Physical and training characteristics of top-class marathon runners

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ABSTRACT

BILLAT, V. L., A. DEMARLE, J. SLAWINSKI, M. PAIVA, and J.-P. KORALSZTEIN. Physical and training characteristics of top-class marathon runners. *Med. Sci. Sports Exerc.*, Vol. 33, No. 12, 2001, pp. 2089–2097. **Purpose:** This study compares the physical and training characteristics of top-class marathon runners (TC), i.e., runners having a personal best of less than 2 h 11 min for males and 2 h 32 min for females, respectively, versus high-level (HL) ($<$ 2 h 16 min and $<$ 2 h 38 min). **Methods:** Twenty marathon runners (five TC and HL in each gender) ran 10 km at their best marathon performance velocity (vMarathon) on a level road. This velocity was the target velocity for the Olympic trials they performed 8 wk later. After a rest of 6 min, they ran an all-out 1000-m run to determine the peak oxygen consumption on flat road ($\dot{V}O_{2peak}$). **Results:** Marathon performance time (MPT) was inversely correlated with $\dot{V}O_{2peak}$ ($r = -0.73$, $P < 0.01$) and predicted 59% of the variance of MPT. Moreover, TC male marathon runners were less economical because their energy cost of running (Cr) at marathon velocity was significantly higher than that of their counterparts (212 ± 17 vs 195 ± 14 $mL \cdot km^{-1} \cdot kg^{-1}$, $P = 0.03$). For females, no difference was observed for the energetic characteristics between TC and HL marathon runners. However, the velocity reached during the 1000-m run performed after the 10-km run at vMarathon was highly correlated with MPT ($r = -0.85$, $P < 0.001$). Concerning training differences, independent of the gender, TC marathon runners trained for more total kilometers per week and at a higher velocity (velocity over 3000 m and 10,000 m). **Conclusion:** The high energy output seems to be the discriminating factor for top-class male marathon runners who trained at higher relative intensities. **Key Words:** MARATHON, OXYGEN CONSUMPTION, TRAINING, GENDER

In a previous study, di Prampero (11) showed that the marathon running speed (vMarathon in $m \cdot min^{-1}$) could be predicted i) from the energy cost of running (Cr) measured by the oxygen cost of running ($mL \cdot kg^{-1} \cdot km^{-1}$), ii) from the subject's maximal oxygen consumption ($\dot{V}O_{2max}$ in $mL \cdot kg^{-1} \cdot min^{-1}$), and iii) from the maximal fraction that can be sustained throughout the race (FR in percent) according to equation 1:

$$\text{vMarathon} = FR\dot{V}O_{2max} * Cr^{-1} \quad (1)$$

Joyner (18) has estimated that the fastest time for the marathon predicted by this model is 1 h 57 min 58 s (vs 2 h 5 min 42 s in the year 2000). This was calculated for a hypothetical subject who had a $\dot{V}O_{2max}$ of 84 $mL \cdot kg^{-1} \cdot min^{-1}$, a lactate threshold (i.e., the first increase in blood lactate above baseline, according to Farrel et al. (12)) at 85% $\dot{V}O_{2max}$ and a low energy cost of running (204 $mL \cdot kg^{-1} \cdot km^{-1}$). Joyner estimated that the marathon velocity could be slightly above the lactate threshold velocity at 90% of $\dot{V}O_{2max}$. For this estimation, he took into account the 2–3% increase in $\dot{V}O_2$ that would occur between 10 min to 2 h and the 7–8% increase in Cr because of the wind resistance over ground compared with treadmill running.

However, we do not know if all these three factors that contribute to marathon performance are exclusive independent variables. For example, do physiological characteristics associated with a high $\dot{V}O_{2max}$ tend to coexpress with characteristics tending to reduce running economy? Indeed, Lacour et al. (20) showed that athletes who exhibited the highest velocity associated with $\dot{V}O_{2max}$ (the ratio of $\dot{V}O_{2max}$/Cr) were those who had a high $\dot{V}O_{2max}$ but a middle value of Cr. However, no study has measured FR and Cr in real conditions: on the road and at the marathon velocity. Furthermore, in treadmill-based studies, FR has been calculated on the basis of $\dot{V}O_{2max}$ tests performed during inclined, not flat, treadmill running (33).

At the end of spring 2000, when the Olympic trials for Sydney were finished, 277 male and 225 female marathon runners performed a marathon in less than 2 h 16 min and 2 h 39 min, respectively. Among these high-level runners, only 35% (98 males and 72 females) had satisfied the Olympic minima set by European countries such as France (2 h 11 min for males and 2 h 32 min for females). No study has examined what physiological and training factors differentiate high-level (HL) from top-class (TC) marathon runners.

Top-class male marathon runners tend to also have high-level personal best during middle distance (runs $<$ 3 min 40 s over 1500 m, $<$ 7 min 40 s over 3000 m, and $<$ 13 min 40 s over 5 km). We hypothesize that they have a high $\dot{V}O_{2max}$ and that they trained at relatively faster velocities than their high-level counterparts, especially at velocities

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TABLE 1. Physiological responses during the 10-km run at vMarathon among top-class and high-level male and female runners.

