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RESEARCH ARTICLE

Running economy in recreational male and female runners with similar levels of cardiovascular fitness

Goncalo V. Mendonca,[1,2] Pedro Matos,[1] and Joana M. Correia[1,2]

[1]*Neuromuscular Research Lab, Faculdade de Motricidade Humana, Universidade de Lisboa, Cruz Quebrada, Dafundo, Portugal; and* [2]*CIPER, Faculdade de Motricidade Humana, Universidade de Lisboa, Cruz Quebrada, Dafundo, Portugal*

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Mendonca GV, Matos P, Correia JM. Running economy in recreational male and female runners with similar levels of cardiovascular fitness. *J Appl Physiol* 129: 508–515, 2020. First published July 23, 2020; doi:10.1152/japplphysiol.00349.2020.—This study explored differences in running economy between well-conditioned young male and female (tested within the early follicular phase of their menstrual cycle) participants, matched for age and percent difference between predicted and actual maximum oxygen uptake ($\dot{V}O_{2max}$). Twenty-five recreational runners (13 men and 12 women), aged 19–27 yr, performed graded treadmill exercise to assess $\dot{V}O_{2max}$. Participants also performed three bouts of submaximal continuous treadmill running at 8, 10, and 12 km/h. Sex comparisons revealed lower maximal aerobic speed (MAS) and $\dot{V}O_{2max}$ in women relative to men ($P < 0.05$). However, the percent difference from predicted $\dot{V}O_{2max}$ was similar between men and women (men: 149.6 ± 18.7%, women: 150.8 ± 16.4%; $P > 0.05$). Absolute running economy ($mL \cdot kg^{-0.75} \cdot km^{-1}$) improved in transition between treadmill speeds, and this occurred similarly in both sexes. Despite this, women showed overall lower oxygen cost of running than men during treadmill locomotion at predetermined absolute and relative intensities ($P < 0.05$). Finally, in a small subset of participants ($n = 6$, 3 male and 3 female participants) with similar MAS (16 km/h), men still exhibited higher $\dot{V}O_{2max}$ and gross oxygen cost of running than women (difference of ~6%, statistics not computed). The present results indicate that, in men and women with similar percent of predicted $\dot{V}O_{2max}$, running economy follows a sexually dimorphic pattern throughout a broad spectrum of treadmill speeds. Ultimately, from a motor performance perspective, our data strongly suggest that lower $\dot{V}O_{2max}$ values in female recreational runners are partially compensated by lower gross oxygen cost of locomotion during submaximal running.

NEW & NOTEWORTHY Our data demonstrate that, compared with that seen in men with similar percent difference from predicted maximum oxygen uptake ($\dot{V}O_{2max}$), scaled gross oxygen cost of running (in absolute and relative terms) is lower in women throughout a broad spectrum of treadmill speeds. Importantly, these findings were obtained after controlling for the effects of the menstrual cycle on running economy, and this is novel.

metabolism; oxygen cost; physical performance; physiology; sex

INTRODUCTION

There is undisputed evidence that running performance follows a sexually dimorphic pattern over a wide range of running distances (i.e., 10–14% difference from 1,500 to 42,000 m) (13, 43). It has been contended that the origin of sexual dimorphism might be related to political factors that discouraged or even precluded women from competing in the past (50). However, radical changes in the societal acceptance of female distance running (e.g., marathon was not added as an Olympic event for women until 1984) have resulted in more opportunities for training and competing over the last 50 years (13). This explains the disproportionate improvements in female running performance within this specific period. Nevertheless, running performance in women has reached a plateau over the last 20 years similar to that seen in men (43). Thus, the remaining sex differences are most likely of biological origin.

Long-distance running performance is associated with a plethora of physiological factors (29), such as the capacity to achieve a high rate of O_2 delivery to the exercising muscle, which potentiates the aerobic synthesis of adenosine triphosphate [high maximal oxygen uptake ($\dot{V}O_{2max}$)] (39). In fact, past research has shown that a linear increase in $\dot{V}O_{2max}$ is strongly associated with improvements in distance running in both men and women (37). However, running performance also depends on the individual anaerobic threshold, as well as on the ability to sustain a high fractional utilization (FU) of $\dot{V}O_{2max}$ for extended periods and on running economy (i.e., the steady-state $\dot{V}O_2$ at a constant submaximal speed) (3, 15, 16, 31, 38).

The pattern of sexual dimorphism in running performance is clearly related to differences in $\dot{V}O_{2max}$ between men and women. For instance, even when the contribution of body fat to sex differences in aerobic capacity is controlled and $\dot{V}O_{2max}$ is expressed to lean body mass, men still retain a considerable aerobic performance advantage (42). Conversely, in well-trained individuals, the FU of $\dot{V}O_{2max}$ during distance running is somewhat higher in female runners (24). This indicates that discrepancies in running performance between men and women are not explained by sex-related differences in their ability to endure high-intensity submaximal exercise.

