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Influence of Lean Body Mass on Performance Differences of Male and Female Distance Runners in Warm, Humid Environments

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ABSTRACT The purpose of this investigation was to evaluate the influence of lean body mass (LBM) and body weight (BW) on the thermoregulatory responses and endurance performance of male and female athletes in warm, humid environments. Ten (5 males, 5 females) healthy, moderately trained athletes with varying physiques performed a self-paced 30-min run on a motorized treadmill in warm (30°C), humid (60% relative humidity) conditions, with the aim of running the greatest distance possible. Males completed one trial, while females completed two trials, one in each of the follicular (Fol) and luteal (Lut) phases of the menstrual cycle in a randomized fashion. There were no significant differences among groups for distance run (males, 5.2 ± 0.4 km; Fol, 4.9 ± 0.1 km; Lut, 4.7 ± 0.1 km). However, following analysis of covariance accounting for LBM and BW, the distances run were significantly different. The adjusted means for distance run after accounting for LBM were 3.4 km for males ($P < 0.05$), 5.9 km for Fol, and 5.6 km for Lut. Adjusted means accounting for BW resulted in run distances of 6.5 km for males ($P < 0.05$), 4.2 km for Fol, and 4.0 km for Lut. Thermoregulatory responses such as rectal and skin temperatures were similar among groups. Avenues of heat loss and gain were altered relative to the menstrual cycle phase. The results suggest that one reason for the disparity in performance between male and female athletes over similar race distances might in part be related to unequal body characteristics and in particular to differences in LBM. Am J Phys Anthropol 118:285–291, 2002.

The disparity between male and female performances in endurance events has attracted a great deal of attention. Recent evidence of world record times for men and women over the last 16 years, for distances of 1,500 m to 42.2 km, indicates that the gap between the sexes has not narrowed (Sparling et al., 1998), despite evidence that at ultramarathon distances women might outperform men (Bam et al., 1997). However, evaluation of performance differences between males and females exercising in warm, humid environments has yielded conflicting results. Early comparisons of thermoregulatory responses suggested that men displayed a greater heat tolerance. However, when males and females matched for aerobic fitness were compared using relative workloads, thermoregulatory differences were less pronounced (Drinkwater et al., 1976). It is suggested that this is partly due to females being advantaged by their smaller body size, greater surface area per unit of body mass, and lower sweat rate (Frye and Kamon, 1981). In contrast, men are unable to benefit from their higher sweat rate due to the reduced evaporative capacity of humid air, although given similar acclimation, women respond in a similar way to men with respect to core temperature and sweating responses (Frye and Kamon, 1981).

Few studies have considered the physical characteristics of individuals as determining factors for performance and the development of thermal strain. Body fat has been the most studied physical characteristic when comparing men and women in a variety of athletic settings, while little attention has been given to the individual components of lean body mass (LBM) and body weight (BW). This is surprising, given that the greater proportion of LBM is skeletal muscle and is largely responsible for heat generation. Futhermore, BW comprises both LBM and body fat, which for females is unlikely to be an

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TABLE 1. Mean ± SE physical characteristics of male and female participants[1]

Subjects	Age (years)	Height (cm)	Weight (kg)	A_D (m^2)	$A_D \cdot kg^{-1}$ ($m^2 \cdot kg^{-1}$)	%BF	LBM (kg)	VO_{2peak} ($mL \cdot kg^{-1} \cdot min^{-1}$)
Mean (F)	20.6	168.0*	60.2*	1.68*	0.028*	19.2	48.7*	51.0
SE	0.75	2.35	0.62	0.01	0.0004	1.76	1.15	1.90
Mean (M)	25.0	184.4	80.8	2.04	0.025	15.7	65.3	59.2
SE	1.62	3.78	4.3	0.07	0.0005	1.37	3.18	3.80

[1] F, female; M, male; A_D, body surface area; A_D/kg, surface area to mass ratio; %BF, percent body fat; LBM, lean body mass; VO_{2peak}, peak oxygen consumption.
* $P < 0.01$ compared with males.

advantage during distance running (Bar-Or et al., 1969). To date only one study (Hayward et al., 1986) reported that the rate of increase in rectal temperature (T_{re}) was greater for subjects with a high mesomorphy (LBM) component while walking at 7 $km.hr^{-1}$ in 30°C and 80% relative humidity (rh). In contrast, others reported that the increase in T_{re} and body heat storage (S) while exercising in the heat (35°C; 60% rh) were inversely related to body mass (Havenith et al., 1995). From these two studies, it is not possible to draw conclusions regarding performance outcomes or whether differences in body characteristics between males and females impact on performance during exercise in warm, humid environments.