Factors	Males		*P* TC vs HL among Males	Females		*P* TC vs HL among Females	*P* between Genders
	TC	HL		TC	HL		
$\dot{V}O_2$ @ 3 km (mL·min^{-1})	70.1 ± 7.9	64.6 ± 3.9	0.17	58.5 ± 3.9	56.8 ± 4.5	0.60	0.03
$\dot{V}O_2$ @ 10 km (mL·min^{-1})	71.4 ± 7.2	63.7 ± 5.7	0.09	55.8 ± 4.7	57.1 ± 6.5	0.83	0.03
HR @ 3 km (beats·min^{-1})	161 ± 3	170 ± 6	0.01	159 ± 9	166 ± 3	0.09	0.09
HR @ 10 km (beats·min^{-1})	167 ± 5	176 ± 7	0.04	165 ± 12	171 ± 4	0.60	0.17
Lactate @ start (mmol·L^{-1})	2.4 ± 1.0	1.9 ± 0.7	0.67	1.5 ± 0.3	1.9 ± 0.6	0.34	0.45
Lactate @ 3 km (mmol·L^{-1})	7.7 ± 6.7	4.6 ± 1.0	0.01	3.7 ± 1.5	4.4 ± 2.0	0.46	0.01
Lactate @ 10 km (mmol·L^{-1})	10.0 ± 3.0	7.2 ± 1.2	0.17	8.7 ± 4.1	8.0 ± 3.3	0.60	0.91
RER @ 3 km	0.92 ± 0.01	0.98 ± 0.08	0.11	0.94 ± 0.01	0.95 ± 0.05	0.75	0.86
RER @ 10 km	0.94 ± 0.01	1.00 ± 0.08	0.11	0.97 ± 0.07	0.95 ± 0.08	0.59	0.91
τ @ v1000 (s)	11 ± 7	14 ± 6	0.12	12 ± 6	16 ± 7	0.15	0.13
$\Delta\dot{V}O_2$6–3min @ vMarathon (mL·min^{-1})	125 ± 250	100 ± 173	0.99	30 ± 10	100 ± 20	0.08	0.42

$\dot{V}O_2$, HR, Lactate, RER @ 3 km are $\dot{V}O_2$, heart rate, blood lactate concentration, and rate of expiratory ratio at the third kilometer during the 10-km run at vMarathon; $\dot{V}O_2$, HR, Lactate, RER @ 10 km are $\dot{V}O_2$, heart rate, blood lactate concentration, and rate of expiratory ratio at the tenth kilometer during the 10-km run at vMarathon; $\Delta\dot{V}O_2$6–3 min @ vMarathon is the difference (in mL·min^{-1}) of rate of oxygen uptake between the sixth and the third minutes during the 10-km run at vMarathon; τ @ v1000 is the time constant (in seconds) of oxygen kinetics during the all-out 1000-m run after the 10-km run at vMarathon.

close to their velocity over 3000–10,000 m, eliciting $\dot{V}O_{2max}$ (5). Therefore, the purpose of this study was to compare the energetic and training factors that contribute to the marathon performance (time) of top-class (2 h 6 min 34 s to 2 h 11 min 59 s for males and 2 h 25 min to 2 h 30 min 59 s for females) versus high-level marathon runners (2 h 12 min to 2 h 16 min for males and 2 h 31 min to 2 h 38 min for females).

METHODS

Subjects

The subjects belong to the national teams of two European countries: Portugal ($N = 11$) and France ($N = 9$). The experiments were performed 8 wk before the Olympic trials. The two groups included 10 top-class and 10 high-level runners, with five males and five females in each group for each level. There were four Portuguese and one French among the TC males and three Portuguese and two French among the TC females. For the high-level group there were three Portuguese and two French and one Portuguese and four French for the males and females, respectively.

The division between the two levels of performance (i.e., the personal best for the marathon) was the Olympic minima set by France (2 h 12 min for men and 2 h 31 min for women). This corresponds to +5% of the world best performance for men and +7% for females (or the 100th performance in 1999). They train at least 10–14 times·wk^{-1} (140–200 km). Before participation in this study, all subjects provided voluntary written informed consent and approval received by ethics committee in accordance with the guidelines of the University of Lille.

Experimental Design

All experiments were carried out on a wind-still, level road, between 10:00 h and 16:00 h according to each subject's preference, at a temperature of 8°C in France and 15°C in Portugal.

Runners were asked to maintain the same habits as before a marathon and were therefore not instructed to refrain from caffeinated foods or beverages before running.

Runners followed a pacing cyclist traveling at the required velocity. The pace was checked every 200 m during the first kilometer and then every 500 m. Visual marks were set at 100-m intervals along the road for the first kilometer and then every 500 m.

After a warm-up race, subjects ran 10 km on a level road at their target marathon velocity for the upcoming Olympics trials race (Table 1). Six minutes after the 10-km run at marathon velocity (vMarathon), the subject had to run as fast as possible over 1000 m to determine $\dot{V}O_{2peak}$ (2). The average velocity over 1000 m was termed v1000m and was expressed as a percentage of the marathon velocity.

Data Collection Procedures

Blood lactate samples were collected 1) after the warm-up, 2) at the third kilometer of the 10-km vMarathon run (when the runners stopped for 15 s), 3) 1 and 5 min after completion of the 10-km run at vMarathon run, and 4) 1 and 3 min after completion of the maximal 1000-m run. The highest of these postrun blood lactate values was taken as the maximal blood lactate for 10 km at vMarathon and v1000m. The capillary blood sample was obtained from the fingertip and immediately analyzed for lactate concentration (YSI 27 analyzer, Yellow Springs Instruments, Yellow Springs, OH).

