-1}$) | $VO_{2peak}$ (ml·kg$^{-1}$·min$^{-1}$) |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 55.0 | 158.7 | 1.55 | 0.028 | 49.9 | 5.2 | 2.8 | 52.2 | 20 | 69.4 |
| 2 | 55.2 | 168.3 | 1.62 | 0.029 | 46.1 | 4.9 | 2.7 | 52.5 | 22 | 65.4 |
| 3 | 56.7 | 167 | 1.64 | 0.029 | 47.5 | 5.0 | 2.8 | 53.9 | 22 | 66.5 |
| 4 | 57.0 | 167.6 | 1.64 | 0.029 | 46.7 | 4.9 | 2.8 | 54.2 | 22 | 63.0 |
| 5 | 57.5 | 170.4 | 1.66 | 0.029 | 49.4 | 5.2 | 2.9 | 54.6 | 23 | 74.4 |
| 6 | 59.8 | 170.6 | 1.68 | 0.028 | 51.2 | 5.3 | 3.2 | 56.6 | 20 | 66.3 |
| 7 | 63.0 | 178.2 | 1.79 | 0.028 | 55.3 | 5.7 | 3.6 | 59.4 | 21 | 59.7 |
| 8 | 64.0 | 170 | 1.74 | 0.027 | 48.4 | 4.8 | 3.1 | 60.9 | 20 | 61.0 |
| 9 | 65.0 | 172.6 | 1.77 | 0.027 | 51.4 | 5.2 | 3.4 | 61.6 | 23 | 64.1 |
| 10 | 65.0 | 169.7 | 1.75 | 0.027 | 51.1 | 5.1 | 3.3 | 61.7 | 20 | 64.6 |
| 11 | 72.6 | 186 | 1.96 | 0.027 | 50.0 | 4.9 | 3.5 | 69.1 | 21 | 65.1 |
| 12 | 74.3 | 175.7 | 1.90 | 0.026 | 59.2 | 5.6 | 4.2 | 70.1 | 21 | 57.8 |
| 13 | 74.7 | 188 | 2.00 | 0.027 | 53.0 | 5.2 | 3.9 | 70.8 | 21 | 67.0 |
| 14 | 76.0 | 179.7 | 1.95 | 0.026 | 54.5 | 5.2 | 3.9 | 72.1 | 21 | 62.0 |
| 15 | 83.6 | 192 | 2.13 | 0.025 | 56.0 | 5.2 | 4.3 | 79.3 | 21 | 61.5 |
| 16 | 90.0 | 189 | 2.17 | 0.024 | 58.0 | 5.2 | 4.7 | 85.3 | 22 | 58.0 |

## Familiarisation and incremental running tests

During a familiarisation session peak oxygen uptake ($\dot{V}O_{2\,peak}$) and peak treadmill running speed (PTRS) were determined in moderate environmental conditions where the $T_a$, rh and wind velocity were set at 21±0.6°C, 50±0.9%, 5±0.6 km·h$^{-1}$, respectively. The individual ($\dot{V}O_{2\,peak}$) and PTRS were determined on a motorised treadmill (Powerjog EG30, Sports Engineering, Birmingham, UK) set at a 1% gradient. Subjects started running at 12 km·h$^{-1}$ with speed increments of 1 km·h$^{-1}$ every minute until they could no longer maintain the pace of the treadmill. The last increment in speed that could be maintained for at least 1 min was defined as PTRS. The speed of the treadmill was set to 70% PTRS in the subsequent sub-maximal trials. During the incremental tests, the subjects wore a nose-clip and breathed through a mouthpiece connected to an automated gas analyser (Oxycon Alpha, Jaeger, The Netherlands). Prior to each test the gas analyser was calibrated with gases of known concentration and the ventilometer was calibrated with a 3-l syringe (Hans Rudolph, Vacumed, Ventura, USA). $\dot{V}O_2$, $CO_2$ production ($\dot{V}CO_2$), minute ventilation ($\dot{V}_E$) and respiratory exchange ratio (RER) were calculated for each breath. $\dot{V}O_{2\,peak}$ (ml·kg$^{-1}$·min$^{-1}$) was the average of the highest values attained over the final minute of exercise. Following the measurements of $\dot{V}O_{2\,peak}$ and PTRS, the subjects rested for approximately 5–7 min and then performed a familiarisation run on the treadmill in order to minimise a “learning effect” for the subsequent experimental trials. They began the familiarisation trial by running at 70% of PTRS for 1–2 min and then as far as possible in 10 min by adjusting their running speed with a touch-pad on the side arm of the treadmill.