Recently, it was suggested that heavier runners are unable to maintain thermal balance in warm, humid conditions compared with their lighter counterparts, implicating large body size as a disadvantage (Dennis and Noakes, 1999). In fact, Marino et al. (2000) showed that lighter runners produce and store less heat compared to heavier runners at similar running speeds, and hence can run faster before reaching a limiting core temperature. However, in this study all participants were males (n = 16), the % body fat was not different among runners, and the LBM had no significant effect on heat balance parameters, probably because of the homogeneity of the elite participants. In addition to these limitations, the female menstrual cycle is also thought to influence thermoregulation during exercise (Stephenson and Kolka, 1993). It is generally accepted that women have a higher basal core body temperature (~0.4°C) during the luteal compared with the follicular menstrual phase (Stephenson and Kolka, 1993). This is thought to disadvantage females during the luteal phase, due to the reduced capacity to store heat and hence limit the rise in core temperature during exercise. To date, there are no studies that have evaluated the relationship between running performance, LBM, and BW between males and females in warm, humid environments while considering the menstrual phase of the female runners.

Therefore, the purpose of this investigation was to examine to what extent the physical characteristics of LBM and BW might account for differences in endurance performance between males and females in warm, humid conditions.

MATERIALS AND METHODS

Subjects and experimental design

Ten subjects (5 males and 5 females) aged 19–30 years participated in the study. The mean physical characteristics of each subject are given in Table 1. All subjects were apparently healthy, having completed a health history questionnaire and an incremental treadmill run to volitional exhaustion. Compared with male subjects, the females did not differ significantly in cardiorespiratory fitness or percent body fat, but did differ significantly in stature, weight, surface area, and lean body mass. As such, the sample comprised of trained runners who participated regularly in competion. The experiment was approved by the Ethics in Human Research Committee of Charles Sturt University, and each participant signed a letter of informed consent following an explanation of the procedures and risks involved. All subjects abstained from strenuous exercise, and from consumption of alcohol and caffeine for at least 24 hr prior to attending the laboratory. During the months of data collection, subjects were permitted to continue exercising but were required to standardize exercise, eating, and drinking routines in the 24 hr prior to each experimental session.

Initially, each subject attended the laboratory to be familiarized with the testing apparatus and measurement of anthropometrical data, and to complete an incremental test to exhaustion. The incremental test was performed on a motorized treadmill (Quinton Instrument Co., Bothell, WA). The protocol began with subjects walking at 5 $km.hr^{-1}$ on a gradient of 4%. The speed was increased every minute by 1 $km.hr^{-1}$ until the subjects could no longer maintain pace. Throughout the incremental tests, subjects breathed through a two-way nonrebreathing valve (Hans Rudolf, St. Louis, MO), and expired air passed through respiratory tubing to a mixing chamber of 5.5 l, sampled at 30-sec intervals by an automated gas analyzer (Quinton Instrument Co.). Peak oxygen consumption (VO_{2peak}) was determined as the highest VO_2 ($ml.kg^{-1}.min^{-1}$) obtained over a 1-min interval. Following this session, the male subjects attended one experimental session, while females attended two experimental sessions: one in each of the follicular (Fol) and luteal (Lut) phases of the menstrual cycle in a randomized fashion. This was done to account for the possible differences in thermoregulatory responses during each of the menstrual phases. In order to determine the menstrual phase and sequencing of tests, the female participants were given a calendar and instructions to record information regarding their menstrual cycle by marking on the calendar when their days of menstrual flow occurred for the months of July, August, and September. In addition, discomforts and irregularities associated with menstrual flow were documented. Three female subjects reported taking low-dosage triphasic oral contraceptives. None reported any menstrual irregularities, and all subjects experienced a regular menstrual cycle (range, 27–32 days).