Whether running economy differs between sexes and whether these differences further contribute to sexual dimorphism in running performance remain controversial. In well-trained athletes, but with dissimilar $\dot{V}O_{2max}$ values, women typically exhibit better running economy than men (4, 34). However, when top-class male and female athletes of equal $\dot{V}O_{2max}$ are compared, men seem to exhibit greater running economy (17) and no sex differences were reported when athletes (high level as well as recreational runners) with similar FU of lactate threshold were compared (9, 21). In contrast, the gross oxygen cost of running tends to be smaller in untrained women versus men (10). Finally, it has been suggested that differences in aerobic endurance capability between perfor-

Correspondence: G. V. Mendonca (gvmendonca@gmail.com).

mance-matched (2h:40m over the marathon) female and male marathon runners are found primarily in the cost of running and the amount of training (24–26, 32).

Despite the importance of all these findings, to our knowledge running economy has never between compared between men and women with similar percent difference from predicted $\dot{V}O_{2max}$. The use of the percent difference from predicted $\dot{V}O_{2max}$ is very common in clinical populations to estimate their negative deviation from the expected value (e.g., Ref. 1). However, this approach is not so common in studies involving well-trained individuals. The latter is important because it cannot be claimed that training status is similar among men and women exhibiting similar $\dot{V}O_{2max}$. As is well known, $\dot{V}O_{2max}$ follows a sexually dimorphic pattern that first begins at puberty and continues throughout adulthood until old age (41). Accordingly, to achieve similar $\dot{V}O_{2max}$ values as males at any age group, females have to be engaged in substantially higher training loads. This notion also holds true for running performance, because past research has shown that, to achieve similar performance time over the marathon distance, women have to train 2 days more per week than men from 2 to 6 mo before the race (24). Consequently, whether gross running economy differs between men and women exhibiting similar percent difference from predicted $\dot{V}O_{2max}$ has not yet been determined.

As importantly, effects of the menstrual cycle on running economy have been shown (19, 51). However, sex differences in running economy have never been explored while controlling for this particular aspect. Thus, the aim of the present study was to investigate whether there are differences in running economy at different velocities for well-conditioned young men and women (tested within the early follicular phase of their menstrual cycle) matched for age and percent difference between predicted and actual $\dot{V}O_{2max}$ values. We hypothesized that, within a given percent difference from predicted $\dot{V}O_{2max}$ values, women would exhibit greater running economy than men.

MATERIALS AND METHODS

Participants. We measured the $\dot{V}O_{2max}$ of 44 recreational runners (18 men and 26 women) recruited from the Faculty's surroundings. Potential participants were recruited if their training habits involved >3 running sessions/wk on a consistent basis over the past 3 yr. Participants were asked to report their weekly running volume at study entry. Inclusion was limited to nonsmoking and normotensive participants (systolic and diastolic BP values repeatedly < 120/80 mmHg) (48). Potential participants were all nonoverweight and free of any known cardiovascular or metabolic disease, as assessed by medical history. None of the included participants was currently using prescriptions or taking any medications. Past research indicates that exercise endurance affects running economy (2, 8). Similarly, better running economy has been documented in well-trained athletes and fit individuals (9). Therefore, for homogeneity purposes, we only included participants with $\dot{V}O_{2max}$ values within 120–180% (ensuring that all participants exhibited $\dot{V}O_{2max}$ values compatible with superior cardiorespiratory capacity) (27) of that predicted with Wasserman's sex-specific equations for normoponderal adults (46): men: $\dot{V}O_{2max}$ (mL/min) = body mass (kg) × [50.72 − 0.372 × age (yr)]; women: $\dot{V}O_{2max}$ (mL/min) = [body mass (kg) + 42.8] × [22.78 − 0.17 × age (yr)].

Nineteen participants were excluded because of one of the following reasons: *1*) $\dot{V}O_{2max}$ < 120% of the predicted value (7 women and 3 men), *2*) high resting blood pressure (2 men), and *3*) irregular menstrual cycles (7 women). Therefore, only 25 participants (13 men and 12 women), aged 19–27 yr, were included in this study. Importantly, in addition to their weekly running volume, all participants were similarly active, accumulating 9 h of physical activity per week as part of their academic work (BSc in Sports and Exercise Science). Participants were already accustomed to cardiopulmonary exercise testing using a treadmill ergometer. For this reason, there were no familiarization sessions for this specific group of participants. All female participants were tested during the early follicular phase of the menstrual cycle (days 2–6), to control for possible effects of the menstrual cycle on running economy and ventilatory threshold (5, 19). None of them was pregnant or using oral contraceptives at the time of the study. Additionally, they all had self-reported regular menstrual cycles of ~28 days. Each participant was requested to avoid heavy exercise for at least 24 h before testing and to have nothing to eat from midnight until the testing session on the subsequent morning. Participants were also asked to refrain from caffeine ingestion and to empty their bladders before testing. Participants were fully informed of the purposes, risks, and discomfort associated with the experiment before providing written informed consent. Informed consent was obtained from all individual participants included in the study. This study was carried out with approval from the University's Institutional Review Board (CEFMH no. 30/2018) and in accordance with the Declaration of Helsinki.