## Experimental trials

Within a minimum of 3, but no more than 7 days following the familiarisation session, the subjects reported to the laboratory for the first of three randomised experimental trials. Each trial was conducted at the same time of day so that the effect of circadian variation could be minimised. During each experiment the rh and wind velocity were kept constant at 60±0.8% and 15±0.6 km·h$^{-1}$, respectively whilst the $T_a$ was set at either 15 ($T_{15}$), 25 ($T_{25}$) or 35°C ($T_{35}$). Ambient temperatures of 15, 25, and 35°C and radiant temperatures ($T_r$) of 13, 23, 33°C, and at 60% rh, resulted in wet bulb temperatures ($T_{wb}$) of 11, 20 and 28°C, respectively [23]. For distance events, the risk of thermal injuries are considered low at wet bulb globe temperatures (WBGTs) of <18°C, moderate at 18–23°C and high at >23°C [33].

Before the experimental trials, the subjects voided, and inserted a rectal thermistor (Mon-a-therm, Mallinckrodt, Ohio, USA) 10 cm beyond the anal sphincter. Four skin thermistors were then secured as previously described [28] and subjects were fitted with a heart rate monitor (Sport Tester, Polar Electro, Oy, Finland). Next a 20-gauge Teflon cannula was inserted in a superficial forearm vein and connected to a three-way stopcock. This cannula was used for the collection of venous blood samples (5 ml) and was kept patent by periodic flushing with 2–3 ml of 0.9% sterile saline containing heparin (5 IU·ml$^{-1}$). Following the collection of a pre-exercise blood sample, body mass was determined with the subject wearing light running shorts and all instrumentation.

The subject then entered the climate chamber and started a sub-maximal run for 30 min at 70% PTRS (range 14.7–16.1 km·h$^{-1}$). Thereafter there was a 5-min interval during which the subject removed socks and shoes and was towelled dry, reweighed and permitted to drink up to 300 ml distilled water. Then the subject ran 8 km (5 miles) as fast as possible by adjusting the running speed. The running speed was noted at the end of each minute and at the end of exercise. A mean running speed was calculated at the end of each 5-min interval and when subjects completed the 8 km. From this an overall mean running speed was calculated for the time taken to complete the run. The changes in body mass were adjusted for fluid ingested and used to calculate total body sweat rates.

Throughout the sub-maximal and 8-km trials, rectal and skin temperatures were monitored continuously with a telethermometer (YSI model 4002, Yellow Springs, Ohio, USA) and recorded at 5-min intervals. Mean skin temperature ($\bar{T}_{sk}$) was calculated as previously described by Ramanathan [28].

## Blood analyses

Blood was only drawn at the beginning and end of the sub-maximal run and at the completion of the 8-km performance run in case it interfered with the runner’s performance. Blood samples were collected into tubes containing lithium heparin and three samples (100 µl) were promptly haemolysed with 20 volumes of distilled water and stored at –80°C for later determination of haemoglobin concentration. Haemoglobin was determined in triplicate using a Beckman DU 62 Spectrophotometer (Beckman, Fullerton, Calif., USA), as described by Hainline [14], and used to estimate the changes in blood volume [9].

## Heart rate and subjective measurements

Heart rate (HR), rating of perceived exertion (RPE) [4] and thermal comfort [2] were recorded at 5-min intervals.

## Heat balance calculations

Assuming similar efficiencies, heat production amounts to approximately 4 kJ·kg$^{-1}$·km$^{-1}$ [25]. Therefore, the rate of heat production ($H$) in J·s$^{-1}$ (or W) equates to the product of the runner’s body mass ($m$, in kg), the running speed ($v$, in m·s$^{-1}$) and ≅4 J produced per kg·m as shown in: Eq. 1:

$$H = m \cdot v \text{ (in kg·m·s}^{-1}) \cdot 4 \text{ (in J·kg}^{-1}\text{·m}^{-1}) \tag{1}$$

The potential rates of heat loss via convection ($C$) and radiation ($R$) were calculated as previously described [21] with Eqs. 2 and 3, respectively while heat storage ($S$) was estimated with Eq. 4:

$$C = (\bar{T}_{sk} - T_a) \cdot v^{0.5} \cdot A_D \cdot 8.3 \tag{2}$$

$$R = (T_{sk} - T_r) \cdot A_D \cdot 5.2 \tag{3}$$

$$S = 0.965 \cdot m \cdot (\Delta \bar{T}_B) \cdot A_D \tag{4}$$

Where:

1. The expression ($\bar{T}_{sk}$–$T_a$) is the difference between mean skin temperature and the ambient air in °C
2. The expression ($\bar{T}_{sk}$–$T_r$) is the difference between mean skin temperature and the mean radiant temperature of nearby surfaces in °C with $T_r$ determined from the temperature of the surface of the climate chamber wall
3. $v^{0.5}$ is the square root of the velocity of air flow (m·s$^{-1}$) over the skin
4. 8.3 is a constant relating heat exchange (J·s$^{-1}$·m$^2$) to the temperature gradient (°C) and the square root of air flow (m·s$^{-1}$) over the skin
5. 5.2 is a constant relating radiation (J·s·m$^2$) to the radiant temperature gradient in °C
6. 0.965 is the specific heat of body tissues (W·kg$^{-1}$·°C$^{-1}$)
7. $m$ is body mass (kg)
8. The expression $\Delta\bar{T}_B$ is the change in mean body temperature over the exercise period calculated from $\bar{T}_B$=00.87 $T_{re}$+0.13 $\bar{T}_{sk}$
9. $A_D$ is body surface (m$^2$)

The heat loss via potential evaporation ($E_P$) was calculated from the predicted sweat rates determined from changes in body mass and the 40.55 kJ·mol latent heat of evaporation of water and its 18 g·mol molecular weight. The evaporation of 1 l of sweat per hour dissipates ≅625 J·s$^{-1}$ assuming that all the sweat is evaporated [8]. The required evaporation ($E_R$) was calculated as the residual component from $H$–$C$–$R$–$S$, where $S$ is the heat storage estimated from Eq. 4.

