Eur J Appl Physiol (1994) 68:155–161

European Journal of Applied Physiology and Occupational Physiology

Maximal oxygen uptake, anaerobic threshold and running economy in women and men with similar performances level in marathons

Jan Helgerud

Department of Sports, University of Trondheim, N-7055 Dragvoll, Norway

Accepted: October 26, 1993

Abstract. Sex differences in running economy (gross oxygen cost of running, C_R), maximal oxygen uptake ($\dot{V}O_{2max}$), anaerobic threshold (Th_{an}), percentage utilization of aerobic power (% $\dot{V}O_{2max}$), and Th_{an} during running were investigated. There were six men and six women aged 20–30 years with a performance time of 2 h 40 min over the marathon distance. The $\dot{V}O_{2max}$, Th_{an}, and C_R were measured during controlled running on a treadmill at 1° and 3° gradient. From each subject's recorded time of running in the marathon, the average speed ($\bar{v}_M$) was calculated and maintained during the treadmill running for 11 min. The $\dot{V}O_{2max}$ was inversely related to body mass (m_b), there were no sex differences, and the mean values of the reduced exponent were 0.65 for women and 0.81 for men. These results indicate that for running the unit $ml \cdot kg^{-0.75} \cdot min^{-1}$ is convenient when comparing individuals with different m_b. The $\dot{V}O_{2max}$ was about 10% (23 $ml \cdot kg^{-0.75} \cdot min^{-1}$) higher in the men than in the women. The women had on the average 10–12 $ml \cdot kg^{-0.75} \cdot min^{-1}$ lower $\dot{V}O_2$ than the men when running at comparable velocities. Disregarding sex, the mean value of C_R was 0.211 (SEM 0.005) $ml \cdot kg^{-1} \cdot m^{-1}$ (resting included), and was independent of treadmill speed. No sex differences in Th_{an} expressed as % $\dot{V}O_{2max}$ or percentage maximal heart rate were found, but Th_{an} expressed as $\dot{V}O_2$ in $ml \cdot kg^{-0.75} \cdot min^{-1}$ was significantly higher in the men compared to the women. The percentage utilization of f_{cmax} and concentration of blood lactate at $\bar{v}_M$ was higher for the female runners. The women ran 2 days more each week than the men over the first 4 months during the half year preceding the marathon race. It was concluded that the higher $\dot{V}O_{2max}$ and Th_{an} in the men was compensated for by more running, superior C_R, and a higher exercise intensity during the race in the performance-matched female marathon runners.

Key words: Sex differences – Marathon – Anaerobic threshold – Aerobic power – Running economy – Body dimensions

Introduction

Aerobic endurance has been shown to depend on factors such as maximal oxygen uptake ($\dot{V}O_{2max}$), fractional utilization of $\dot{V}O_{2max}$, anaerobic threshold (Th_{an}), and gross energy cost of running (C_R) or running economy (Saltin and Åstrand 1967; Costill et al. 1973; Bransford and Howley 1977; Farrell et al. 1979; Conley and Krahenbuhl 1980; Di Prampero et al. 1986; Bunc and Heller 1989; Padilla et al. 1992). These factors have been investigated with respect to sex differences in long distance runners and correlated to performance level in marathon races. However, the female subjects in most of these studies have had low to moderate endurance performance levels (e.g. Saltin and Åstrand 1967; Ramsbottom et al. 1989; Helgerud et al. 1990). Furthermore, previous studies reporting sex differences in aerobic endurance have often used women and men with relatively large differences in performance capacity. Helgerud et al. (1990) have suggested that differences in aerobic endurance capability between performance-matched female and male marathon runners are found primarily in C_R and the amount of training. Because their subjects were medium trained athletes not especially trained for marathon running, these results may not apply to elite athletes or when performance-matched marathon runners of both sexes possessing a high performance level are studied.

As has been suggested by von Døbeln (1956) oxygen uptake ($\dot{V}O_2$) is a measure of power, and should be expressed in ml per kg lean body mass raised to a power close to 2/3 to be mass independent. The inverse relationship between C_R and body mass (m_b) has already been observed in elite distance runners (Williams et al. 1987; Padilla et al. 1992). This view has been supported by Bergh et al. (1991) who have claimed that neither submaximal $\dot{V}O_2$ nor $\dot{V}O_{2max}$ increased in proportion to m_b during running in a large number ($n = 134$) of endurance athletes of both sexes. The relationship between $\dot{V}O_2$ and m_b has been given by the allometric equation:

$$\dot{V}O_2 = a \cdot m_b^b \quad (1)$$

where a is the mass coefficient and b is the reduced exponent (Åstrand and Rodahl 1986). Bergh et al. (1991) have concluded that b is less than unity for all groups. Hence, b is less than 1 and $\dot{V}O_2 \cdot kg^{-1}$ is inversely related to m_b. These data indicate that for running it would be better to express $\dot{V}O_2$ in terms of the unit $ml \cdot kg^{-0.75} \cdot min^{-1}$ rather than using the conventional unit $ml \cdot kg^{-1} \cdot min^{-1}$. This ought to be considered when comparing individuals or groups with different m_b, e.g. when men are compared with women.