Study design. The experimental design included two visits to the laboratory on nonconsecutive days (between 0700 and 0900). Testing was performed with a maximum of 72 h between visits. During the first visit, standing height and body mass measurements were taken with the participants wearing lightweight clothes and no shoes. Height was taken with a stadiometer, with measures obtained to the nearest 0.5 cm. Body mass was measured on a digital scale to the nearest 0.01 kg (BG 42; Breuer GmbH, Söflinger, Germany). Body mass index (BMI) was then calculated by dividing the participants' mass in kilograms by the square of their height in meters. Brachial blood pressure was measured in duplicate with an automatic oscillometric device after 5 min of seated rest. For analysis, the average of the two values was used. If the values were not within 5 mmHg, a third measurement was taken and the two closest values were averaged and used for analysis. Subsequently, each participant completed a graded treadmill test consisting of a ramp protocol to volitional exhaustion. This test was used with three specific purposes: *1*) to ensure that all participants with a $\dot{V}O_{2max}$ < 120% of the predicted value were excluded at this stage; *2*) to explore the effects of submaximal running on the FU $\dot{V}O_{2max}$ in each participant (by expressing the submaximal $\dot{V}O_2$, obtained on the second visit at each running speed, as a function of $\dot{V}O_{2max}$), and *3*) to determine the individual maximal aerobic speed (MAS) of each participant. On the second visit, all participants performed three bouts of continuous submaximal treadmill running at 8, 10, and 12 km/h. All tests were performed on a motorized treadmill (Laufergotest; Jaeger, Germany). During testing, expired gas measurements were taken with a portable mixing chamber (Metamax I; Cortex, Leipzig, Germany), which was calibrated before each test with a known volume and with known gas concentrations. Heart rate was measured by means of a Polar RS 800 G3 heart rate monitor (Polar R-R recorder; Polar Electro, Kempele, Finland). Testing was carried out in the laboratory with an environmental temperature between 21 and 24°C and a relative humidity between 44 and 56%.

Maximal exercise test. Before testing, each participant rested quietly in a seated position for 5 min. Testing began with a submaximal walk at a constant speed of 4 km/h. Then, after 2 min of walking, speed was increased to 8 km/h. From this point, speed was further increased by 1 km/h every minute until volitional exhaustion. Treadmill grade was held constant at 1% throughout the entire duration of exercise. This was done because running on a treadmill at 1% grade reflects overground running $\dot{V}O_2$ with greater accuracy (28).

Submaximal exercise test. Testing was performed after a quiet rest of 10 min in the seated position. Past research has shown that measuring submaximal $\dot{V}O_2$ is reliable when using an incremental protocol at different intensity levels up to 90% $\dot{V}O_{2max}$ (26). For this reason, the submaximal exercise test involved 6 min of continuous running at a constant speed of 8 km/h. Subsequently, treadmill speed was increased and held constant at 10 and then 12 km/h for another 6 min each. As specified for maximal exercise testing, running economy was measured at a 1% incline. The submaximal treadmill speeds were selected on the basis of the results reported by Black et al. (9). Across this specific range of speeds, both male and female recreational runners exercise with a respiratory exchange ratio (RER) < 1.0, thus ensuring an insignificant anaerobic contribution to energy expenditure.

Data analysis. The $\dot{V}O_2$ and heart rate data obtained throughout the maximal exercise test were displayed in 20-s averages. The highest $\dot{V}O_2$ attained at the end of the test was accepted as $\dot{V}O_{2max}$ if a plateau in $\dot{V}O_2$ with an increase in treadmill speed was observed. One female participant did not achieve a plateau in $\dot{V}O_2$ at exercise termination and had to repeat the maximal test after 2 days of recovery. Her $\dot{V}O_{2peak}$ obtained at the first visit was similar to the $\dot{V}O_{2max}$ attained at the second. MAS was defined as the lowest treadmill speed compatible with $\dot{V}O_{2max}$, and maximal heart rate was identified as the highest value recorded during each test. For each participant, the first ventilatory threshold (VT_1) was determined from the time course of the relationship between the ventilatory equivalent of oxygen [minute ventilation ($\dot{V}E$)/$\dot{V}O_2$] and carbon dioxide ($\dot{V}E/\dot{V}CO_2$). Accordingly, the VT_1 was defined as the minimal speed at which the $\dot{V}E/\dot{V}O_2$ exhibited a systematic increase without a concomitant increase in $\dot{V}E/\dot{V}CO_2$ (47). VT_2 was also identified by visual analysis of the breakpoints of $\dot{V}E/\dot{V}CO_2$ and $\dot{V}E/\dot{V}O_2$ and minute ventilation changes over time. The second increase in minute ventilation with a concomitant rapid increase in $\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$ defined VT_2 (47). Both VTs were determined by two independent investigators and expressed in terms of both absolute and relative intensities (%$\dot{V}O_{2max}$).

The submaximal $\dot{V}O_2$ data were also displayed as 20-s averages. The mean of the last 3 min of each 6-min run was defined as the participant's submaximal steady-state $\dot{V}O_2$ (49). Furthermore, the increment in $\dot{V}O_2$ between the 3rd and 6th minutes of the transition ($\Delta\dot{V}O_{2,\ 6-3}$) was calculated to confirm the attainment of steady state by male and female participants. According to past research, there is an inverse relationship between running economy and body mass in endurance-trained persons (6). Thus, for running it is preferable to express $\dot{V}O_2$ in terms of the unit milliliters per kilogram$^{-0.75}$ per minute rather than using the conventional unit mlliliters per kilogram per minute (6). This is particularly important when comparing individuals or groups with different body mass (e.g., men vs. women) (24). Thus, we computed allometric scaling of $\dot{V}O_2$, and data were then compared with those obtained without scaling.