Statistics

Separate ANOVAs for repeated measures on time and trials (1–3) were applied to determine treatment effects during exercise. The statistics pertaining to avenues of heat loss and storage were analysed by separate ANOVAs for repeated measures on trials (1–3). If a main effect was detected post-hoc comparisons were made with either Tukey's HSD for pairwise comparisons or one-way ANOVA for significant interactions. Comparisons between unequal sample sizes were made using harmonic means. Correlation coefficients and simple linear regressions were used to analyse relationships between physical characteristics, decreases in running speed, heat production and avenues of heat loss. In all cases $n$=16 unless stated otherwise. Significance was accepted at $P<0.05$. All data are presented as mean ±SD.

## Results

Effect of $T_a$ on treadmill running speed

The mean PTRS during the sub-maximal run for each temperature condition was 14.9±0.7 km·h$^{-1}$ (see Fig. 1). During the performance run, 4 of the 16 subjects were unable to complete the test, stopping between 15 and 30 min into the run. During the 8-km performance run, subjects progressively increased their average running speeds at $T_{15}$ (17.8±1.0 km·h$^{-1}$) and $T_{25}$ (17.5±1.0 km·h$^{-1}$). In contrast, at $T_{35}$ the average running speed was lower (15.8±1.5 km·h$^{-1}$, $P<0.05$; see Fig. 1). The times to complete the 8 km at $T_{15}$ and $T_{25}$ were 27.0±1.5 and 27.4±1.5 min, respectively while the completion time for $T_{35}$ was 30.4±2.9 min ($P<0.05$, $n$=12).

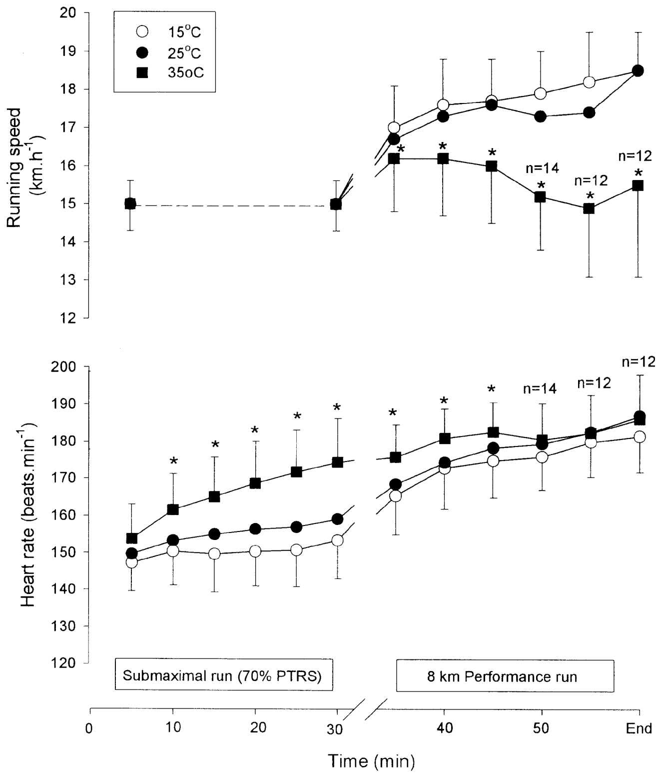


**Fig. 1** **A** Running speed for the sub-maximal and 8-km performance runs in three ambient conditions. Running speed in the sub-maximal run was the same for each condition (*broken line*). Running speeds during the performance run at 35°C were all significantly (*$P<0.05$) reduced compared with those at 15 and 25°C. **B** The heart rate response for the sub-maximal and 8-km performance runs. Heart rates were significantly (*$P<0.05$) higher during the sub-maximal run and up to 45 min into the performance run at 35°C. At all time points $n$=16 unless indicated otherwise

Effect of $T_a$ on blood volume and heart rate

The decreases in blood volume were not different among trials and were approximately 2%, 5% and 6% for $T_{15}$, $T_{25}$ and $T_{35}$, respectively. Despite the similar reductions in blood volume, heart rates were higher at $T_{35}$ than at $T_{15}$ or $T_{25}$ during the sub-maximal run (see Fig. 1). The heart rates at the end of the sub-maximal run were higher at $T_{35}$ (174±12 beats·min$^{-1}$; $P<0.05$) compared with $T_{25}$ (159±10 beats·min$^{-1}$) and $T_{15}$ (153±10 beats·min$^{-1}$; see Fig. 1). However, at the end of the 8-km performance run heart rates were similar at 181±10, 187±8 and 186±12 beats·min$^{-1}$ for $T_{15}$, $T_{25}$ and $T_{35}$ ($n$=12), respectively (see Fig. 1).