Before commencing the experimental run, subjects were weighed nude, a rectal thermistor was inserted, and a heart rate transmitter strap and skin thermistors were secured. Next, subjects entered the climate chamber and were prepared for running. During the experimental sessions, subjects were required to complete a 30-min self-paced treadmill run with the gradient set at 4%, the aim being to run the greatest distance possible in the allotted time. All experimental sessions were conducted at the same time of day for individual subjects in 33°C and 60% relative humidity (rh), with wind speed of 3 $m.s^{-1}$. Subjects were permitted to drink a maximum of 300 ml of tap water during the run, to minimize the effects of dehydration. To minimize the effects of fatigue and acclimatization, all testing was separated by a minimum of 3 days for males and 14 days for females. It was assumed that subjects were not naturally heat-acclimatized, as the average daily temperature and rh were 7–26°C and 54–70%, respectively, during the preceding 3 months.

Anthropometric measurements

During the initial visit to the laboratory, height was recorded to the nearest 0.1 cm and body weight to the nearest 10 g, using a precision stadiometer and electronic balance, respectively (HW-100KAI, GEC, Avery Ltd., Australia). Body surface area (A_D) was determined by the method of DuBois and DuBois (1916). Body density was calculated by standard hydrostatic weighing methods, and percent body fat (%BF) was determined by the equation of Siri (1961). Residual lung volume was estimated from a measurement of vital capacity, as previously described (Morrow et al., 1986). Lean body mass (LBM) was estimated with Equation 1:

$$\mathrm{LBM(kg)} = \text{body weight} - \text{body fat}. \qquad (1)$$

In addition to the anthropometric measurements, each subject completed a familiarization treadmill run in order to minimize any learning effect during the subsequent experimental trials.

Temperature measurements and heat balance calculations

Rectal temperature (T_{re}) was monitored as an index of core temperature by a 12-gauge disposable rectal thermistor (Mon-a-therm, Mallinckrodt Medical, Inc., St. Louis, MO) inserted 10 cm beyond the anal sphincter. Skin temperature was measured at four sites using thermistors (427 series, YSI, Yellow Springs, OH) placed on the left side of the body, and mean skin temperature ($\bar{T}_{sk}$) was calculated as previously described (Ramanathan, 1964). The skin and rectal thermistors were connected to an eight-channel telethermometer (Zentemp 5000, Zencor Pty. Ltd., Australia) and monitored continuously during exercise. Potential rates of heat loss via convection (C) and radiation (R) were estimated with Equations 2 and 3 (Kerslake, 1972):

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

$$R = (\bar{T}_{sk} - T_r) \cdot A_D \cdot 5.2, \qquad (3)$$

where ($\bar{T}_{sk} - T_a$) is the difference between mean skin temperature and the ambient air in degrees Celsius, $v^{0.5}$ is the square root of the velocity of air flow over the skin in $m.s^{-1}$, A_D is the body surface area in m^2, 8.3 and 5.2 are constants relating heat exchange in $J.s.m^2$, and ($\bar{T}_{sk} - T_r$) is the difference between mean skin temperature and mean radiant temperature of the walls of the climate chamber.

Heat production (H) in watts (W) was calculated using Equation 4 (Nielsen, 1996):

$$H = kg \cdot m.s^{-1} \cdot 4J.kg^{-1}, \qquad (4)$$

where kg is the body weight, $m.s^{-1}$ is the running speed, and 4 is the approximate heat in Joules produced per kilogram. The rate of heat storage (S) was calculated from Equation 5 (Lee and Haymes, 1995):

$$S = 0.97 \cdot m(\Delta\bar{T}_b/dt) \cdot A_D^{-1}, \qquad (5)$$

where 0.97 is the specific heat of body tissue in W, m is the body weight in kg, $\Delta\bar{T}_b/dt$ is the change in mean body temperature during exercise estimated from a weighted combination of $\bar{T}_{sk}$ and T_{re} ($\bar{T}_b - T_{re} \cdot 0.65 + \bar{T}_{sk} \cdot 0.35$; Burton, 1935). The potential heat loss via evaporation was calculated from the predicted sweat rates where 1 l of sweat per hour dissipates ∼625 W. The required evaporation was then calculated as the residual component from H-C-R-S. Sweat rates were estimated from the change in nude body mass, corrected for fluid ingestion and urine output.