Measurement of $\dot{V}O_2$ was performed throughout each test using a telemetric system weighing 0.7 kg, which was worn on the back and abdomen (K4 b^2, COSMED, Rome, Italy). Expired gases were measured, breath by breath, and averaged every 5 s. The response times of the oxygen and carbon dioxide analyzers take less than 120 ms to reach 90% of the flow sample. The ventilation range of the flowmeter is 0 to 300 L·min^{-1}. The time delay of the gas analyzer (time necessary for the gas to transit through the sampling line before being analyzed) is about 500 ms. This time delay is automatically measured and is considered in the calculations when a delay calibration procedure is performed according to the manufacturer's specifications. The algorithms used in the K4 b^2 have been developed according to Beaver et al. and Wasserman et al. (3,32). Before each test, the O_2 analysis system was calibrated using ambient air, whose partial

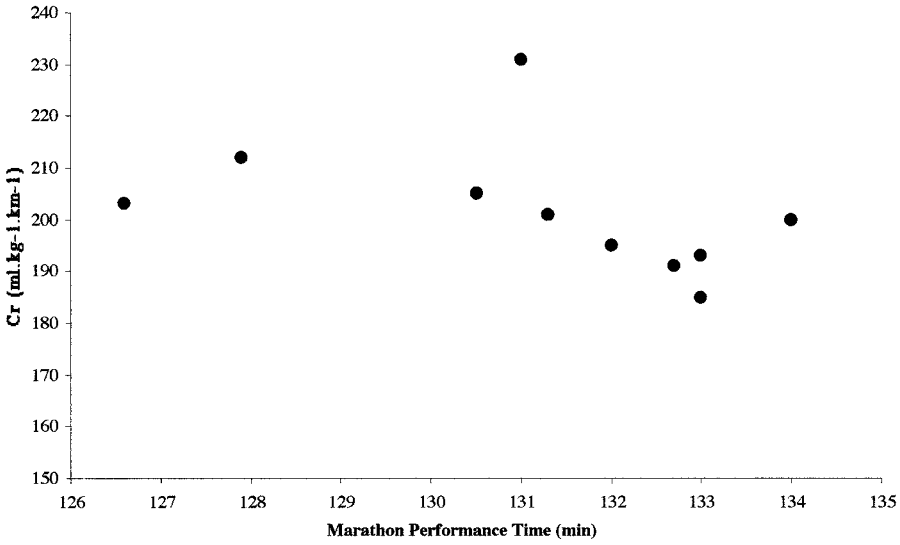

FIGURE 1—Scatter plot depicting relationship between MPT in minutes and energy cost of running (mL·kg^{-1}·min^{-1}) measured in a 10-km run at the velocity of the marathon; r = −0.44, *P* = 0.21.

O_2 composition was assumed to be 20.9% and a gas of known CO_2 concentration (5%) (K4 b^2 instruction manual). The calibration of the turbine flowmeter of the K4 b^2 was performed with a 3-L syringe (Quinton Instruments, Seattle, WA). In the 1000-m exhaustive run, $\dot{V}O_{2peak}$ was defined as the highest $\dot{V}O_2$ obtained in two successive 15-s interval runs.

Data Analyses

Training log analysis. The final 12 wk of specific training before the marathon trials was analyzed from the training log of the trainer. In addition, the runner was asked to describe his or her typical week. Training sessions were classified according to their velocity: less than vMarathon, equal to vMarathon, equal to v1/2-marathon (21.1 km), v10,000m, and v3000m. The total distance and number of sessions run per week were also computed.

Oxygen kinetics parameters. The $\dot{V}O_2$ kinetics during the all-out 1000-m run was best described by a mono exponential function according to the following equation:

$$\dot{V}O_2(t) = \dot{V}O_{2baseline} + A * (1 - e^{-(t/\tau)}) \qquad (2)$$

where $\dot{V}O_2$ (t) is the oxygen uptake at time (t), the $\dot{V}O_2$ baseline is the oxygen uptake at the end of the warm-up, A is the amplitude of the oxygen uptake, and τ is the time constant.

Statistical Analysis

The nonparametric Mann-Whitney test was used to compare top-class and high-level groups of performance within each gender (four groups of five subjects only). After having checked the equality of variance, an independent *t*-test was used to compare physiological characteristics and training logs between genders, since the sample was sufficient (two groups of 10 subjects). Correlation between energetic parameters and marathon performance time for each of the groups were determined using the Pearson product moment correlation coefficient, and their relationships with performance were evaluated using a stepwise regression (*F* to enter = 4). Results are presented as mean ± standard deviation (SD). Statistical significance was set at $P < 0.05$.

RESULTS

Velocity was very constant, since the coefficient of variation was less than 2% from the first to the tenth kilometer. All the runners started faster during the first half kilometer as in a race (+5 ± 2% of vMarathon).

Factors that Discriminate Top-Class from High-Level Marathon Performance in Male and Female Runners

Males. Top-class (TC) male marathon runners had a significantly higher $\dot{V}O_{2max}$ than their high-level (HL) counterparts (79.6 ± 6.2 vs 67.1 ± 8.1 mL·kg^{-1}·min^{-1}, $P = 0.04$) (Table 1). Moreover, TC male marathon runners were less economical, since their Cr at marathon velocity was significantly higher than those of their HL counterparts (210 ± 12 vs 195 ± 4 mL·kg^{-1}·km^{-1}, $P = 0.009$). Energy cost of running was, therefore, not significantly correlated with marathon performance time (MPT) (r = −0.44, $P = 0.21$) (Fig. 1). For males, the factor that discriminated MPT during a marathon was $\dot{V}O_{2peak}$ (r = −0.77, $P = 0.007$) (Fig. 2). $\dot{V}O_{2peak}$ determined 59% of the variance and was the only factor that entered into the stepwise regression predicting MPT (Tables 2 and 3).

For males, the velocity in the all-out run over 1000 m after the 10-km run at vMarathon was not a predictor for performance (r = −0.57, $P = 0.11$).

Females. In females, neither $\dot{V}O_{2peak}$ nor Cr nor FR$\dot{V}O_{2peak}$ were correlated with marathon performance time, and none of these factors entered into the stepwise regression (Tables 2 and 3).