Many studies have examined C_R, but they have rarely taken into account individual performance (Padilla et al. 1992). Comparisons between C_R of well-trained male and female distance runners are not consistent, and few have made simultaneous assessment of C_R (Bransford and Howley 1977; Bunc and Heller 1989; Padilla et al. 1992; Daniels and Daniels 1992).

The purpose of the present study was
1. To compare the morphological and physiological characteristics of male and female long-distance runners matched by age and marathon running performance; and
2. To assess C_R in well-trained men and women athletes.

Methods

Subjects. Six intermediate national standard elite male and six female elite long-distance runners took part in the study. All the subject gave their informed consent for participation. The subjects' mean age, mass, height, and percentage body fat are shown in Table 1.

The subjects' athletic background and level of physical activity were assessed by use of a questionnaire.

Experimental procedure. The procedures for measuring $\dot{V}O_{2max}$ and f_{cmax} have been described in a previous study (Helgerud et al. 1990). The expired air was collected in Douglas bags and analysed using a paramagnetic Beckman model 755 oxygen analyser and a Beckman model 864 infra-red CO_2 analyser (Beckman Instruments, Calif., USA). The volume of air in the Douglas bags was measured using a Wilhelm Ritter KG (Kunststoff-Werkstätten, Bochum-Rangendreer, Germany) wet gas meter. Heart rate (f_c) was recorded continuously by using an electrocardiograph (Danica Electronic A/S, Denmark). The Th_{an} was defined as the highest exercise intensity measured as $\dot{V}O_2$ during a constant running speed for 20 min, where the blood lactate concentration ($[la^-]_b$) increased less than 1 $mmol \cdot l^{-1}$ during the last 15 min. After warming up for 10 min (at about 50% $\dot{V}O_{2max}$), Th_{an} was determined using a graded protocol. The subjects ran at five increasing intensities for 5 min (about 60%–95% $\dot{V}O_{2max}$), with a 30-s pause between each to take blood samples from a fingertip. The $[la^-]_b$ was measured by a Roche model 640 lactate analyser (Roche, Basel, Switzerland) (Soutter et al. 1978).

Treadmill speed was increased in increments of 20 $m \cdot min^{-1}$, and f_c and $\dot{V}O_2$ were recorded over the last 2 min at each speed. From a preliminary study it was concluded that Th_{an}, using the graded protocol, was reached at a $\dot{V}O_2$ which gave a value of $[la^-]_b$ that was about 1.5 $mmol \cdot l^{-1}$ higher than the warm-up values. The $\dot{V}O_2$ at Th_{an} was determined by interpolation (straight lines) between the two closest measured values (Helgerud et al. 1990). Each subject had a warm-up at 75% of his or her recorded average speed for a marathon ($\bar{v}_M$), before the treadmill speed was increased to $\bar{v}_M$, and maintained at this speed for 11 min. The procedures for measuring $\dot{V}O_2$, f_c and $[la^-]_b$ have been described by Helgerud et al. (1990). At each speed, C_R was calculated from the $\dot{V}O_2$, resting values included, divided by the running speed. The C_R was also calculated at Th_{an}, the maximal exercise intensity at which it has been shown that a reliable relationship exists between intensity and $\dot{V}O_2$ (Komi et al. 1981; Bunc and Heller 1989).

Protocol. Tests on a treadmill set at an uphill gradient were carried out 7–14 days after the marathon race: day 1 (treadmill at 1° gradient) determination of Th_{an}, measurement of $\dot{V}O_{2max}$, and f_{cmax}; day 2 (treadmill at 3° gradient) Th_{an}, 45-min break, $\bar{v}_M$, $\dot{V}O_{2max}$ and f_{cmax}. The subjects were given at least 1 day of rest between the 2 test days.

Statistical analysis. The significance of differences measured in the group studied on different days was evaluated using the two-tailed Wilcoxon matched-pairs signed-ranks test. Comparison between the men and women were made with two-tailed Mann-Whitney *U*-test. A combined probabilities test was used to compare the within-group results of the five running-speeds (Fischer 1954). Correlations were calculated by the Spearman rank-correlation coefficient (r_S). The relationship between $\dot{V}O_2$ and m_b was evaluated using linear regression analyses. Results were accepted as significant at $P<0.05$.