By plotting submaximal $\dot{V}O_2$ data against running speed (8–12 km/h), individual regression equations were obtained for each participant. Then, the running speeds required to elicit 80%, 85%, 90%, and 95% $\dot{V}O_{2max}$ at 1% grade were calculated. This allowed us to convert the submaximal $\dot{V}O_2$ corresponding to each relative intensity to gross oxygen cost per kilometer of running distance. In addition, to explore whether the oxygen cost of running exhibits a sexually dimorphic pattern in male and female participants with similar running performance, we selected six participants (3 men and 3 women) showing similar MAS (equivalent to 16 km/h). Running economy as well as $\dot{V}O_{2max}$ were then compared between these two small subsets of participants.

Statistical analysis. All data are reported as means ± SD. Before the sexes were compared, data were tested for normality and homoscedasticity with the Kolmogorov–Smirnov and Levene's tests, respectively. An independent researcher in our laboratory who was blinded to group allocation analyzed data. Past research has shown that men and women have different gross oxygen cost during treadmill running at 11 km/h with a 1.5% incline (men 0.752 ± 0.053 vs. women 0.686 ± 0.038 mL·kg$^{-0.75}$·m^{-1}) (26). Based on these data, a total sample size of 25 participants was estimated to have >95% power of correctly rejecting the null hypothesis (14). Independent *t* tests were used to explore possible sex differences in the values derived from maximal exercise. A two-way ANOVA [sex (men vs. women) × treadmill speed (8 vs. 10 vs. 12 km/h)] with repeated measures was conducted on submaximal exercise data to determine the effects of sex on absolute and relative oxygen cost of running. Adjustment for multiple comparisons was made with the Bonferroni correction. All statistical calculations were computed with SPSS version 25.0, and a significance level of $P < 0.05$ was used. Comparisons of running economy between men and women (6 participants) with similar MAS are only descriptive and not based on statistical computations.

Table 1. *Physiological variables and concomitant speed recorded at maximal exercise and at the ventilatory threshold in both sexes*

	Male	Female	*P* Value
Ventilatory threshold			
$\dot{V}O_2$ at VT_1, mL·kg^{-1}·min^{-1}	52.0 ± 7.5	43.0 ± 6.3	0.04
FU at VT_1, %	73.7 ± 3.3	81.4 ± 7.1	0.002
Speed at VT_1, km/h	14.0 ± 1.5	12.6 ± 1.4	0.02
$\dot{V}O_2$ at VT_2, mL·kg^{-1}·min^{-1}	61.7 ± 8.1	47.9 ± 5.7	<0.0001
FU at VT_2, %	87.5 ± 2.4	90.8 ± 3.5	0.01
Speed at VT_2, km/h	16.2 ± 1.9	13.3 ± 1.4	<0.0001
Maximal exercise			
$\dot{V}O_{2max}$, mL·kg^{-1}·min^{-1}	70.4 ± 8.4	52.8 ± 5.5	<0.0001
$\dot{V}O_{2max}$, mL·kg$^{-0.75}$·min^{-1}	203.8 ± 25.1	145.3 ± 15.1	<0.0001
Maximal aerobic speed, km/h	18.1 ± 1.8	14.8 ± 1.2	<0.0001
HR_{max}, beats/min	195.8 ± 11.4	193.1 ± 8.2	0.10
Maximum RER	1.11 ± 0.03	1.12 ± 0.03	0.09
$\dot{V}E_{max}$, L/min	150.9 ± 20.1	96.2 ± 14.2	<0.0001

Values are means ± SD. FU, fractional utilization; HR_{max}, maximum heart rate; RER, respiratory exchange ratio; $\dot{V}E_{max}$, maximum minute ventilation; $\dot{V}O_2$, oxygen uptake; $\dot{V}O_{2max}$, maximum oxygen uptake; VT_1, 1st ventilatory threshold; VT_2, 2nd ventilatory threshold. $n = 13$ males and $n = 12$ females.

RESULTS

The groups of participants were of similar age (men 22.1 ± 1.6, women 22.3 ± 2.5 yr) and BMI (men 22.4 ± 1.2, women 22.1 ± 2.1 kg/m^{-2}) ($P > 0.05$). In contrast, men were taller (men 177.0 ± 4.9, women 161.9 ± 5.8 cm) and heavier (men 70.2 ± 4.8, women 57.7 ± 5.3 kg) than women ($P < 0.0001$). Running volume was similar between the groups of participants (men 41.2 ± 6.3, women 40.4 ± 7.4 km/wk).

Maximal exercise test data. As depicted in Table 1, sex differences were transversal at VT_1 and VT_2 ($P < 0.05$). Although the absolute values of VT_1 and VT_2 were higher in men than women ($P < 0.05$), this was not sustained after both VTs were expressed in relative terms. Under these circumstances, women attained their VTs at higher FU $\dot{V}O_{2max}$ ($P < 0.05$). Even though men achieved higher $\dot{V}O_{2max}$ than women (with and without allometric scaling of body mass) ($P < 0.05$), both groups of participants terminated maximal exercise at similar values of heart rate and RER ($P > 0.05$). It is also important to note that, despite the sexual dimorphism in $\dot{V}O_{2max}$, the percent difference from predicted $\dot{V}O_{2max}$ did not differ between men and women (men 149.6 ± 18.7%, women 150.8 ± 16.4%; $P = 0.86$). Finally, sex comparisons revealed lower MAS and minute ventilation in women compared with men ($P < 0.05$).