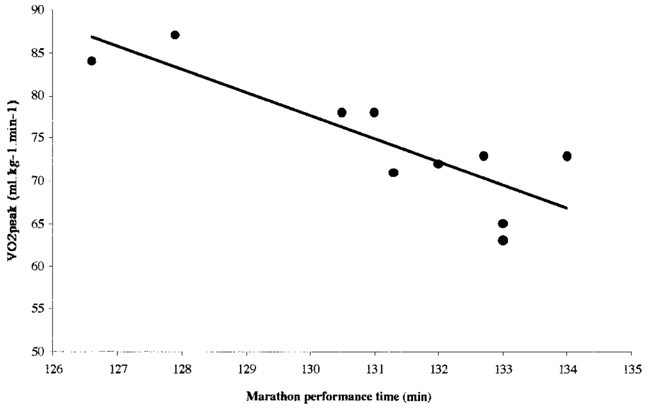

FIGURE 2—Scatter plot depicting relationship between MPT in minutes and $\dot{V}O_{2peak}$ measured in an exhaustive 1000-m run on flat road ($mL \cdot kg^{-1} \cdot min^{-1}$); r = −0.77, *P* = 0.007.

However, for females the velocity for the all-out 1000-m run was highly correlated with the mean performance time ($r = -0.85$, $P < 0.001$) and entered in the stepwise regression predicting MPT (Tables 2 and 3). The fastest female marathon runners were those who were still able to run fast during the 1000-m run 6 min after the 10-km run at vMarathon.

To take into account the fact that the oxygen consumption does not increase proportionally to the body mass, we computed the energy cost of running with an exponent less than 1 (4). It is interesting to note that there was no significant difference in Cr, even when this was expressed in $kg^{-0.75}$ of body mass (568 ± 35 vs 539 ± 52 $mL \cdot kg^{-0.75} \cdot km^{-1}$, for males and females, respectively; $P = 0.2$). Moreover, males and females had the same ability to use a high fraction of $\dot{V}O_{2peak}$ (FR$\dot{V}O_{2peak}$ being around 90%) (Table 2).

Surprisingly, $\dot{V}O_{2peak}$ was not correlated with the velocity over 1000 m either for males ($r = 0.38$, $P = 0.31$) or for females ($r = 0.19$, $P = 0.59$), which can explain why independently v1000m is correlated with marathon performance for females and $\dot{V}O_{2peak}$ is correlated with marathon performance for males.

Relationship among the Three Physiological Factors for Marathon Performance.

For males, there was a correlation between $\dot{V}O_{2peak}$ and Cr ($r = 0.65$, $P = 0.04$). This was also true for all 20 runners of both genders; in addition, the energy cost of running was correlated with the marathon performance time ($r = 0.44$, $P = 0.05$). This means that the runners who had the highest $\dot{V}O_{2peak}$ were also those who had the highest energy cost of running at the marathon velocity, i.e., who were the less economical. For males, $\dot{V}O_{2peak}$ was inversely related to FR (in percent $\dot{V}O_{2peak}$) over the marathon ($r = -0.65$, $P = 0.05$).

In summary, it seems that for TC males who run a marathon at 19.5 ± 0.3 $km \cdot h^{-1}$ versus 19.0 ± 0.1 $km \cdot h^{-1}$ for their high-level counterparts, the rate of oxygen consumption is more determinant for performance than economy or endurance (FR$\dot{V}O_{2peak}$). For females running at 17.0 ± 0.3 (TC) versus 16.2 ± 0.3 $km \cdot h^{-1}$ (HL), different combinations of FR$\dot{V}O_{2peak}$ and Cr seem to be possible, but the ability to run fast during an all-out run over 1000 m after a 10-km run at vMarathon was related to marathon performance time.

Cardiorespiratory and Metabolic Responses during the 10-km Run at vMarathon and v1000m

$\dot{V}O_2$ measured during the last 3 min of the 10-km run at vMarathon was not significantly different from that registered between the sixth and the ninth minutes. Cardiovascular and metabolic responses (blood lactate and respiratory exchange ratio (RER)) in the 10-km run were not significantly different between gender or performance groups, except for heart rate, which was significantly lower in the top-class versus high-level group (Table 1). Moreover, there was no increase in $\dot{V}O_2$ between the third and the sixth minutes of the run at vMarathon; $\Delta\dot{V}O_2$6–3 min, an indirect measurement of the slow component of $\dot{V}O_2$ kinetics (32), was less than 150 $mL \cdot min^{-1}$ (Table 1). However, the runners accumulated lactate throughout the 10-km run and had a rather high RER, especially the HL runners (Table 1), since two of them were above 1.

For all runners, the level of $\dot{V}O_2$ had already leveled off during the all-out 1000-m run, meaning that it takes at maximum $3 \times \tau$ (i.e., 120 s) to reach a steady state of $\dot{V}O_2$. For the nine Portuguese male runners who had previously performed an incremental test on the inclined treadmill (10%, Paiva, M., personal communication), we observed that $\dot{V}O_{2peak}$ measured over the 1000-m run was significantly lower than on the treadmill (78.7 ± 7.0 vs 71.7 ± 11 $mL \cdot kg^{-1} \cdot min^{-1}$, $t = 2.46$, $P = 0.03$). Inclined treadmill

TABLE 2. Physiological factors for marathon performance time among top-class and high-level male and female runners.