Table 1. Physical and physiological characteristis of the subjects

Variables	Men ($n=6$)		Women ($n=6$)	
	Mean	SEM	Mean	SEM
Age (years)	25	0.7	27	1.2
Mass (kg)	68.8	1.6	55.6	2.4
Height (cm)	179	3.0	169	2.2
% Fat[a]	7.1	0.5	17.0	0.8
$\dot{V}O_{2max}$				
($l \cdot min^{-1}$)[b]	4.87	0.07	3.65	0.15
($ml \cdot kg^{-1} \cdot min^{-1}$)[b]	70.7	0.7	66.1	1.4
($ml \cdot kg^{-0.75} \cdot min^{-1}$)[b]	203	1.1	180	3.9
f_{cmax} ($beats \cdot min^{-1}$)[b]	187	3.8	186	3.8
Marathon performance time (min)	159.72	1.85	161.85	1.91

[a] Based on skinfold measurements (Sloan 1967; Sloan et al. 1962)
[b] Gradient of the treadmill 3° (5.25%)
$\dot{V}O_{2max}$, Maximal oxygen uptake
f_{cmax}, Maximal heart rate

Results

The main characteristics of the subjects' test results are shown in Table 1. Compared with the women, the men were on average 13.2 kg heavier, had 9.9% less body fat ($P<0.01$), and their $\dot{V}O_{2max}$ were 1.22 $l \cdot min^{-1}$, 4.6 $ml \cdot kg^{-1} \cdot min^{-1}$, and 23 $ml \cdot kg^{-0.75} \cdot min^{-1}$ higher ($P<0.05$). There were no significant sex differences with regard to age, height, f_{cmax} or performance level over the marathon distance. The $\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$) was on average 3% higher when running on the treadmill at 3° gradient, compared to the value reached at 1° gradient, both for the men and for the women ($P<0.05$). No sex differences in $\dot{V}O_{2max}$ expressed in $ml \cdot kg^{-1} \cdot min^{-1}$ were found be-

Table 2. Results from the submaximal test (treadmill at 1° gradient)

Sex	Running speed ($m \cdot min^{-1}$)	$\dot{V}O_2$ (STPD) ($l \cdot min^{-1}$) Mean	SEM	($ml \cdot kg^{-1} \cdot min^{-1}$) Mean	SEM	(% $\dot{V}O_{2max}$) Mean	SEM	($ml \cdot kg^{-0.75} \cdot min^{-1}$) Mean	SEM	f_c (beats·min^{-1}) Mean	SEM	f_c (% max) Mean	SEM	$\dot{V}_E$ (BTPS) ($l \cdot min^{-1}$) Mean	SEM	R Mean	SEM	$[la^-]_b$ ($mmol \cdot l^{-1}$) Mean	SEM
Male (n=6)	160	2.36	0.08**	34.1	0.8	49.3	1.3	98	2.7	119	3.5	64.2	1.7	58.3	5.9	0.87	0.04	0.77	0.06
	220	3.15	0.12**	45.5	0.9	66.0	1.7	131	3.3	140	2.5	76.0	1.4	74.9	6.2*	0.87	0.01	0.81	0.05*
	240	3.44	0.13**	49.7	0.9	72.0	2.0	143	3.7	150	2.4	81.2	1.5*	83.1	6.7	0.89	0.01	1.00	0.06
	260	3.74	0.09**	54.1	1.0	78.4	2.0	155	3.0	159	1.9	86.2	1.2	93.5	4.3*	0.91	0.01	1.55	0.08**
	280	4.14	0.11**	59.9	0.5	86.8	1.5	172	2.3	168	1.5	90.7	1.2*	110.0	5.3	0.94	0.01	2.93	0.20*
	300	4.48	0.11	64.8	0.6	93.8	1.4	186	2.4	176	1.8	94.9	1.2	131.1	5.7	1.00	0.02	5.67	0.58
Female (n=6)	160	1.79	0.07	32.5	1.2	50.7	2.2	88	3.1	129	5.1	68.9	2.1	45.8	5.2	0.88	0.04	1.27	0.17
	200	2.19	0.05	39.8	1.3	62.0	2.0	108	2.8	143	5.1	76.5	2.2	49.6	2.6	0.84	0.02	1.14	0.15
	220	2.41	0.06	43.9	1.7	68.3	2.6	119	4.1	152	4.9	81.1	2.0	55.5	3.7	0.84	0.02	1.11	0.12
	240	2.69	0.08	48.7	1.5	75.9	2.6	133	3.6	161	4.7	86.2	1.5	62.3	4.7	0.84	0.02	1.43	0.14
	260	2.99	0.08	54.2	1.6	84.3	2.5	147	3.8	169	4.7	90.6	1.5	72.0	6.2	0.87	0.01	2.45	0.18
	280	3.30	0.09	59.8	1.8	93.0	2.6	163	4.1	179	4.5	95.7	1.0	87.8	7.5	0.96	0.02	5.38	0.60