Table 2. *Submaximal exercise data including running economy obtained in both sexes with and without allometric scaling*

	8 km/h		10 km/h		12 km/h	
	Male	Female	Male	Female	Male	Female
Nonallometric scaling						
$\dot{V}O_2$, mL·kg^{-1}·min^{-1}*	29.9 ± 1.4	30.1 ± 2.2	36.9 ± 1.8	36.7 ± 1.8	43.8 ± 2.0	43.1 ± 2.2
O_2 cost, mL·kg^{-1}·min^{-1}*	224.7 ± 10.8	225.9 ± 17.2	221.5 ± 13.9	220.0 ± 10.6	219.0 ± 10.1	215.7 ± 11.1
Allometric scaling						
$\dot{V}O_2$, mL·kg$^{-0.75}$·min^{-1}*#†	86.5 ± 4.3	82.9 ± 7.3	106.9 ± 5.3	101.0 ± 6.6	126.7 ± 6.1	118.8 ± 7.7
O_2 cost, mL·kg$^{-0.75}$·min^{-1}*#	649.9 ± 32.4	622.5 ± 54.5	640.8 ± 27.4	606.3 ± 39.5	633.5 ± 30.3	594.2 ± 38.7
Additional cardiorespiratory data						
HR, beats/min*#	126.5 ± 11.3	140.5 ± 12.5	145.2 ± 14.8	159.4 ± 13.6	159.2 ± 17.8	173.0 ± 14.6
$\dot{V}E$, L/min*	45.9 ± 4.8	42.6 ± 5.9	58.9 ± 6.7	54.9 ± 8.7	73.2 ± 9.5	71.0 ± 13.5
RER*	0.86 ± 0.03	0.87 ± 0.05	0.89 ± 0.03	0.90 ± 0.05	0.91 ± 0.05	0.93 ± 0.04
Δ6–3, mL/min	43.4 ± 66.9	57.1 ± 46.8	14.6 ± 65.7	8.7 ± 40.8	49.5 ± 63.1	37.8 ± 53.0
FU $\dot{V}O_{2max}$, %*#	42.9 ± 4.7	57.4 ± 6.0	53.0 ± 6.2	70.1 ± 7.0	63.1 ± 8.7	82.4 ± 8.5

Values are means ± SD. FU $\dot{V}O_{2max}$, fractional utilization of maximum oxygen uptake; HR, heart rate; RER, respiratory exchange ratio; $\dot{V}E$, minute ventilation; $\dot{V}O_2$, oxygen uptake; Δ6–3, change in oxygen uptake between the 3rd and 6th minutes of exercise. *Significant speed main effect ($P < 0.05$). #Significant sex main effect ($P < 0.05$). †Significant interaction effect ($P < 0.05$). $n = 13$ males and $n = 12$ females.

Submaximal exercise test data. Table 2 shows that we obtained a significant speed main effect for both nonscaled ($F = 1295.5$, $P < 0.0001$) and scaled ($F = 1276.2$, $P < 0.0001$) submaximal $\dot{V}O_2$. Follow-up analyses revealed that both parameters increased progressively in transition between running speeds ($P < 0.05$). However, although the magnitude of increase in this parameter was similar between sexes without scaling, this was not sustained after $\dot{V}O_2$ was scaled allometrically (speed × sex interaction: $F = 4.1$, $P = 0.04$). As can be seen in Fig. 1*A*, the slope of $\dot{V}O_2$ rise in transition between running speeds was less steep in female participants.

We observed significant speed main effects for gross oxygen cost of running with ($F = 10.9$, $P = 0.0001$) and without ($F = 10.9$, $P < 0.0001$) scaling, thus indicating that running economy improved in transition between treadmill speeds. In contrast to that seen with nonscaled oxygen cost, there was a sex main effect for scaled running economy ($F = 5.5$, $P = 0.02$). This shows that female participants had overall lower oxygen cost than male participants during treadmill running. As presented in Table 2, RER and Δ6–3 did not differ between sexes in either time point ($P > 0.05$). Moreover, Δ6–3 remained considerably small and constant in men and women across all running speeds ($P > 0.05$), confirming the attainment of steady-state $\dot{V}O_2$.

Heart rate increased progressively in response to treadmill running speed (speed main effect: $F = 276.0$, $P < 0.0001$) in both sexes. However, the chronotropic response to exercise was overall higher in women versus men (sex main effect: $F = 6.5$, $P = 0.02$). Even though minute ventilation also increased between running speeds (speed main effect: $F = 267.6$, $P < 0.0001$), no sex differences were seen in this particular parameter. In addition, as listed in Table 2, the relative intensity of exercise increased similarly between sexes in response to the selected treadmill speed progression (speed main effect: $F = 601$, $P < 0.0001$), yet women relied on higher FU $\dot{V}O_{2max}$ than men at all treadmill running speeds (sex main effect: $F = 39.8$, $P < 0.0001$).