Effect of $T_a$ on subjective ratings

At the end of the sub-maximal run the values for RPE were 10±2 and 11±2 at $T_{15}$ and $T_{25}$, respectively and 12±2 at $T_{35}$ ($P<0.05$). During the performance run RPE at $T_{15}$ and $T_{25}$ were similar while RPE at $T_{35}$ was increased at 45 and 50 min ($P<0.05$, $n$=12). The final RPE value was higher for both $T_{25}$ and $T_{35}$ compared with $T_{15}$ ($P<0.05$). As expected the thermal comfort rating increased over time ($P<0.05$) throughout exercise in all conditions. Consequently, thermal comfort ratings were different ($P<0.05$) among trials.

Effect of $T_a$ on $T_{re}$ and mean $T_{sk}$

The pre-exercise $T_{re}$ was similar (36.8°C) among conditions. At 25 min and then at the end of the sub-maximal run $T_{re}$ at $T_{35}$ was higher at 38.5±0.3°C ($P<0.05$) compared with 38.0±0.3°C at $T_{15}$ and 38.1±0.3°C at $T_{25}$. Due to the time interval between the sub-maximal and performance run, $T_{re}$ was lower for each condition 5 min into the performance run than at the end of the sub-maximal run. However, over the remaining time during the performance run $T_{re}$ remained significantly different among conditions with parallel rises of ≅1.2°C evident. At the end of the performance run, $T_{re}$ was different among conditions at 38.6±0.4°C at $T_{15}$, 39.1±0.4°C at $T_{25}$ and 39.5±0.4°C ($P<0.01$, $n$=12) at $T_{35}$. The fact that four subjects were unable to complete the performance run at $T_{35}$ did not have a significant effect on the end of exercise $T_{re}$. That is, $T_{re}$ was no greater in those subjects that stopped compared with those subjects that were able to continue. In addition, the physical characteristics of the subjects that stopped running were not notably different

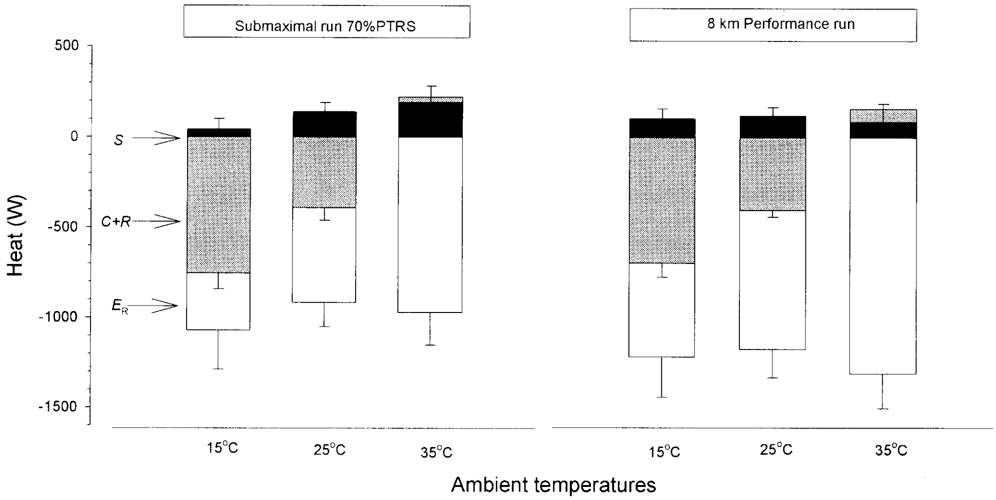


**Fig. 2** The avenues of heat loss and gain during the sub-maximal and 8-km performance runs where *S* is heat storage, *C+R* is convection plus radiation and $E_R$ is required evaporation. Note that during both sub-maximal and performance runs at 35°C, *C+R* resulted in heat gain. In all ambient conditions *S* was limited during the performance run due to the higher *S* achieved during the preceding sub-maximal run

**Table 2** Results of linear regressions for individual temperature conditions for heat storage (*S*) and body mass; and for *S* and $A_D/m$. Where $y=a+bx$, *r* is the correlation co-efficient, NS is not significant

| | Ambient Temperature °C | *y*-intercept (*a*) | Slope (*b*) | *r* | Significance |
|---|---|---|---|---|---|
| Heat storage and body mass | 15 | 28.4 | 0.04 | – | NS |
| | 25 | –16.78 | 2.36 | 0.50 | 0.04 |
| | 35 | –18.86 | 3.17 | 0.74 | 0.0008 |
| Heat storage and $A_D/m$ | 15 | 40.2 | 0 | – | NS |
| | 25 | 527.34 | –14180.3 | –0.42 | 0.05 |
| | 35 | 830.33 | –23392.4 | –0.77 | 0.001 |

from those of the other subjects. Ten minutes after commencing the sub-maximal run, $\bar{T}_{sk}$ remained relatively constant throughout but was significantly ($P<0.05$) different among temperature conditions. Throughout the sub-maximal and performance periods, $\bar{T}_{sk}$ ranged 25–26°C, 31–32°C and 34–35°C for $T_{15}$, $T_{25}$ and $T_{35}$, respectively.