Factors	Males		*P* TC vs HL among Males	Females		*P* TC vs HL among Females	*P* between Genders
	TC	HL		TC	HL		
Age (yr)	33.4 ± 2.0	30.3 ± 2.2	0.14	32.8 ± 2.2	38.2 ± 7.3	0.14	0.0004
Weight (kg)	60.2 ± 2.9	59.3 ± 2.5	0.53	50.2 ± 3.6	49.2 ± 4.3	0.67	0.0001
Height (cm)	172 ± 2	172 ± 2	0.75	164 ± 6	161 ± 5	0.29	0.0005
MPT (min)	129 ± 2	133 ± 1	0.008	149 ± 3	156 ± 3	0.02	0.0001
vMarathon ($km \cdot h^{-1}$)	19.5 ± 0.3	19.0 ± 0.1	0.008	17.0 ± 0.3	16.2 ± 0.3	0.02	0.0001
vMarathon % v3000m	85.7 ± 0.9	86.4 ± 1.5	0.46	86.0 ± 3.8	84.0 ± 2.4	0.17	0.37
v1000m ($km \cdot h^{-1}$)	22.0 ± 0.8	21.8 ± 0.2	0.62	20.0 ± 0.9	18.5 ± 0.9	0.03	0.0001
v3000m ($km \cdot h^{-1}$)	22.8 ± 0.6	22.0 ± 0.5	0.04	19.7 ± 0.9	19.3 ± 0.3	0.40	0.0001
$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	79.6 ± 6.2	67.1 ± 8.1	0.04	61.2 ± 4.8	62.6 ± 5.0	0.46	0.009
FR$\dot{V}O_{2max}$ (%)	89.8 ± 6.7	95.7 ± 8.7	0.17	91.2 ± 3.7	91.1 ± 5.5	0.92	0.19
Cr ($mL \cdot kg^{-1} \cdot km^{-1}$)	210 ± 12	195 ± 4	0.009	196 ± 17	212 ± 24	0.40	0.98

MPT, marathon performance time.

TABLE 3. Stepwise regression for marathon time performance factors in top-class vs high-level runners, male and female.

	All the Runners		Males		Females	
	Partial Correlation Coefficient	F to Enter	Partial Correlation Coefficient	F to Enter	Partial Correlation Coefficient	F to Enter
$\dot{V}O_{2peak}$ ($mL \cdot kg^{-1} \cdot min^{-1}$)	−0.62	10.7	−0.77	9.87	0.31	0.84
v1000m ($km \cdot h^{-1}$)	−0.93	116.7	−0.57	3.33	−0.85	20.3
FR$\dot{V}O_{2peak}$ (%)	−0.17	0.5	0.53	2.77	−0.39	1.42
Cr ($mL \cdot kg^{-1} \cdot km^{-1}$)	0.12	0.23	−0.41	1.38	0.40	1.56
	MPT = 278.4–6.63 v1000		MPT = 145.2–0.19 $\dot{V}O_{2max}$		MPT = 216.67–3.33 v1000	

MPT, marathon performance time (in minutes).

$\dot{V}O_{2max}$ and the $\dot{V}O_{2peak}$ value measured on a level road over 1000 m are significantly correlated ($r = 0.81$, $P = 0.005$). Therefore, the $\dot{V}O_{2peak}$ obtained during the all-out 1000-m run was the maximal value that the runner could reach on a flat road, since we measured fast oxygen kinetics over the 1000 m (as for vMarathon) (between 20 and 40 s). The RER (1.10 ± 0.05) and blood lactate (10.8 ± 2.1 $mmol \cdot L^{-1}$) measured at the end of the all-out 1000 m were in accordance with criteria assessing the attainment of $\dot{V}O_{2peak}$ (2) and the average velocity was nonsignificantly different from their personal best at 3000 m ($P = 0.3$).

Training Differences among Performance Level and Gender

Training volume. For males, the total distance run per week was significantly higher for top-class runners (206 ± 26 km vs 168 ± 20 km, $P = 0.03$) (Table 4). The total distance run per week was not significantly different for females between performance levels (166 ± 11 vs 150 ± 17 km for TC and HL, respectively, $P = 0.1$). Top-class male marathon runners trained 13.0 ± 0.7 versus 11.5 ± 1.7 $sessions \cdot wk^{-1}$ for the male HL ($P = 0.09$) and top-class female marathon runners trained 12.2 ± 0.4 $sessions \cdot wk^{-1}$ versus 10.4 ± 1.7 $sessions \cdot wk^{-1}$ for their HL counterparts ($P = 0.04$).

Training intensity. For males, total weekly distance run (206 ± 26 km vs 168 ± 20 km, $P = 0.03$) and the distance run at high intensity (v3000m or v10,000m) (20.4 ± 1.7 km vs 17.8 ± 1.8 km, $P = 0.05$) were significantly higher for top-class male marathon runners compared with their high-level counterparts (Table 4). However, both groups performed 2 ± 0 $sessions \cdot wk^{-1}$ at v3000m or v10,000m. The general training load distribution reported by HL runners was identical to TC: 18% of total distance run at velocities greater than vMarathon, 4% of distance run at vMarathon, and 78% of total weekly distance less than vMarathon. Only distance per training session was different. Within the training volume performed at velocities greater than or equal to v10,000m, training intensity was further divided into intensities above or below v3000m. Top-class male marathon runners run 40% of this distance at v3000m (8.2 ± 2.0 km) versus 41.5% (7.4 ± 1.3 km) for their high-level counterparts. For men, there was no correlation between training characteristics reported in Table 4 and marathon performance time.

For females, TC runners did not run a greater distance per week at high velocities (≥ v10,000m) (Table 4) but trained more sessions at these velocities (2 ± 0 $sessions \cdot wk^{-1}$ vs 1.2 ± 0.5 $sessions \cdot wk^{-1}$, $P = 0.04$). Top-class females ran a longer distance at their v3000m than their high-level counterparts. Therefore, of the 14.8 km run at greater than v10,000m, TC females run ~50% (7 ± 1.4 km) at v3000m, compared with 28% (3.9 ± 1.3 km) for the HL females. Therefore, top-class females ran faster than their HL counterparts (more sessions at v3000m) in more sessions per week. Performance was correlated for females with the distance run at v3000m + v10,000m ($r = -0.79$, $P = 0.004$) and the number of sessions run per week ($r = -0.75$, $P = 0.01$).

During this period of 12 wk of specific training before the trials, it is worth noting that, independent of the marathon performance time or gender, very few runners train at the specific marathon velocity (Table 4).