Heart rate measurements and rating of perceived exertion

Heart rate (HR) was monitored continuously and recorded at 5-min intervals during the run with a heart rate monitor (Polar Vantage, Oy, Kempele, Finland). Ratings of perceived exertion (RPE) were recorded at 5-min intervals during exercise, using the 6–20 point scale of Borg (1982).

Statistical analysis

All statistical analyses were performed with SPSS version 10.0 software. Univariate analysis of variance did not reveal a significant interaction between

TABLE 2. Actual and adjusted run distances (km) for each group[1]

	Actual distance (km)	Adjusted distance (km) (LBM)	Adjusted distance (km) (BW)
Males	5.20 ± 0.42	3.47 ± 0.70	6.53 ± 0.65**
Females (follicular)	4.90 ± 0.13	5.93 ± 0.42*	4.24 ± 0.43
Females (luteal)	4.74 ± 0.20	5.65 ± 0.44*	4.03 ± 0.38

[1] Values are means ± SE, LBM is lean body mass, BW is body weight.
* $P < 0.05$ compared with males.
** $P < 0.05$ compared with both female groups.

the covariate and the independent variable and, therefore, the assumption for analysis of covariance (ANCOVA) was met (Hazard-Munro, 2001). The effect sizes for different variables were calculated according to the procedures outlined by Portney and Watkins (1993, p. 651–667) and were found to range between 0.40–1.41. The total sample size was estimated to range between N = 7–9 for independent comparisons and N = 10–14 for analysis of variance. Independent repeated-measures ANCOVA correcting for LBM and BW were performed when comparing males with females. When a significant main effect for a covariate was detected, the mean (y) was adjusted, using Equation 6 (Shavelson, 1996):

$$y = \bar{y} - bw(\bar{x}_j - \bar{x}_G), \qquad (6)$$

where $\bar{y}$ is the unadjusted mean of the group, bw is the pooled within-group regression coefficient, $\bar{x}_j$ is the mean of the covariate for the group, and $\bar{x}_G$ is the grand mean of the covariate. The sources of significant differences were located using Tukey's HSD post hoc test. Independent *t*-tests were used where appropriate. The level of significance was set at $P < 0.05$. All values are reported as the mean ± standard error of the mean (SE).

RESULTS

Exercise performance and oxygen consumption

The results of the distances run are shown in Table 2. The actual distances run were not significantly different between males and females in either phase of the menstrual cycle. However, when distances were adjusted to account for LBM, females outperformed males regardless of menstrual cycle phase. The differences were 2.56 km more in the follicular phase, and 2.25 km more in the luteal phase. Conversely, when adjusting distances to account for BW, males outperformed females by 2.31 km in the follicular phase and 2.45 km in the luteal phase. The VO_{2peak} values were not significantly different between males and females (59 vs. 51 $mL.kg^{-1}.min^{-1}$, respectively).

Thermoregulatory responses and heat balance

Males and Fol females started exercise with a similar T_{re} of 37.42 ± 0.28°C. The end of exercise T_{re} was significantly increased from preexercise values for males to 39.20 ± 0.12°C ($P < 0.05$), and for Fol females to 39.30 ± 0.10°C ($P < 0.05$). For Lut females, T_{re} at the start of exercise was higher (37.7°C; $P < 0.05$) than the starting T_{re} of males and Fol females, indicating that females were in the luteal phase of the menstrual cycle. Despite the higher starting temperature, the end of exercise T_{re} for Lut females were similar to those for males and Fol females at 39.20 ± 0.01°C (change in T_{re} from starting, $P < 0.05$). Other than the difference at the start of exercise, T_{re} was similar among conditions throughout exercise. The overall mean skin temperatures during the run were 34.1 ± 0.3°C for males, 33.5 ± 0.9°C for Fol females, and 34.3 ± 0.5°C for Lut females, and were not significantly different among groups. The only difference in individual mean skin temperatures became apparent at 20–30 min of exercise, when the females in the follicular phase had a lower ($P < 0.05$) mean skin temperature compared with males and Lut females.