## Effect of $T_a$ on heat balance

### *Sub-maximal run*

Heat production during the sub-maximal run was 1113±180 W. This value was similar for all ambient conditions given that subjects were running at the same speed (i.e. 70% PTRS). The value of *S* during the sub-maximal run increased as $T_a$ increased. At $T_{15}$, $T_{25}$ and $T_{35}$, *S* was 44±57, 141±50 and 193±45 W, respectively and was significantly ($P<0.05$) different among conditions (see Fig. 2). Heat loss by *C+R* at $T_{15}$ was –754±88 W whereas at $T_{25}$ *C+R* was –389±35 W ($P<0.05$). However, Fig. 2 shows that at $T_{35}$ *C+R* resulted in a heat gain of 28±26 W as $\bar{T}_{sk}$ was either similar or above $T_a$. Heat production minus *S*, *C* and *R* gave the required heat loss via evaporation ($E_R$). The value of $E_R$ was –316±219, –527±133 and –949±182 W for $T_{15}$, $T_{25}$ and $T_{35}$, respectively and was different ($P<0.05$) among temperature conditions (see Fig. 2). The value of $E_P$ calculated from mean total body sweat rates was –587±131 W at $T_{15}$ but at $T_{25}$ and $T_{35}$ it was –890±201 W and –1123±261 W, respectively. This resulted in $E_P$ excesses of 46%, 41% and 15% in $T_{15}$, $T_{25}$ and $T_{35}$, respectively.

### *Performance run*

During the performance run, *H* was 1320±195, 1294±192 and 1165±152 W at $T_{15}$, $T_{25}$ and $T_{35}$, respectively, in accordance with a reduced running speed at higher $T_a$ (Fig. 2). In each temperature condition *S* was limited to 107±54, 122±46 and 88±38 W (Fig. 2) for $T_{15}$, $T_{25}$ and $T_{35}$, respectively and was most likely the result of the value of *S* achieved by the end of the sub-maximal run. The heat loss via *C+R* was –694±77 W at $T_{15}$, –398±37 W at $T_{25}$ and at $T_{35}$ *C+R* resulted in a heat gain of 70±40 W. The $E_R$ was –519±227, –771±159 and –1148±193 W for $T_{15}$, $T_{25}$ and $T_{35}$, respectively. The difference between $E_R$ and $E_P$ resulted in $E_P$ excesses of 13% and 15% at $T_{15}$ and $T_{25}$, respectively. However, at $T_{35}$, the $E_R$ was slightly more than $E_P$.

## Effect of physical characteristics on heat balance parameters

The results of the effect of physical characteristics on heat balance parameters are from the sub-maximal run during $T_{35}$ given the need for a fixed running speed for

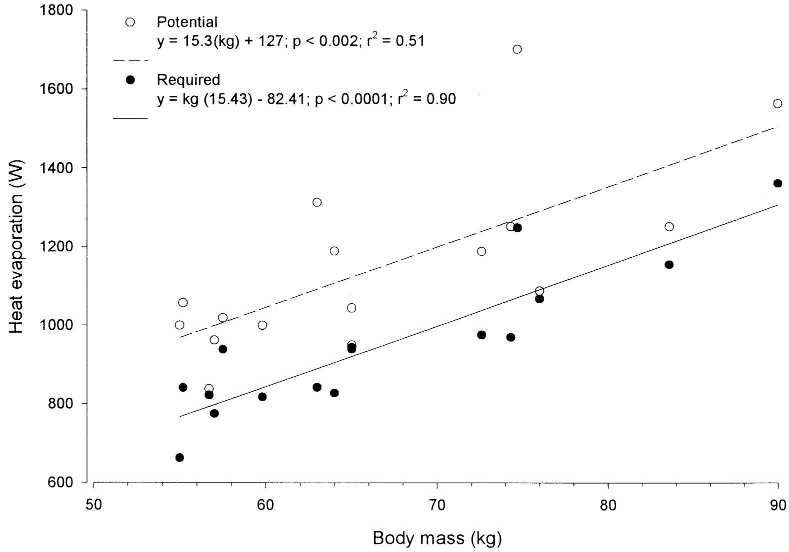


**Fig. 3** The relationship between body mass and required and potential evaporation at 35°C. Note that body mass accounts for only 51% of the variance for potential evaporation whilst body mass accounts for 90% of the variance for required evaporation