There is a greater difference in training between genders in top-class compared with high-level runners. Indeed, top-class male marathon runners ran more kilometers per week at v3000m or v10,000m ($U = 7.5$, $P = 0.03$) and at the marathon velocity compared with the TC females ($U = 3.0$, $P = 0.03$). Moreover, TC males ran more kilometers per week than TC females (206 ± 26 km vs 166 ± 11 km, $U = 0.05$, $P = 0.01$) in a nonsignificantly greater number of sessions (13.0 ± 0.7 $sessions \cdot wk^{-1}$ vs 12.2 $sessions \cdot wk^{-1}$ ± 0.4, $U = 4.5$, $P = 0.06$).

In high-level marathon runners, males did not cover a greater distance per week compared with females ($U = 0.5$, $P = 0.1$) and did not practice for more sessions per week ($U = 6$, $P = 0.3$). However, they performed more sessions per week at v3000m or v10,000m (2.0 ± 0 vs 1.4 ± 0, $U = 5$, $P = 0.04$) and covered significantly greater distances at these velocities (17.8 ± 1.8 km vs 12.4 ± 2.3 km, $U = 5$, $P = 0.04$). In these weekly kilometers run at v3000m or v10,000m, males ran almost twice (180%) the number of kilometers than females at v3000m.

DISCUSSION

We have, first, to underline that we have focused this investigation on national and internationally elite runners which are, by definition, few in number. The small sample sizes ($N = 5$ for each gender and group of performance) have the effect of tending to overestimate the size of population differences, since the only group differences that are detected are the large ones.

TABLE 4. Training log among top-class and high-level male and female runners.[a]

Training Factors	Males TC	Males HL	*P* TC vs HL among Males	Females TC	Females HL	*P* TC vs HL among Females	*P* between Genders
Total weekly distance (km)	206 ± 26	168 ± 20	0.03	166 ± 11	150 ± 17	0.10	0.01
Number of sessions per week (*N*)	13.0 ± 0.7	11.5 ± 1.7	0.09	12.2 ± 0.4	10.4 ± 1.7	0.04	0.11
Duration of long training session (min)	125 ± 11	116 ± 27	0.90	113 ± 25	89 ± 22	0.15	0.07
Weekly distance run at vMarathon (km)	8.0 ± 0	7.0 ± 4.2	0.99	12.0 ± 3.0	9.0 ± 1.4	0.24	0.07
	(*N* = 3)	(*N* = 2)		(*N* = 3)	(*N* = 2)		
Weekly distance run @ v1/2 Marathon (km)	18.0 ± 0	12.5 ± 3.5	0.22	11.3 ± 2.5	8.2 ± 1.7	0.04	0.04
	(*N* = 1)	(*N* = 2)			(*N* = 4)		
Weekly distance run @ v10,000m (km)	12.2 ± 1.8	10.4 ± 0.9	0.06	7.8 ± 1.8	8.5 ± 3.0	0.71	0.003
					(*N* = 4)		
Weekly distance run @ v3000m (km)	8.2 ± 2.0	7.4 ± 1.3	0.34	7.0 ± 1.4	3.9 ± 1.3	0.03	0.04
Weekly sessions run @ v3000m + v10,000m (*N*)	2.0 ± 0	2.0 ± 0	0.99	2.0 ± 0	1.2 ± 0.5	0.05	0.06
Weekly sessions run @ v3000m (*N*)	1.0 ± 0	1.0 ± 0	0.99	1.0 ± 0	0.6 ± 0.5	0.13	0.10

[a] When the number is not specified, that means that all the five runners did that type of training.

This study suggests that top-class male runners (< 2 h 12 min) have a higher $\dot{V}O_{2peak}$ than their high-level counterparts (> 2 h 12 min, < 2 h 16 min) with a significantly higher energy cost of running. Indeed, in this group of elite runners, those athletes who had the highest $\dot{V}O_{2peak}$ were also those who had the higher energy cost of running. This finding has not previously been reported in the literature. However, comparison of $\dot{V}O_{2peak}$ obtained during flat, level road running with inclined treadmill $\dot{V}O_{2max}$ testing may be important in this context. Moreover, $\dot{V}O_{2peak}$ was highly correlated with performance in males. For females, neither $\dot{V}O_{2peak}$ nor Cr or FR$\dot{V}O_2$peak were significantly different between the TC and HL runners. It appears that for females, different combinations of $\dot{V}O_{2max}$, FR$\dot{V}O_{2max}$, and energy cost of running (within certain minimum constraints) can be utilized to achieve world class performance. However, it should be underlined that in the present study, the best females had a performance time equal to 102.0% of the best world performance, compared with 100.8% for the best male. It is conceivable that this difference in relative performance level has influenced the comparison.

The energetic factors for top-class performance in the marathon. In males, the top-class male marathon runners had a $\dot{V}O_{2peak}$ almost equal to 80 $mL \cdot kg^{-1} \cdot min^{-1}$. Hagan et al. (15) reported a $\dot{V}O_{2max}$ of 88.8 $mL \cdot kg^{-1} \cdot min^{-1}$ in a marathon runner performing the marathon in 2 h 19 min. This was a rather high $\dot{V}O_{2max}$ value for such marathon performance time, even if the runner had a low FR and was not economical (high Cr). Moreover, these authors measured $\dot{V}O_{2max}$ during level treadmill running. In our subjects who had previously performed an inclined treadmill $\dot{V}O_{2max}$ test ($N = 9$), the $\dot{V}O_{2peak}$ measured during the post-10 km flat 1000-m test was ~10% lower (Paiva, M., personal communication). In previous studies, where elite athletes have been defined as athletes with personal records below 2 h 30 min, $\dot{V}O_{2max}$ was reported to be between 71 $mL \cdot kg^{-1} \cdot min^{-1}$ ($N = 10$; average MPT, 2 h 23 min) (8) and 74.2 $mL \cdot kg^{-1} \cdot min^{-1}$ ($N = 5$; average MPT, 2 h 16 min) (31) or 74.1 $mL \cdot kg^{-1} \cdot min^{-1}$ ($N = 8$; average MPT, 2 h 15 min) (27) and 79.0 $mL \cdot kg^{-1} \cdot min^{-1}$ ($N = 13$; average MPT, 2 h 13 min) (10). However, all these studies measured $\dot{V}O_{2max}$ on an inclined treadmill under rested conditions. Our results raise questions about how $\dot{V}O_{2peak}$ in runners should be measured if the goal is to reflect flat course running capacity.