* $P<0.05$; ** $P<0.01$; STDP, standard temperature and pressure, dry; BTPS, body temperature and pressure, saturated; $\dot{V}O_2$, oxygen uptake, resting value included; $\dot{V}O_{2max}$, maximal oxygen uptake; f_c, heart rate; $\dot{V}_E$, expired minute ventilation; R, respiratory exchange ratio; $[la^-]_b$, blood lactate concentration

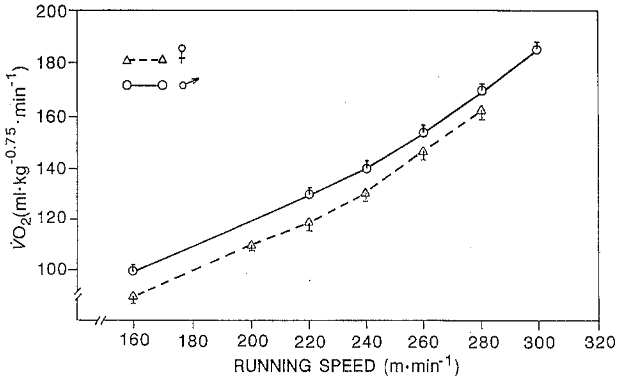

Fig. 1. Average oxygen uptake ($\dot{V}O_2$, rest included) expressed in $ml \cdot kg^{-0.75} \cdot min^{-1}$ as a function of running speed, treadmill at 1° gradient (mean and SEM)

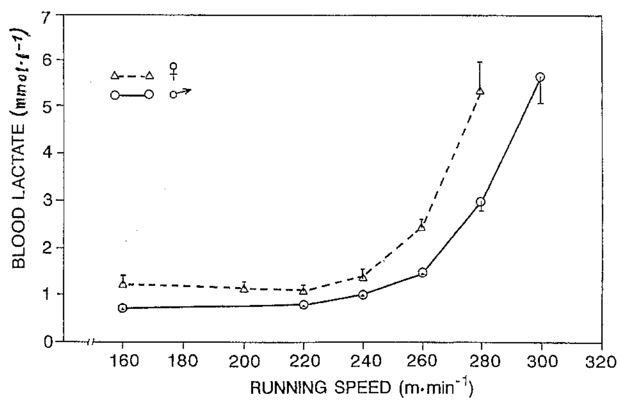

Fig. 2. Average blood lactate concentration as a function of running speed, treadmill at 1° gradient (mean and SEM)

tween the performance-matched marathon runners at 1° uphill gradient on the treadmill. The $\dot{V}O_{2max}$ expressed in $ml \cdot kg^{-0.75} \cdot min^{-1}$ was about 10% higher in the men than in the women both at 1° and 3° gradients ($P<0.05$), whereas f_{cmax} was approximately equal for the two sexes (186–187 beats·min^{-1}). The $\dot{V}O_{2max}$ was related to m_b (m_b^b Eq. 1), the values of the exponent b being 0.81 (r_S=0.87, P=0.03) and 0.65 (r_S=0.97, P=0.001) for the men and the women, respectively. The sex differences in exponent b were not significant.

The physiological responses during sub-maximal exercise (Table 2) showed no significant differences between the men and the women with respect to $\dot{V}O_2$ in $ml \cdot kg^{-1} \cdot min^{-1}$ or when comparing %$\dot{V}O_{2max}$, and %f_{cmax}.

The C_R was approximately 10–12 $ml \cdot kg^{-0.75} \cdot min^{-1}$ higher in the men compared with the women ($P<0.05$) at the same running speeds (Fig. 1). The $[la^-]_b$ values in the women were higher ($P<0.001$) than in the men during the Th_{an} test-protocol (Fig. 2). If, however, the $[la^-]_b$ was expressed as a function of % $\dot{V}O_{2max}$, no significant sex-differences were found.

The C_R at speeds between 160 and 300 $m \cdot min^{-1}$ was independent of the speed in all subjects. The mean

Table 3. Physiological parameters at anaerobic threshold (Th_{an}) determined from the submaximal test (Table 2)

Sex	$v_{Th_{an}}$ (m·min^{-1})		$\dot{V}O_2$ (STPD) (l·min^{-1})		(ml·kg^{-1}·min^{-1})		(% $\dot{V}O_{2max}$)		(ml·kg$^{-0.75}$·min^{-1})		f_c (beats·min^{-1})		f_c (% max)		$\dot{V}_E$ (BTPS) (l·min^{-1})		R		$[la^-]_b$ (mmol·l^{-1})	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Male (n=6)	272	3.1	4.00	0.11**	57.8	0.9	84.4	0.9	166	3.1***	164	2.0	89.1	1.1	103.5	4.2**	0.92	0.01	2.27	0.06
Female (*n*=6)	264	2.6	3.05	0.09	55.3	1.4	86.5	1.9	151	3.3	172	3.8	92.1	0.9	74.1	6.2	0.89	0.02	2.77	0.17