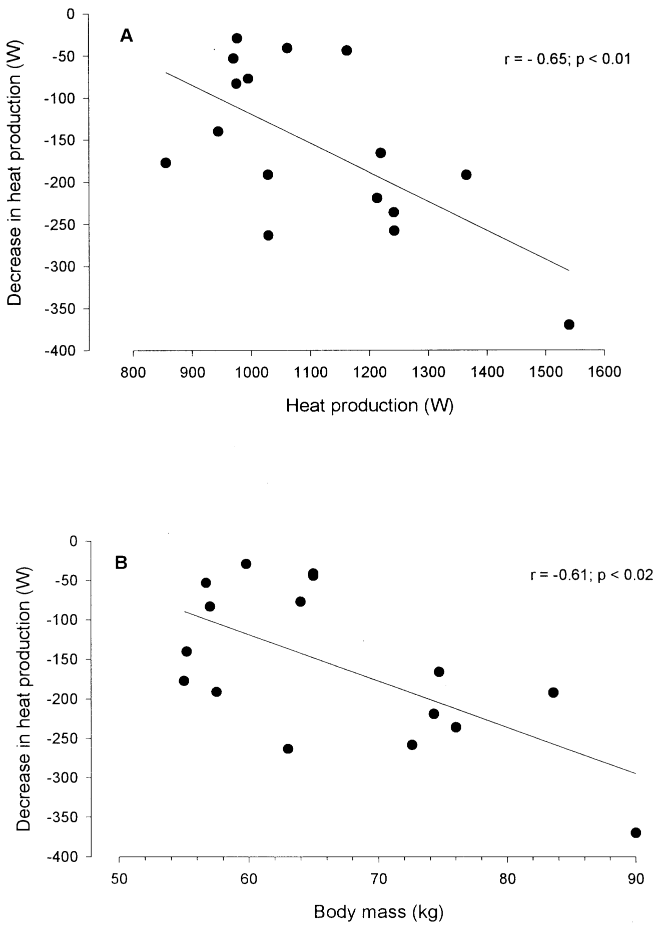


**Fig. 4** The relationships between body mass and heat production with decreases in heat production

different calculations. The regression analyses did not detect any significant relationship between fat mass and $E_P$ ($r$=0.24, $P$=0.37) or $E_R$ ($r$=0.08, $P$=0.74). Similarly, lean body mass was not correlated with either $E_P$ ($r$=0.33, $P$=0.20) or $E_R$ ($r$=0.20, $P$=0.50). However, there was a positive relationship between body mass and both $E_P$ and $E_R$ (Fig. 3). Table 2 shows the results of the regression analyses for $S$ versus body mass and $A_D/m$ for each temperature condition. At $T_{15}$, there was no relationship between body mass and $S$, whereas at $T_{25}$ the relationship between body mass and $S$ was moderate and positive ($r$=0.50, $P$<0.04; Table 2). This relationship was strengthened further at $T_{35}$ ($r$=0.74, $P$<0.0008; Table 2). The ratio of $A_D/m$ resulted in similar relationships with $S$ among the different ambient conditions. Again, at $T_{15}$, a relationship was not apparent while only a moderate inverse relationship occurred at $T_{25}$ ($r$=–0.42; $P$<0.05; Table 2). At $T_{35}$, the relationship between $A_D/m$ and $S$ was strengthened ($r$=–0.77; $P$<0.001; Table 2).

Effect of physical characteristics and heat production on running speeds and rates of heat production at 35°C

No significant relationship was detected for decreases in heat production and either fat mass ($r$=0.14, $P$=0.61) or lean body mass ($r$=0.03, $P$=0.92). However, decreases in $H$ were negatively correlated with the increase in heat production ($r$=–0.65, $P$<0.01; Fig. 4A) and body mass ($r$=–0.61, $P$<0.02; Fig. 4B). The relationships between the mean running speed ($m \cdot s^{-1}$) and body mass in the three ambient conditions are shown in Fig. 5. At 15 and 25°C running speed was not correlated with body mass ($P$>0.05) whilst at 35°C, the mean running speed was significantly correlated with body mass ($y$=6.30-0.0265$x$; $r$=–0.77; $P$<0.0004).

## Discussion

The novel finding of this study is the apparent advantage that runners with a lower body mass have over their heavier counterparts during prolonged exercise under high environmental heat loads. By using highly trained endurance runners with a range of body masses (range