The new finding in this study is that $\dot{V}O_{2peak}$ discriminates top-class male (2 h 9 min 20 s ± 2 min 0 s), from high-level male marathoners (2 h 11 min 54 s ± 42 s). Moreover, when we consider males within the same group (2 h 6 min to 2 h 16 min), performance (time over the marathon) is correlated with $\dot{V}O_{2peak}$. This is in opposition to the results of Costill (6), who reported that $\dot{V}O_{2peak}$ was not correlated with performance in a group of marathon runners with a performance time below 2 h 30 min ($r = 0.01$). Costill et al. (9) also reported a relatively low $\dot{V}O_{2max}$ in some top-class marathon runners such as the famous world best performance of Derick Clayton in 1969, who had a personal best of 2 h 8 min 33 s despite a $\dot{V}O_{2max}$ of only 69.7 $mL \cdot kg^{-1} \cdot min^{-1}$. Similarly, Sjödin and Jacobs (29) reported a $\dot{V}O_{2max}$ value of 67 $mL \cdot kg^{-1} \cdot min^{-1}$ in a runner performing the marathon in 2 h 10 min. This is the reason why, in the 1980s, numerous studies focused on the fractional utilization of $\dot{V}O_{2max}$ during the marathon and on the energy cost of running. In this present study, we found no relationship between the energy cost of running or FR and performance in either males or females. However, for males, even if the RER was not significantly different between TC and HL (0.94 ± 0.01 vs 1.00 ± 0.08, $P = 0.1$, probably because of the small sample sizes), this difference would be relevant to performance in a 2-h race, where the glycogen utilization rate becomes crucial. However, we obliged the runners to run at a constant velocity, and it is uncertain if it was a real advantage, since they could not have any recovery. Moreover, it has even been reported that the K4 b^2 apparatus (700 g), which is worn on the back, is negligible for Cr (14); this could have increased the constraint of the test, since our subjects were lighter and/or ran faster than in Hausswirth et al.'s study (16).

Among the 10 males studied here, $\dot{V}O_{2peak}$ explained 59% of the variance in MPT, whereas no other factors entered a stepwise linear regression. Previous studies had shown that the percentage variation in performance time attributed to $\dot{V}O_{2max}$ (expressed relative to body mass) was calculated to be 74% and 67% for the marathon (7,13). Hagan et al. (15) reported that for a group of experienced marathon runners (2 h 19 min to 3 h 50 min), 73% of the marathon performance time could be explained by $\dot{V}O_{2peak}$, total number of workouts, and average training speed 9 wk before the race. Sjödin and Svedenhag (30) reported the importance of a high $\dot{V}O_{2max}$ for a high-level performance in a marathon as demonstrated by the significantly different values of $\dot{V}O_{2max}$ in marathon runners with different levels of performance and by the correlation of 0.78 ($P = 0.001$) between $\dot{V}O_{2max}$ and marathon race pace. However, the mean personal best of the so-called elite marathon runners was 2 h 21 min (2 h 18 min to 2 h 30 min) with a $\dot{V}O_{2max}$ equal to 71.8 ± 1.2 $mL \cdot kg^{-1} \cdot min^{-1}$ (62.9 to 77.9). This is far below the level of our subjects (9 min for our top-class group and 5 min for our high-level group). Other studies, such as those by Saltin and colleagues (28) involving elite Kenyan and Swedish distance runners, have come to conclusions quite different from ours. Indeed, differences in $\dot{V}O_{2max}$ were small or nonexistent between world class Kenyans and slower Scandinavians, but differences in running economy and energy metabolism at high intensities were different, with the world class Kenyans having more favorable running economy and lower lactate and ammonia accumulation at high intensities. However, the runners investigated by Saltin and colleagues were 5- and 10-km specialists, not marathon runners. It may be that a high $\dot{V}O_{2max}$ is more obligatory (and therefore less variable) for high-level performance over these shorter distances.

There have been very few studies published on elite female marathon runners, probably because this distance was only made Olympic in 1984 (vs 1896 for males). Comparing males and females at the same moderate absolute performance level (3 h 20 min), Helgerud et al. (17) found that females had the same $\dot{V}O_{2max}$, a higher FR, but poorer Cr than males. However, the authors use allometric scaling of body weight to compare Cr. At the same high relative level of performance (Olympics minima), we found that females had the same Cr as males. To our knowledge, no previous study has compared Cr in males and females at high level of marathon performance.

Wilmore and Brown (34) reported a $\dot{V}O_{2max}$ of 71 $mL \cdot kg^{-1} \cdot min^{-1}$ in the best holder with a marathon performance time of 2 h 49 min 40 s. This performance was lower than that of our high-level group even if the $\dot{V}O_{2max}$ value is higher. However, these data were obtained on an inclined treadmill. Davies and Thompson (10) found an average $\dot{V}O_{2max}$ of 58 $mL \cdot kg^{-1} \cdot min^{-1}$ in nine female marathon runners with a rather slow average best time of 3 h 9 min. Since these studies, female performance has improved (much more than that of the males, i.e., 12% vs 2%). In a more recent study including elite marathon runners, Pate et al. (26) found a mean $\dot{V}O_{2max}$ of 66.4 $mL \cdot kg^{-1} \cdot min^{-1}$ for performances ranging from 2 h 28 min 54 s to 2 h 39 min 21 s. These data are in agreement with both our performance data and our $\dot{V}O_{2max}$ values. However, in our study, $\dot{V}O_{2max}$ did not discriminate the performance for females and was not correlated with performance ($r = 0.31$, $P = 0.40$). A combination of FR, Cr, and $\dot{V}O_{2peak}$ could not predict the marathon performance in a multiple regression set by stepwise regression.