** $P<0.01$; *** $P<0.001$; $v_{Th_{an}}$, average speed at anaerobic threshold; for other definitions see Table 2

Table 4. Physiological parameters at average speed of marathon (v_M)

Sex	$\bar{v}_M$ (m·min^{-1})		$\dot{V}O_2$ (STPD) (l·min^{-1})		(ml·kg^{-1}·min^{-1})		(% $\dot{V}O_{2max}$)		(ml·kg$^{-0.75}$·min^{-1})		f_c (beats·min^{-1})		f_c (% max)		$\dot{V}_E$ (BTPS) (l·min^{-1})		R		$[la^-]_b$ (mmol·l^{-1})		$\frac{\dot{V}O_2 \text{ at } \bar{v}_M \cdot 100}{\dot{V}O_2 \text{ at } Th_{an}}$ (%)	
	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM	Mean	SEM
Male (*n*=6)	264	2.8	3.93	0.11**	56.7	0.3	82.1	0.9	164	2.0**	163	2.9	87.9	0.6*	106.4	5.3**	0.93	0.01	1.58	0.02*	98.2	1.8
Female (*n*=6)	261	2.9	3.09	0.09	55.8	1.5	86.7	1.8	152	3.3	173	5.0	92.4	1.2	76.1	3.4	0.91	0.02	2.65	0.26	101.0	1.5

* $P<0.05$; ** $P<0.01$; Th_{an}, anaerobic threshold $\bar{v}_M$, average speed in marathon; for other definitions see Table 2

Table 5. Athletic background and amount of training of the subjects over the previous 6 months

Variables	Men ($n=6$)		Women ($n=6$)	
	Mean	SEM	Mean	SEM
Athlethic background				
Endurance training (years)	6.0	1.6	6.5	1.0
Competitive sport (years)	8.5	1.8	9.5	2.0
Race running (years)	5.5	1.4	6.0	2.0
Completed marathon races (n)	3.0	1.6	9.0	4.2
Weekly endurance training over the previous 6 months				
Days	6.2	0.3	7.0	0.1
Hours	8.4	0.8	10.5	0.9
High-intensity workouts (n)	1.6	0.4	2.5	0.2
Weekly running over the previous 6 months				
First 4 months:				
Days	4.0	0.7[a]	6.0	0.4
Hours	5.3	1.3	9.5	1.2
% Total endruance training	63.1	10.6	90.5	6.2
Kilometres	59	13.2	101	9.0
High intensity workouts (n)	1.2	0.4	2.5	0.2
Last 2 months:				
Days	5.9	0.6	7.0	0.3
Hours	7.9	0.8	9.8	0.7
% Total endurance training	94.0	7.5	93.3	3.5
Kilometres	88	10.3	102	6.4
High intensity workouts (n)	1.9	0.4	2.5	0.2

[a] $P<0.05$

value of C_R at a speed equal to Th_{an} was 0.613 (SEM 0.020) $ml \cdot kg^{-0.75} \cdot m^{-1}$ for the men and 0.570 (SEM 0.034) $ml \cdot kg^{-0.75} \cdot m^{-1}$ for the women ($P<0.05$). The overall mean value of C_R was 0.211 (SEM 0.005) $ml \cdot kg^{-1} \cdot m^{-1}$, and its coefficient of variation was 5.2%. No significant correlation was observed between C_R and m_b.

In both groups Th_{an} was about 85% $\dot{V}O_{2max}$ and 90% f_{cmax} (Table 3). The $\dot{V}O_2$ ($l \cdot min^{-1}$, $ml \cdot kg^{-0.75} \cdot min^{-1}$) and expired minute ventilation ($\dot{V}_E$) were higher in the men ($P<0.01$).

A running velocity equivalent to $\bar{v}_M$ required a utilization of 82.1 (SEM 0.9)% $\dot{V}O_{2max}$ for the male runners and 87.6 (SEM 1.8)% $\dot{V}O_{2max}$ for the female runners, but the difference was not significant (Table 4). The women had higher % f_{cmax} (4.5%) and $[la^-]_b$ (1.07 $mmol \cdot l^{-1}$) values than men at $\bar{v}_M$ ($P<0.05$). For the two sexes the values of the physiological parameters at $\bar{v}_M$ and Th_{an} were almost identical. The male runners showed a tendency towards higher running speed at Th_{an} than at $\bar{v}_M$ ($P=0.06$), but the only significant difference was their 0.69 $mmol \cdot l^{-1}$ higher $[la^-]_b$ at Th_{an}.

Selected results from the questionnaire are presented in Table 5. The women ran 2 days more per week than men from 2 to 6 months before the marathon race ($P<0.05$).