Sweat rates were not different between menstrual phases at 0.30 ± 0.04 $l.hr^{-1}$ and 0.25 ± 0.04 $l.hr^{-1}$ for Fol and Lut, respectively. However, the sweat rate for males was 0.51 ± 0.1 $l.hr^{-1}$ and significantly ($P < 0.05$) greater compared with females for all trials. Figure 1 shows the combined avenues of heat loss and gain during the performance run for each group. The combined values for heat loss via C + R were significantly higher for Lut females (−90.35 ± 0.22 W; $P < 0.05$) compared with males (−52.20 ± 0.52 W) and Fol females (−34.90 ± 0.25 W). Males required significantly more heat to be lost through evaporation (−780.80 ± 0.21 W; $P < 0.05$) compared with Fol females (−511.85 ± 0.10 W) and Lut females (−450.73 ± 0.10 W). No differences in required evaporation were observed between menstrual phases. S was similar among conditions. For males, S was 77.70 ± 8.0 W, for Fol females S was 85.90 ± 5.0 W, and for Lut females S was 60.0 ± 12.3 W.

Heart rate and RPE

Heart rate was similar among conditions throughout the exercise period. At the conclusion of exercise, heart rates were 190 ± 3, 191 ± 2, and 189 ± 6 $beats.min^{-1}$ for males, Fol females, and Lut females, respectively. As a percentage of maximal heart rate, these values correspond to 96%, 97%, and 96%, respectively. The RPE values reported by male participants were significantly higher at up to 25 and 30 min of exercise compared with females in either part of the menstrual phase. Final RPE values were 15 ± 1, 15 ± 1, and 16 ± 1 for males, Fol females, and Lut females, respectively.

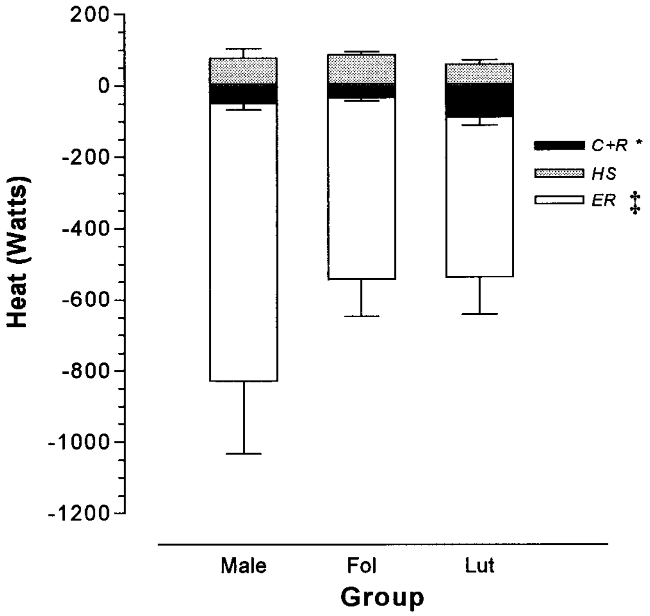

Fig. 1. Avenues of heat loss and gain during 30-min self-paced treadmill run. HS, heat storage; C + R, convection plus radiation; ER, required evaporation. Groups are of males, follicular females (Fol), and luteal females (Lut). $^{*}P < 0.05$ Lut compared with males and Fol. $^{\ddagger}P < 0.05$ males compared with Fol and Lut.