Scaled running economy computed at similar relative intensities between sexes is depicted in Fig. 1*B*. Contrary to that seen in running economy at predetermined absolute speeds, the oxygen cost of running remained constant throughout all relative intensities (relative intensity main effect: $F = 1.3$, $P = 0.27$). Irrespective of this, women showed better running economy than men, and this was consistent between different relative intensities (sex main effect: $F = 33.2$, $P < 0.0001$). Finally, Fig. 2 compiles data on three men and three women with similar MAS (i.e., 16 km/h). Despite comparable treadmill speed performance, men still exhibited higher $\dot{V}O_{2max}$ than women at the termination of exercise testing (5.6% difference). Conversely, the slope of rise in $\dot{V}O_2$ with speed was less steep

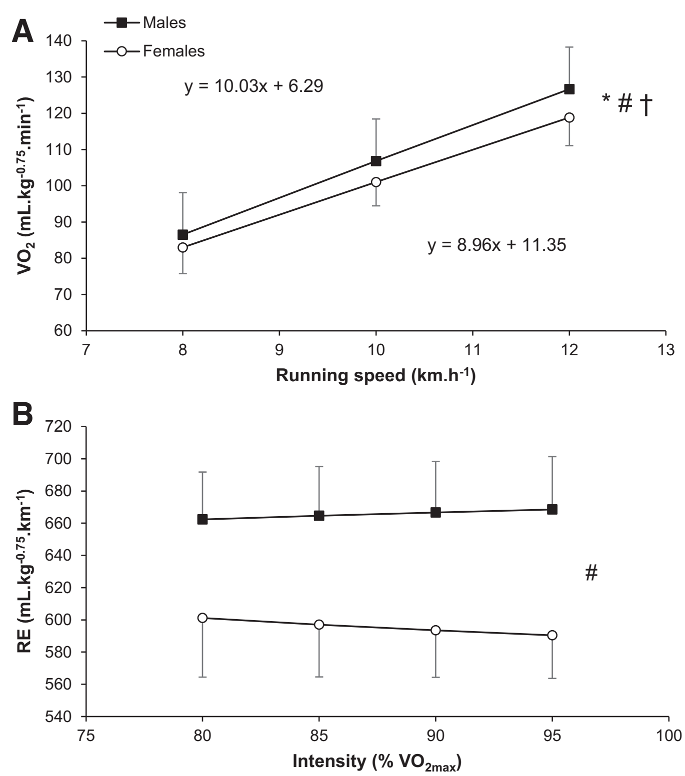

Fig. 1. *A*: submaximal oxygen uptake ($\dot{V}O_2$) as a function of running speed, treadmill at 1% gradient. *B*: running economy (RE) at different relative intensities. $\dot{V}O_{2max}$, maximum oxygen uptake. Between-sex comparisons (13 men vs. 12 women) were made with repeated-measures analysis of variance. Equations were computed with least squares linear regression on data derived from each group of participants. Values are means and SD. Significance: *speed, #sex, †interaction main effect ($P < 0.05$).

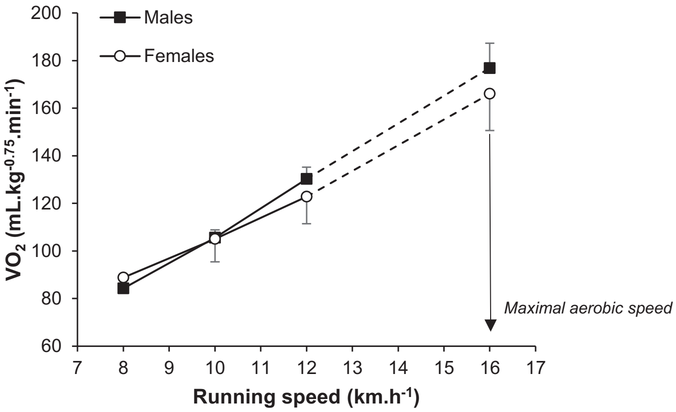

Fig. 2. Submaximal and maximal oxygen uptake ($\dot{V}O_2$) of male ($n = 3$) and female ($n = 3$) recreational runners with similar maximal aerobic speed as a function of running speed, treadmill at 1% gradient. These comparisons are only descriptive and not based on any statistical analyses. Values are means and SD.

in women (8.4 ± 1.4, min/max: 6.8–9.2 mL·kg$^{-0.75}$·min^{-1}/km·h^{-1}) than in men (11.5 ± 1.2, min/max: 10.5–11.9 mL·kg$^{-0.75}$·min^{-1}/km·h^{-1}), and this resulted in a 5.8% lower cost of running at 12 km/h, albeit these comparisons are only descriptive and not based on any statistical analyses.

DISCUSSION

This study examined running economy in young men and women with similar percent difference from predicted $\dot{V}O_{2max}$. We also controlled for the influence of the menstrual cycle on gross oxygen cost. According to our results, with allometric scaling of body mass women show better running economy compared with men. This is consistent across a broad spectrum of submaximal running speeds and sustained when the sexes are compared at predetermined relative intensities.

We observed that although women have lower oxygen cost of running with allometric scaling of body mass, this is not the case for unscaled running economy. With allometric scaling, the sexual dimorphism in running economy is evident for gross oxygen cost expressed per unit of either running distance or time (km and min, respectively). Past research has shown that, in endurance-trained persons, dividing $\dot{V}O_2$ by body mass induces erroneous interpretations when comparing individuals or groups who differ in body mass (6, 44). In addition, allometric scaling decreases the standard deviation in running economy between persons and, compared with that seen with unscaled running economy, represents a more sensitive predictor of long-distance running performance in both competitive and recreational runners (26, 32). Thus, it can be concluded that the present outcomes are meaningful when viewed from a physiological as well as from a motor performance perspective.