Discussion

The $\dot{V}O_{2max}$ was 66.1 $ml \cdot kg^{-1} \cdot min^{-1}$ in the women. These $\dot{V}O_{2max}$ values are among the highest that have ever been reported in women distance runners (Daniels et al. 1986; Pate et al. 1987; Bunc and Heller 1989; Bergh et al. 1991; Padilla et al. 1992). Results from most other studies investigating women distance runners have reported $\dot{V}O_{2max}$ values at or below approximately 60 $ml \cdot kg^{-1} \cdot min^{-1}$ and lower (e.g. Pate et al. 1985; Di Prampero et al. 1986; Ramsbottom et al. 1989; Helgerud et al. 1990). However, mean $\dot{V}O_{2max}$ of 70.7 $ml \cdot kg^{-1} \cdot min^{-1}$ in the men was lower than previously reported for elite male distance runners, often possessing $\dot{V}O_{2max}$ values in the range of 74–78 $ml \cdot kg^{-1} \cdot min^{-1}$ (Costill and Fox 1969; Davies and Thompson 1979). Consequently, the men in the present study did not qualify as elite athletes.

The $\dot{V}O_{2max}$ during running was proportional to m_b raised to a power of less than 1. There were no sex differences and the values of the exponent b (Eq. 1) were 0.81 and 0.65 for the men and the women, respectively. These data agree with measurements which have been made by von Døbeln (1956) and Bergh et al. (1991), and the exponents are close to the value of $m_b^{0.67}$ predicted from the theory of similarity (Åstrand and Rodahl 1986). As has been suggested by Bergh et al. (1991) $\dot{V}O_{2max}$ expressed in $ml \cdot kg^{-0.75} \cdot min^{-1}$ would be more appropriate than the unit $ml \cdot kg^{-1} \cdot min^{-1}$ to indicate the capacity of the oxygen transporting system. Thus, the conventional method of expressing $\dot{V}O_{2max}$ in $ml \cdot kg^{-1} \cdot min^{-1}$ tends to underestimate the running performance in subjects with high compared to those with low m_b (Åstrand and Rodahl 1986; Bergh et al. 1991). There is still a controversy regarding the relationship between $\dot{V}O_{2max}$ and m_b. Studying elite male and female middle-distance runners Lacour et al. (1990) and Padilla et al. (1992) have found no significant correlation between $\dot{V}O_{2max}$ and m_b. Although no sex difference was found in the present study when $\dot{V}O_{2max}$ was expressed as $ml \cdot kg^{-1} \cdot min^{-1}$ running at 1° gradient, the unit $ml \cdot kg^{-0.75} \cdot min^{-1}$ showed 10% higher values in the men compared to performance-matched women. Correspondingly, the difference in $\dot{V}O_{2max}$ between the sexes was found to be 6% in a study investigating performance-matched men and women with a performance of about 3 h 20 min for marathon runs (Helgerud et al. 1990). The most likely reason for these discrepancies in reported values for $\dot{V}O_{2max}$ could be the relatively large sex difference in m_b (Table 1). Thus, women must compensate for their lower $\dot{V}O_{2max}$ ($ml \cdot kg^{-0.75} \cdot min^{-1}$) through other physiological mechanisms that influence running performance capability.

The finding that f_{cmax} values (about 187 beat·min^{-1}) were similar in women and men (Table 1) is in agreement with results from other studies (e.g. Pate et al. 1985; Ramsbottom et al. 1989; Helgerud et al. 1990). Pate et al. (1987) have found f_{cmax} of 189 beats·min^{-1} in their group of elite female runners possessing approximately similar $\dot{V}O_{2max}$ as the present group.

An inverse relationship between C_R and m_b has been reported for elite distance runners of both sexes (Williams et al. 1987; Bergh et al. 1991; Padilla et al. 1992). The variability of C_R and m_b in the present study corresponds to measurements that have been made by Bergh et al. (1991; 20 women and 27 men) and Padilla et al. (1992; 14 women and 24 men), but no significant correlation was observed between C_R and m_b. The reason for this lack of correlation presumably lay in the small number of subjects in the present study. Applying Eq. 1 to the data on female runners reported by Padilla et al. (1992) demonstrated that $\dot{V}O_2$ at a given running speed scaled with $m_b^{0.62}$ ($r_S = 0.68$, $P = 0.007$). Thus it seems reasonable to concur with the conclusion of Bergh et al. (1991). When comparing C_R in individuals with different m_b it would be better to express submaximal $\dot{V}O_2$ as ml·kg$^{-0.75}$·min^{-1}.