DISCUSSION

Previous studies investigating the differences between male and female endurance competitors indicated that males outperformed females (Sparling et al., 1998). However, many studies used exercise protocols at either fixed workloads or exercise to exhaustion. In contrast, competitive events do not require these constant or fixed workloads, but rather the intensity varies in a random way. In the present study, a self-paced running protocol was used, and differences in performance were observed between males and females but not between females in either part of their menstrual phase. The significantly smaller LBM of females compared with males (48.7 vs. 65.3 kg) is able to account for the adjusted difference in distance run over 30 min in warm, humid conditions. That is, when distances run are corrected for LBM as a covariate, females outperform males by ~2.3 km, independent of menstrual phase. Conversely, when distances are corrected for BW, males outperform females, indicating that females are disadvantaged by their absolute BW.

Some previous studies (Frye et al., 1992; Burse, 1979; Fox et al., 1969; Morimoto et al., 1967) examining the thermoregulatory responses during exercise between male and female athletes under similar environmental conditions neglected to account for the potential influence of the female menstrual cycle. However, other studies (Frye and Kamon, 1981; Avellini et al., 1980; Shapiro et al., 1980) recognized the potential influence of hormonal changes to thermoregulation during exercise, and attempted to account for these changes in the experimental design. For example, resting T_{re} is usually 0.4°C higher during the luteal phase of the menstrual cycle, and has been thought to contribute to the reduced exercise endurance of female athletes during this time. In the present study, however, Lut females did not significantly underperform compared with Fol females. Interestingly, final rectal temperatures were similar for Fol, Lut, and males, indicating that running intensity might be regulated by level of thermal strain. It was recently postulated that an athlete can only store a limited amount of heat before being forced to reduce exercise intensity or stop the exercise bout (Noakes, 2000). The phenomenon of a critical limiting body temperature has been observed in a range of mammalian species (Fuller et al., 1998; Fruth and Gisolfi, 1983; Caputa et al., 1986; Nielsen et al., 1993). The mechanism responsible for reduced performance when high internal temperature ensues has yet to be clearly delineated, although it is hypothesised that a reduced motor drive is likely to play a part. Recently, Kay et al. (2001) showed that pacing during exercise might be regulated by a subconscious mechanism so that the organism is able to avoid cellular death as a result of hyperthermia. Indirect evidence for this hypothesis comes from precooling studies, where reduced thermal strain accounts for increased running and cycling performance (Booth et al., 1997; Kay et al., 1999).

Another factor that may have contributed to similar thermoregulatory responses among conditions was the fact that three of the females were taking oral contraceptive preparations, which provide consistency in hormonal and thermoregulatory responses during exercise (Rogers and Baker, 1997; Grucza et al., 1993). On balance, however, performances in the present study between females in either of the menstrual phases is not dissimilar to performances in previous studies (LeBrun, 1993) which also discounted the possibility of differences in metabolism due to oral contraceptives (Bailey et al., 2000).

Whereas heat production during running depends on body mass and heat loss depends on surface area and air velocity over the skin, a smaller stature with a relatively larger surface area; characteristic of female athletes, appears advantageous in events where the body mass must be carried over long distances (Kerslake, 1972). Therefore, when comparing males and females with different body sizes it is important to consider avenues of heat loss and gain. For example, the males in the present study had a significantly lower ratio of surface area to mass compared with the females (0.025 vs. 0.028 $m^2.kg^{-1}$) and, therefore, were less likely to maintain thermal equilibrium due to a reduced capacity to dissipate heat to the environment (Epstein et al., 1983; Marino et al., 2000). Although heat storage among the groups was similar, Lut females were able to take advantage of heat loss via C + R, albeit with a reduced required evaporation compared with males and Fol females. Interestingly, the

Fol females were unable to take advantage of heat loss via C + R coupled with higher heat storage. This result could be due to the Fol females starting the exercise bout with a significantly lower rectal temperature, thereby increasing the capacity to store heat. However, another reason might be that women, during the luteal phase of their menstrual cycle, have a higher threshold for the onset of sweating (Kolka and Stephenson, 1985), and hence will need to maintain thermal equilibrium through means other than evaporation of sweat. Previous research showed that persons with a higher surface area to mass ratio have a distinct advantage in heat loss via C + R when evaporation of sweat is limited or diminished (Shvartz et al., 1973). It follows that if the threshold for the onset of sweating is increased, then a higher surface area to mass ratio would be advantageous for heat loss via C + R. As shown in Figure 1, Lut females had an increased heat loss via C + R compared with Fol females and males. This supports the proposition that Lut females took advantage of heat loss via C + R due to their high surface area to mass ratio.