It is important to note that our findings further extend those of previous studies because we showed that the sexually dimorphic pattern in running economy is sustained, even when comparing men and women with similar percent difference from predicted $\dot{V}O_{2max}$ and while controlling for the impact of the menstrual cycle on $\dot{V}O_2$ (19). Since running economy is intimately dependent on individual training status (20), we believe that matching men and women using $\dot{V}O_{2max}$ for the purpose of exploring sexual dimorphism in running economy was an important methodological limitation in past reports. Thus, to overcome this limitation, we used the percent difference from predicted $\dot{V}O_{2max}$ to match both groups of participants. Furthermore, to avoid heterogeneity between groups, we only included participants with $\dot{V}O_{2max}$ values within 120–180% of that predicted with sex-specific equations. As importantly, it was recently shown that the variation of female running economy during the menstrual cycle is of ~6% (19). Since this is clearly within the magnitude of the reported sex differences in running economy, the lack of control of the menstrual cycle might have contributed to the inconsistencies reported in the available literature (9, 20, 24, 26, 32).

Running economy was measured in both sexes during submaximal running at intensities below the VT_1. This allowed us to compare men and women under steady-state $\dot{V}O_2$ conditions, as confirmed by the steadiness of low Δ6–3 values at all treadmill speeds (repeatedly <150 mL/min). The RER was also similar between sexes and consistently <1.0 at all running speeds. Past reports have argued that, when comparing males and females, running economy should be expressed as energy cost to control for the effects of sexual dimorphism in relative intensity and substrate oxidation during dynamic exercise (9, 20, 21). Despite being unequivocal that fuel source affects running economy (e.g., greater oxygen requirements for fat oxidation) (36), we observed sex differences in gross oxygen cost during running at similar RER values between groups. Thus, under these circumstances, computing energy cost for exploring sex differences in running economy would not affect our findings. Nevertheless, despite similar RER between sexes, the FU $\dot{V}O_{2max}$ was significantly higher in female participants across all running speeds, which indicates that the relationship between fat oxidation and relative intensity also displays a sexually dimorphic pattern. Specifically, our data suggest that fat oxidation is shifted toward higher relative intensities in women than in men, thus supporting previous findings (12). Ultimately, this may explain why in well-trained individuals the FU $\dot{V}O_{2max}$ during distance running is somewhat higher in female runners (24). It may also provide a partial explanation for the higher relative VT in women observed in the present study (i.e., with the use of carbohydrate as the primary fuel source for running occurring at higher relative intensities in women vs. men matched for the percent difference from predicted $\dot{V}O_{2max}$).

As shown in Table 1, even though the difference between men and women for $\dot{V}O_{2max}$ was ~25%, the sexual dimorphism in MAS was only ~18%. Considering that MAS is highly dependent on both $\dot{V}O_{2max}$ and running economy (17), it can be concluded that better running economy in women (~6%) partially compensates the negative impact of their lower $\dot{V}O_{2max}$ (mL·kg$^{-0.75}$·min^{-1}) on MAS. In addition, the smallest worthwhile change for running economy (i.e., the magnitude of change required to elicit a meaningful improvement in running economy) corresponds to ~2.2–2.6% (40), a value that is clearly lower than the difference observed between sexes in the present study (~6%). This substantiates that the magnitude of the difference obtained here is physiologically meaningful and further supports the notion that greater running economy in women has a positive impact on their running performance. Further corroborating the physiological relevance of our findings, one past study has shown that the absolute and relative reliability of gross oxygen cost at a running speed equivalent to

12 km/h are both very high (coefficient of variation of 1.6% and intraclass correlation coefficient of 0.97) (33).

From a mechanistic perspective, there is general agreement that minute ventilation plays an important role in running economy (22, 45). Past studies have shown that an increased demand of breathing heightens the oxygen cost of running and that a decrement in minute ventilation with training provides a partial explanation for improved running economy (22, 45). We found no differences in minute ventilation between men and women, and this occurred consistently across the three submaximal running speeds. Women presented lower tidal volume but higher breathing frequencies than men. This is not surprising based on the anthropometric differences between sexes. However, achieving minute ventilation similar to male runners was indeed surprising—this means that their body surface area-adjusted minute ventilation (results not shown) was higher than that seen in men—and even under these circumstances, they exhibited better running economy. Clearly, this excluded the O_2 cost of breathing from the list of possible candidates explaining improved running economy in women. Thus, in persons with similar percent difference from predicted $\dot{V}O_{2max}$, sex differences in running economy cannot be explained by different O_2 demand of breathing. It has also been suggested that higher heart rate values are partly responsible for poor running economy between individuals (35). However, since women exhibited higher heart rate values than men across all submaximal treadmill speeds, our data show that the sexual dimorphism in running economy is not secondary to between-sex differences in the chronotropic response to exercise.

Besides being more economical than men, women also displayed a less steep slope in the rise of $\dot{V}O_2$ (mL·kg^{-1}·min^{-1}) in response to positive variations in treadmill speed, and this indicates that women have higher levels of mechanical efficiency in transition between incremental running speeds. However, since this effect was virtually dissipated after conversion of $\dot{V}O_2$ to oxygen cost per unit of distance, its impact in running performance may not be highly relevant when considering exercise durations $>$ 1 min. When running economy was expressed as a function of traveled distance, we found that both male and female runners lowered their oxygen cost of locomotion from 8 to 12 km/h. These findings are similar to that previously reported in the available literature (9), thus corroborating that the optimal speed for running in well-trained young adults is approached at 12 km/h (9).