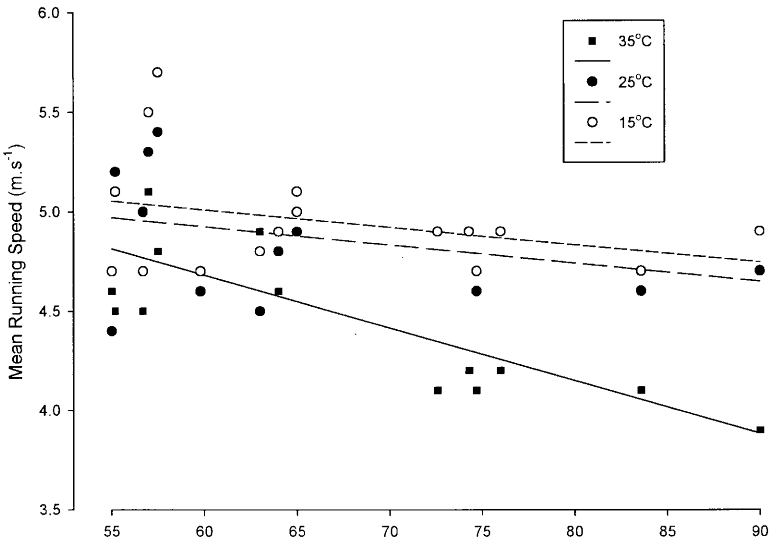


**Fig. 5** The relationship between body mass and the mean running speed during the 8-km performance run in the three ambient conditions. At 15 and 25°C there was no significant correlation. A significant correlation is evident at 35°C (*y*=6.30-0.0265*x*; *r*=0.77, *P*<0.0004)

55–90 kg) it is evident that heavier runners display greater imbalances between heat production and dissipation during prolonged exercise in hot (35°C) humid environments compared with cooler environments of 15 and 25°C. Furthermore, not only do heavier runners display greater imbalances between heat production and evaporation, their decrease in heat production is also greater than that of runners with a lower body mass (Fig. 4). This demonstrates that heavier runners accrue a greater absolute heat load. In addition, it is apparent that heavier runners self-select slower running speeds and that this speed is inversely related to their body mass (Fig. 5) when running in warm humid environments.

The time taken to complete the 8-km performance runs was greater at $T_{35}$ than at $T_{15}$ and $T_{25}$, with the decrement in running performance accompanied by higher values of $T_{re}$ and $T_{sk}$. The higher $T_{re}$ are particularly relevant as it is becoming increasingly evident that high body core temperatures possibly lead to a diminished drive for exercise performance, and this seems to be the case whether or not individuals are heat acclimatised [26]. In the present study, four subjects were unable to complete the performance run at $T_{35}$. However, whether the participants finished the 8-km performance run or not, there was no significant difference in the rise in $T_{re}$. That is, in both finishers and non-finishers, $T_{re}$ did not increase beyond the critically high value of 39.5–40°C that frequently coincides with the termination of exercise in the heat [26]. In addition to the higher $T_{re}$ and skin temperatures, the subjective ratings of thermal comfort were increased relative to the ambient temperatures. Although, RPE values were similar at $T_{15}$ and $T_{25}$ and were significantly higher at $T_{35}$ for the sub-maximal run and for part of the performance run, the difference in heart rates was not significant among conditions at the end of the performance runs. Although this can be partly explained by the higher running speeds achieved at both $T_{15}$ and $T_{25}$ compared with $T_{35}$ (Fig. 1), it is difficult to explain why these athletes would end exercise at similar heart rates for each temperature condition even though the 8-km run time was different for $T_{35}$ compared with $T_{15}$ and $T_{25}$. These heart rate data suggest that heart rate might be a limiting factor in prolonged exercise.

Factors that have been suggested to exacerbate the risks of thermal illness include the WBGT indexes [23, 34], medical history and/or treatment of the individual, and hydration status has also been shown to influence endurance performance [18, 20]. The individual's level of acclimation and training has also been shown to influence exercise performance in the heat [13].

Another factor which is thought to increase thermal strain is body mass. For example, it is well established that obesity has an adverse effect on exercise heat tolerance [16], due to the lower specific heat and lower water content of adipose tissue resulting in a reduced capacity for heat storage. In the present study the fat content was not significantly related to any of the heat balance parameters. This finding might reflect the fact that the participants in the study were all highly trained endurance runners with similar levels of relative body fat. This is not unlike data reported previously [15], where it was found that neither skinfolds nor percent body fat was correlated with heat storage. Similarly, a high mesomorphic component was also shown to augment thermal strain, presumably due to the increased distances for heat transfer to the body surfaces [17]. However, because heat production during running depends on body mass (Eq. 1) and heat loss depends on $A_D$ (Eqs. 2 and 3), a runner's body mass has an approximately twofold greater effect on heat production than on heat dissipation. These factors have been shown to be important determinants of work efficiency and heat tolerance [11]. Additionally a low $A_D/m$ ratio is thought to be an unfavourable characteristic if physical work is to be carried out in the heat. The present results clearly indicate that a high $A_D/m$ ratio is advantageous as $T_a$ rises from 15 to 35°C with respect to heat storage (Table 2). Hayward et al. [17], in their assessment of physique and thermoregulation in warm humid conditions, found that when the $A_D/m$ ratio was less than 0.024 $m^2 \cdot kg^{-1}$ thermal strain was significantly increased. As can be seen from the regression analyses (Table 2) heavier subjects experienced significantly greater thermal strain than lighter runners due to their lower $A_D/m$ ratio. More importantly, however, the regression analysis shows that the level of heat storage becomes increasingly dependent on body mass as the ambient temperature rises.