Although females have been shown to have a lower sweat rate compared with men even following acclimation (Avellini et al., 1980), the males in the present study had a greater required evaporation but this was unable to compensate them, as the majority of sweat was probably lost through drippage, given the high humidity. A higher sweat rate is advantageous in dry heat, but in conditions where the vapor pressure gradient is reduced (rh > 60%), as in the present study, a higher sweat rate will not compensate for the absolute heat gain (Nielsen, 1996).

An observation from the present study that may also help explain the performance difference of males and females is the relationship between oxygen consumption and LBM. The data from Table 1 indicate that females have about 25% less LBM than males. Lean body mass is predominantly comprised of muscle and skeletal mass and, according to published data, skeletal mass is approximately 6.81% of LBM for males (Friedl et al., 1992) and 4.96% for females (Baumgartner et al., 1991). Taking the data from Table 1 and correcting for skeletal mass, the LBM is 60.8 and 46.3 kg for males and females, respectively. Clearly, females have a smaller muscle mass. For the purpose of illustration, if one considers the difference in LBM together with the peak oxygen uptake values (Table 1), then the rate of oxygen uptake per kg of LBM for males is 77 $\text{ml.kg}^{-1}.\text{min}^{-1}$ ($4.7\ \text{l.min}^{-1} \div 60.8$ kg). In contrast, the rate of oxygen uptake for the females is 65 $\text{ml.kg}^{-1}.\text{min}^{-1}$ ($3.0\ \text{l.min}^{-1} \div 46.3$ kg). This difference shows that females in the present study have less muscle for a lower peak oxygen consumption in order to transport their body weight. In accordance with this model are the data of Cureton and Sparling (1980), who compared the running performance of females to males by increasing the weight of the males by the same amount of fat weight of the females in the study. Even when increasing the dead metabolic weight of the males, it did not hinder them from outperforming the females in absolute terms. Therefore, even when body fat was equalized, men were still able to run faster or longer due to higher peak oxygen consumption at higher running speeds. In addition to this evidence are the data of Cureton et al. (1986), who showed that males still outperform females even when the oxygen-carrying capacity of blood was reduced to match that of females.

In addition, it seems that the present females are inherently more efficient than their male counterparts. That is, when corrected for LBM, females outperform males with less oxygen consumption per kg of LBM. The reasons for better efficiency in these females are not clear; however, one possible reason might be related to size. Generally, endurance competitors are small and have lighter body masses, which is particularly the case for females (Bam et al., 1997; Speechly et al., 1996). Speechly et al. (1996) studied female and male endurance runners matched for 42.2-km performance and found that female subjects outran their male counterparts over 90-km distances. However, the better performance by females could not be attributed to a higher $\text{VO}_{2\text{peak}}$, running economy, or endurance training. These authors did not consider size as an alternative reason for better performance of the females, even though the differences between males and females for mass and LBM were 15 and 15.2 kg, respectively. These data, coupled with those of Marino et al. (2000), provide an alternative hypothesis, which suggests that smaller individuals produce and store less metabolic heat compared with larger individuals, and are therefore able to attenuate the rate of rise in body core temperature. Thus, in the present study, the females were able to utilize their relative leanness with less oxygen consumption per kg LBM and less metabolic heat production to “outperform” the males.

Finally, an evolutionary perspective suggests that differences between males and females might be explained by structural deviations. For example, compared with males, females have a diminished range of motion about the hip, and for a given length of stride, females are required to rotate the hip through a greater range of motion than males (Napier, 1967). This would no doubt require greater energy. In order to compensate for the higher energy cost, females might need to employ more efficient oxygen consumption during locomotion. However, this hypothesis needs further development and testing.

This study is not the first to show that females might be able to outperform men in endurance events. However, it is not our contention that females will surpass males in endurance events. Rather, the present findings suggest that the reasons for the disparity in performance between males and females, at least under warm, humid conditions, might in part be related to the size of the individual.

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