The comparative analyses performed on relative running economy confirm the results obtained for absolute oxygen cost. In accordance, women achieved better running economy than men at relative intensities ranging from 80% to 95% $\dot{V}O_{2max}$, and this is in agreement with some (24, 26), but not all (11, 17), prior reports. However, although running economy improved as a function of absolute treadmill speed, this was not the case with relative intensity. Our findings indicate that, as demonstrated in one previous study, under these circumstances running economy was constant at different relative intensities (26). From a performance-centered approach, these findings may be particularly relevant. For instance, as is well known, the $\dot{V}O_2$ at the average speed of marathon running varies between 73% and 87% $\dot{V}O_{2max}$ (slightly higher in women vs. men) (24, 25). Thus, when put into perspective, these data suggest that during long-distance running women have to exert themselves at higher FU $\dot{V}O_{2max}$ to reach a similar oxygen cost of running per kilometer of traveled distance. This may very well be the reason why women can endure marathon running at higher FU $\dot{V}O_{2max}$ than men.

Finally, with the purpose of exploring sex differences in men and women with similar exercise performance at graded exercise test termination, we compared running economy and $\dot{V}O_{2max}$ in a small subset of male and female participants with similar MAS. As shown in one previous study examining sex differences in running economy in men and women with similar performance level in marathons (24), we found that $\dot{V}O_{2max}$ expressed in milliliters per kilogram$^{-0.75}$ per minute was higher in men by 5.6%. In contrast, as described for comparisons involving total sample size, the slope of $\dot{V}O_2$ rise in transition between running speeds was less steep in women, and this resulted in a 5.8% in gross oxygen cost at a treadmill speed of 12 km/h. Thus, it can be concluded that the higher $\dot{V}O_{2max}$ in men was compensated for by improved running efficiency and economy in the performance-matched female recreational runners.

Conclusions. The present results indicate that, in men and women with similar percent difference from predicted $\dot{V}O_{2max}$, running economy follows a sexually dimorphic pattern throughout a broad spectrum of treadmill speeds. In specific, women exhibit better running economy (absolute and relative) than men after gross oxygen cost is adjusted to scaled body mass. It should be noted that these data were obtained after controlling for possible interactions between gross oxygen cost and the menstrual cycle (i.e., female participants were tested in the early follicular phase of their menstrual cycle). Moreover, from a mechanistic perspective, we also showed that the sexual dimorphism in running economy does not depend on sex differences in minute ventilation or heart rate during submaximal exercise. Finally, we also showed that differences in running economy between men and women subsisted in a small subset of participants with similar MAS. Ultimately, from a motor performance perspective, our data strongly suggest that lower $\dot{V}O_{2max}$ values in female recreational runners are partially compensated by lower gross oxygen cost of locomotion during submaximal running.

Limitations. This study has at least three important limitations. First, running economy was measured in the laboratory on a motorized treadmill, and this may underestimate true oxygen cost during overground running in both sexes. Differences between overground and treadmill running are evident because, as speed increases, the effects of air and wind resistance become more pronounced (18). Furthermore, the technique of running on a treadmill is different from running over ground, where the hamstrings are used to a greater extent to produce propulsive horizontal and vertical forces (28). To overcome this limitation, a slight incline on the treadmill gradient (1%) was used to increase the oxygen cost of running in compensation for the lack of air resistance and propulsive hamstring activation (28). Irrespective of this, it should be reinforced that even if this particular aspect affected our results, its effects must have exerted a similar impact in men and women. Second, despite the fact that all participants were required to wear the same running shoes in both testing sessions, unfortunately we were not able to ensure footwear standardization among participants. This represents a limitation because, as shown in previous work, the aerobic demand of treadmill running may vary ~2.8% depending on cushioning (23). Thus, further research is warranted to explore sexual dimorphism in running economy in well-trained individuals equipped with standardized running shoes. Third, relative running economy was determined by extrapolation of data derived from submaximal steady-state $\dot{V}O_2$. Past research has shown that there can be a substantial $\dot{V}O_2$ slow component within the heavy and severe exercise domain, even in highly trained individuals (7). For this reason, the magnitude of sexual dimorphism in gross oxygen cost of running at such relative intensities might be different from that illustrated in Fig. 1*B*. However, past research has shown that the amplitude of the $\dot{V}O_2$ slow component is similar between the sexes in response to heavy exercise (30). Therefore, despite being contaminated by a downward shift in $\dot{V}O_2$ (not accounting for the $\dot{V}O_2$ slow component in either sex), sex differences in relative running economy are likely well depicted by the content of Fig. 1*B*.

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DISCLOSURES

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

AUTHOR CONTRIBUTIONS

G.V.M., P.M., and J.M.C. conceived and designed research; G.V.M., P.M., and J.M.C. performed experiments; G.V.M. and P.M. analyzed data; G.V.M. and P.M. interpreted results of experiments; G.V.M. prepared figures; G.V.M. drafted manuscript; G.V.M. edited and revised manuscript; G.V.M., P.M., and J.M.C. approved final version of manuscript.

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