The effect of body mass on heat storage at 15°C was not apparent as indicated by the horizontal slope of the regression line. However, the slope and significance of the regression line increased as the $T_a$ rose to 35°C. The $A_D/m$ ratio also plays a major role in heat dissipation, particularly if $E_R$ is close to $E_P$ [11]. That is, the more $A_D$ per unit mass available for evaporation the less the thermal strain. The present results show that $E_R$ was less than $E_P$ during the sub-maximal run in each of the temperature conditions, but that differences between $E_R$ and $E_P$ were reduced during higher compared with lower $T_a$. Interestingly, during the 8-km performance run at $T_{15}$ and $T_{25}$ the differences between $E_R$ and $E_P$ were substantially reduced. However, at $T_{35}$ $E_R$ was higher than $E_P$ indicating a greater imbalance between heat production and total body sweat rates. Most likely, at $T_{35}$ compared with $T_{15}$ and $T_{25}$, a greater portion of the sweat produced dripped off the body rather than evaporating. This effect of reduced evaporation through increased drippage of sweat would compromise thermoregulation under these conditions. However, according to the present data, even if all the sweat produced evaporated it would still not be sufficient to compensate for the greater required evaporation in warm humid conditions. In addition, the fact that heavier runners sweated more did not compensate them for their higher rate of heat production. Further to this point, when body mass is plotted against decreases in heat production during running at $T_{35}$ (Fig. 4), it becomes apparent that heavier runners reach a “heat storage limit” sooner than do lighter runners. That is, heavier runners have a reduced capacity to continue to produce heat beyond a critical limit and at a rate that would enable them to match the speed of runners with a smaller body mass.

The proposition of a “heat storage limit” has not been previously dealt with in any great detail. A heat storage limit has been demonstrated by Taylor and Rowntree [35] using a running cheetah as a model. At high running speeds 90% of heat produced was stored by the cheetah. Hence, the duration of the cheetahs’ sprint is determined by the amount of heat it is able to store before reaching a limiting body temperature. However, because the cheetah is a small animal (34–44 kg) it is able to store large amounts of heat and, unlike sprinters, long distance runners cannot continue to use heat storage without reaching high internal temperatures [35]. Therefore, body mass becomes increasingly important in distance events when ambient conditions are hot and water vapour pressure gradients are reduced. According to the present results, body mass is the best predictor of a decrease in heat production and running speed during distance running in warm humid environments. As heat storage depends on body mass and surface area, a heavier runner will be more disadvantaged in races run in warm humid conditions.

In addition to the present findings, the observations pertaining to actual race performances provide strong evidence that heavier runners are disadvantaged in warm humid environments. For example, finishing times of marathon races at $T_a$ of 20–25°C are 6–10% slower compared with marathons run at a $T_a$ of 10–12°C [6, 12]. In fact, the current world record marathon times for men (2 h:06 min: 50 s) and women (2 h:21 min:06 s) were both set at a $T_a$ of 10–12°C.

A follow-up analysis of the effects of heat stress on performances during the 1996 Olympic Games concluded that heat stress did not reach levels that would compromise thermal balance; that is 35°C, rh>60% [34]. In fact, records were set for both men and women for running and walking races of 5 km or longer. In contrast, the times for these events were significantly increased during the previous Olympics in Barcelona. The evidence indicates that the Barcelona Olympics were conducted in more severe ambient conditions [34]. Interestingly, however, the winner of the men’s 1996 Olympic marathon was 1.58 m tall and weighed a mere 45 kg [7] with an $A_D$ of 1.42 $m^2$. According to the model presented, an individual with these physical characteristics should be able to run at ≅18.4 $km \cdot h^{-1}$, and because of their high $A_D/m$ ratio (0.031 $m^2 \cdot kg^{-1}$) is able to store body heat at a slower rate than a heavier runner. This evidence indicates that there may be an optimal body mass suited to marathon or distance running. An analysis of the data on heights and masses of males winning the Boston Marathon indicates that these characteristics have remained relatively constant for over a century [27]. That is, the mean height is 171.3±5.4 cm and mass is 61.6±5.1 kg [27]. These data are in contrast to the secular trend of the general population, which indicates an increase in height of about 1 cm per decade [27].

The present findings suggest that heavier distance runners may indeed experience some form of cumulative heat stress. If so, this may also explain why male and female runners with a lower body mass can progressively compensate for their lower peak work rates by running at higher relative exercise intensities over increasing race distances [1, 5]. Hence, at any given speed the absolute metabolic heat production of smaller competitors will be less than that of the heavier runners. This may be one reason why smallness is an asset in distance running.

In conclusion, the data indicate that runners with a lower body mass have a distinct advantage compared with heavier runners in distance races run in conditions where heat dissipation mechanisms are at their limit. It seems that the capacity to continue to produce heat is a critical aspect of running long distances in humid heat and that this is at least in part related to the size (mass) of the runner.

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