The $\dot{V}O_2$ of running observed in the present study was slightly higher than has been reported earlier (Daniels et al. 1986; Pate et al. 1987; Williams et al. 1987; Bunc and Heller 1989; Bergh et al. 1991; Padilla et al. 1992; Daniels and Daniels 1992), and the reason for this may be that these studies have used horizontal treadmill running whereas the present study was carried out at 1° gradient. The C_R was constant within the range 60–95% $\dot{V}O_{2max}$, and this result is consistent with data obtained by Di Prampero et al. (1986) in male recreational runners and by Bunc and Heller (1989) in different groups of trained distance runners of both sexes. The $\dot{V}O_2$ of running was approximately 10–12 ml·kg$^{-0.75}$·min^{-1} higher in the men than in the women when compared at the same running speeds (Fig. 1). This results in an identical C_R expressed in ml·kg^{-1}·ml^{-1} in the men and the women, which is consistent with numerous previous observations (Daniels et al. 1977, 1986; Sparling and Cureton 1983; Bunc and Heller 1989; Padilla et al. 1992). For a given m_b this results in lower C_R (ml·kg^{-1}·m^{-1}) in female than in male distance runners, because m_b of the women has been consistently lower (Padilla et al. 1992). The superior C_R in women could be expected on the basis of their more extensive running regimens compared to the men over the prior 6 months (about 33 km weekly as shown in Table 5). The preceding discussion illustrates the need to identify appropriate performance-based criteria to assess sex differences in C_R. The superior C_R in the female subjects in the present study may contribute to compensating in part for their lower $\dot{V}O_{2max}$ relative to the performance-matched male subjects.

Although no sex differences in Th_{an} expressed as $\%\dot{V}O_{2max}$ and $\%f_{cmax}$ were found (Table 3), the $\dot{V}O_2$ at Th_{an} was about 15 ml·kg$^{-0.75}$·min^{-1} higher for the male when compared to the female runners. This may be due to the correspondingly higher $\dot{V}O_{2max}$ in the men. The same tendency was also observed (Table 3) with a somewhat higher running speed at Th_{an} (8 m·min^{-1}) for the men compared to the women. Significantly higher $[la^-]_b$ was found at identical sub-maximal running velocities for the women compared to the men (Fig. 2). This observation is in agreement with results from a previous study (Helgerud et al. 1990). If, however, the $[la^-]_b$ was expressed as a function of $\%\dot{V}O_{2max}$, there were no differences between the sexes or between groups with different performance levels in marathon running. The 10 m·min^{-1} higher running speed in the men at a reference $[la^-]_b$ can be explained by their higher $\dot{V}O_{2max}$ (Table 1) in the present as well as in the previous study (Helgerud et al. 1990).

As shown in Table 4 the female runners had somewhat higher utilization of $\dot{V}O_{2max}$ at $\bar{v}_M$ (82% and 87% in the men and the women, respectively). This tendency was also reflected by significantly higher $\%f_{cmax}$ and $[la^-]_b$ at $\bar{v}_M$ in the women. The extensive endurance training of the women has probably resulted in an increased "aerobic fitness", indicating that they were able to exercise at a higher proportion of their $\dot{V}O_{2max}$ compared to the men. For both sexes the values of the physiological parameters at $\bar{v}_M$ also indicated that on average the subjects keep close to their Th_{an} during marathon races.

The subjects' high performance level in marathon running demonstrated a higher estimated fractional utilization of $\dot{V}O_{2max}$ (82%–87%) during a marathon than has been observed in less physically fit subjects (about 78% $\dot{V}O_{2max}$) in a previous study (Helgerund et al. 1990). This calculated value agrees with previously reported data (Costill and Fox 1969; Costill et al. 1973; Farrell et al. 1979; Davies and Thompson 1979), supporting the view that the fractional utilization of $\dot{V}O_{2max}$ depends essentially on the duration of exercise (Saltin 1973; Di Prampero et al. 1986). This maximal sustainable fraction during distance running has been shown to be partly dependent on the state of training (Costill et al. 1973). It is therefore important to evaluate athletic background and amount of training before concluding that differences in physiological responses are sex-related. The present study showed that the female runners trained more than the male (Table 5). These differences are most pronounced when the weekly running is compared in the 6th to the 2nd month before the marathon. The women ran in this period 2 days each week ($P < 0.05$), 4.2 h ($P = 0.06$), 42 km ($P = 0.06$) more than the men. The women also had a mean of 1.3 ($P = 0.06$) more high intensity workouts each week. Thus, part of the sex differences observed in the present study may have been due to a substantial difference in training between the men and the women. Furthermore, several of the insignificant differences between the two sexes may have been due to the small number of subjects as well as the heterogeneity of the men.

Conclusion

The present results indicated that the higher $\dot{V}O_{2max}$ and Th_{an} expressed in $ml \cdot kg^{-0.75} \cdot min^{-1}$ in the men are compensated for in performance-matched women by more running training, superior running economy, and their ability to exercise at a higher proportion of $\dot{V}O_{2max}$ during the marathon race.