Surprisingly, whereas $\dot{V}O_{2peak}$ was not a good predictor of performance, v1000m measured after a 10-km run at vMarathon was an excellent predictor of performance. The ability to run fast for a short period of time (or distance) has already been reported as being determinant for performance during long-distance running. Noakes et al. (23) and Kolbe et al. (19) reported that for good male runners, peak treadmill running velocity during a progressive test to $\dot{V}O_2$ peak was a better predictor of running performance (time over the distance) over 10 to 90 km or during a half-marathon ($r = -0.93$ to $r = -0.83$) than $\dot{V}O_{2max}$. The fact that the velocity over 1000 m (run after 10 km at vMarathon) is highly correlated with MPT could be because the top-class marathon runners are still able to maintain the recoil characteristics of the muscles for a stretch load even in a fatigued condition, as after 10 km run at vMarathon (21). Fatigue can be peripheral, relating to a failure of sarcolemma and sarcoplasmic reticulum in excitation and contraction processes but also of central origin (1). Indeed, an important factor in endurance athlete performance is no doubt the neuromuscular system's ability to work in fatigued conditions (24). However, because of a possible type I error, the findings of this study probably do not support a real gender difference at the same relative (and not absolute) performance level, between the relationship between the v1000 and MPT.

Neither the energy cost of running nor the fractional utilization of $\dot{V}O_{2max}$ predicted marathon performance in the male or female athletes studied here. In the present study, we measured Cr under conditions highly specific to the marathon road pace. Previous studies have found both a relationship (12) and no relationship (13) between Cr and marathon time.

Training characteristics. Training characteristics showed that top-class male runners run more total weekly kilometers than their high-level counterparts, more than 200 $km^{-1} \cdot wk^{-1}$, as well as more kilometers at or above v10,000m (more than 20 $km \cdot wk^{-1}$). However, the relative distribution of running intensity between HL and TC males was actually identical. This high-velocity training elicits high levels of force and brief contact time that in part can replace the strength training in accordance with the training of the best world marathon runners (22).

Regular training at velocities well above vMarathon seems to characterize top-class marathoners. Portuguese marathoner Carlos Lopes (2 h 7 min 11 s in 1985) performed two speed workouts per week, 15 × 400 m at v3000m and 6 × 2000 m at v10,000m, almost all of the year with a high weekly total distance (200 to 240 km) (25). One of the TC athletes in the present study (2 h 6 min 34 s in London, April 2000) also has personal bests of 3 min 38 s for 1500 m, 7 min 38 s for 3000 m, and 13 min 2 s for 5000 m. These good middle-distance performances by a marathon specialist are maintained with regular training at velocities well above vMarathon.

Top-class female marathon runners trained many kilometers with two or three sessions a week at a high velocity (90 to 110% $v\dot{V}O_{2max}$, i.e. v10,000m to v1500m). This training is in accordance with the training by of one of the greatest female marathon runners, the Norwegian Greta Waitz, who ran the 42,195 m in 2 h 25 min 29 s (in 1983 at London). She trained twice a day (except on Sunday) and ran ~15 $km \cdot wk^{-1}$ at or above competition 10-km velocity (22). In that present study, TC females ran a greater distance at the velocity v3000m than their high-level counterparts, who prefer training at their v10,000m.

At the same relative level of performance, males and females report similar training intensity distribution. Both males and females ran few training sessions at marathon or half-marathon pace (close to the lactate threshold velocity). The training performed at vMarathon was often reserved for the end of the long-distance weekly training (the last 5 to 10 km of the 30-km run). Training at specific race pace (vMarathon for these athletes), which has been suggested to improve running economy (33), does not seem to be the strategy of top-class marathoners. The fact that these elite marathoners perform the majority of their training at velocities well above or below vMarathon does contrast with common wisdom that large values of training be performed at the lactate threshold intensity. This finding is, however, consistent with observations made from several different endurance sports, especially rowing and cross-country skiing. This pattern of training load distribution primarily above and below the lactate threshold intensity has been termed “polarized training” (15). Many questions are unanswered, but this training approach may induce important training adaptations at both central and peripheral levels while minimizing the risk of overtraining, which appears to be greatly increased when daily training loads become too monotonic, on the basis of work by Foster and others (14). Training distance and, in particular, the average weekly distance over the preceding 2 to 3 months has been shown to be crucial for marathon success (15,29). In the present study, we observed, in addition to the weekly distance, that training intensity also differentiates high-level and top-class marathon runners.

CONCLUSION

The present study showed that the maximal oxygen consumption for males and the velocity run on a 1000-m run after 10 km at vMarathon in females differentiated top-class from high-level runners. TC male marathon runners trained more total kilometers per week and at a higher velocity (velocity over 3000 m and 10,000 m). Among females runners, TC trained more kilometers per week at v3000m than HL.

Neither running economy nor fractional utilization of $\dot{V}O_{2max}$ at vMarathon was significantly different between top-class and high-level marathon runners. Among females, only post-10 km v1000m discriminated TC from HL. Therefore, high peak oxygen consumption and the ability to run fast in a 1000-m run after 10 km at vMarathon seems to be the discriminating factors for international top-class marathoners when compared with runners at a slightly lower level.

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