Acknowledgements. The technical assistance of Svein Leirstein is gratefully acknowledged. This study was partly supported by grants from the Norwegian Research Council for Science and the Humanities, Council for Medical Research.

References

Åstrand PO, Rodahl K (1986) Textbook of work physiology. McGraw-Hill, New York

Berg U, Sjødin B, Forsberg A, Svedenhag J (1991) The relationship between body mass and oxygen uptake during running in humans. Med Sci Sports Exerc 23:205–211

Bransford DR, Howley ET (1977) Oxygen cost of running in trained and untrained men and women. Med Sci Sports Exerc 9:41–44

Bunc V, Heller J (1989) Energy cost of running in similarly trained men and women. Eur J Appl Physiol 59:178–183

Conley DL, Krahenbuhl GS (1980) Running economy and distance running performance of highly trained athletes. Med Sci Sports Exerc 12:357–360

Costill DL, Fox EL (1969) Energetics of marathon running. Med Sci Sports Exerc 2:81–86

Costill DL, Thomason H, Roberts E (1973) Fractional utilization of the aerobic capacity during distance running. Med Sci Sports Exerc 5:248–252

Daniels J, Daniels N (1992) Running economy of elite male and elite female runners. Med Sci Sports Exerc 24:483–489

Daniels J, Krahenbuhl G, Foster C, Gilbert J, Daniels S (1977) Aerobic responses of female distance runners to submaximal and maximal exercise. In: Milvy P (ed) The marathon: physiological, medical and psychological studies. Ann NY Acad Sci 301:726–733

Daniels J, Scardina N, Hayes J, Foley P (1986) Elite and subelite female middle- and long-distance runners. In: Landers DM (ed) Sport and elite performers. Human Kinetics, Champaign, Ill., pp 57–72

Davies CTM, Thompson MW (1979) Aerobic performance of female marathon and male ultra marathon athletes. Eur J Appl Physiol 41:233–245

Di Prampero PE, Atchou G, Brückner JC, Moia C (1986) The energetics of endurance running. Eur J Appl Physiol 55:259–266

Døbeln W von (1956) Maximal oxygen uptake, body size and total haemoglobin in normal man. Acta Physiol Scand 38:193–199

Farell PA, Wilmore JH, Coyle EF, Billing JE, Costill DL (1979) Plasma lactate accumulation and distance running performance. Med Sci Sports Exerc 11:338–344

Fischer RA (1954) Statistical methods for research workers. Liver and Loyd, Edinburgh

Helgerud J, Ingjer F, Strømme F (1990) Sex differences in performance-matched marathon runners. Eur J Appl Physiol 61:433–439

Komi PV, Ito A, Sjødin B, Wallenstein R, Karlsson J (1981) Muscle metabolism, lactate breaking point, and biomechanical features of endurance running. Int J Sports Med 2:148–153

Lacour JR, Padilla-Magunacelaya S, Barthélémy JC, Dormois D (1990) The energetics of middle distance running. Eur J Appl Physiol 60:38–43

Padilla S, Bourdin M, Barthélémy, Lacour JR (1992) Physiological correlates of middle-distance running performance. A comparative study between men and women. Eur J Appl Physiol 65:561–566

Pate RR, Barnes C, Miller W (1985) A physiological comparison of performance-matched male and female distance runners. Res Q Exerc Sport 56:245–250

Pate RR, Sparling PB, Wilson GE, Cureton KJ, Miller BJ (1987) Cardiorespiratory and metabolic responses to submaximal and maximal exercise in elite women distance runners. Int J Sports Med [Suppl] 8:91–95

Ramsbottom R, Williams C, Boobis L, Freeman W (1989) Aerobic fitness and running performance of male and female recreational runners. J Sports Sci 7:9–20

Saltin B (1973) Oxygen transport by the circulatory system during exercise in man. In: Keul J (ed) Limiting factors of physical performance. Thieme, Stuttgart, pp 235–252

Saltin B, Åstrand PO (1967) Maximal oxygen uptake in athletes. J Appl Physiol 23:353–358

Sloan AW (1967) Estimation of body fat in young men. J Appl Physiol 23:311–315

Sloan AW, Burt JJ, Blyth CS (1962) Estimation of body fat in young women. J Appl Physiol 17:967–970

Soutter WP, Sharp F, Clark DM (1978) Bedside estimation of whole blood lactate. Br J Anaesth 50:445–450

Sparling PB, Cureton KJ (1983) Biological determinations of the sex difference in 12 min run performance. Med Sci Sports Exerc 15:218–223

Williams KR, Cavanagh PR, Ziff JL (1987) Biomechanical studies of elite female distance runners. Int J Sports Med [Suppl] 8:107–118