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The energy cost of running increases with the distance covered

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Summary. The net energy cost of running per unit of body mass and distance (C_r, ml $O_2 \cdot kg^{-1} \cdot km^{-1}$) was determined on ten amateur runners before and immediately after running 15, 32 or 42 km on an indoor track at a constant speed. The C_r was determined on a treadmill at the same speed and each run was performed twice. The average value of C_r, as determined before the runs, amounted to 174.9 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$, SD 13.7. After 15 km, C_r was not significantly different, whereas it had increased significantly after 32 or 42 km, the increase ranging from 0.20 to 0.31 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$ per km of distance (D). However, C_r before the runs decreased, albeit at a progressively smaller rate, with the number of trials (N), indicating an habituation effect (H) to treadmill running. The effects of D alone were determined assuming that C_r increased linearly with D, whereas H decreased exponentially with increasing N, i.e. $C_r = C_{r0} + aD + He^{-bN}$. The C_{r0}, the "true" energy cost of running in nonfatigued subjects accustomed to treadmill running, was assumed to be equal to the average value of C_r before the run for N equal to or greater than 7 (171.1 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$, SD 12.7; $n = 30$). A multiple regression of C_r on N and D in the form of the above equation showed firstly that C_r increased with the D covered by 0.123%$\cdot km^{-1}$, SEM 0.006 (i.e. about 0.22 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$ per km, $P < 0.001$); secondly, that in terms of energy consumption (obtained from oxygen consumption and the respiratory quotient), the increase of C_r with D was smaller, amounting on average to 0.08%$\cdot km^{-1}$ (0.0029 $J \cdot kg^{-1} \cdot m^{-1}$, $P < 0.001$) and thirdly that the effects of H amounted to about 16% of C_{r0} for the first trial and became negligible after three to four trials.

Key words: Energy cost of running - Distance - Fatigue

Introduction

We have shown in a previous paper (di Prampero et al. 1986) that the endurance speed (v_{end}) in long distance running can be predicted from the net energy cost of running per unit of distance (C_r), the subject's maximal oxygen consumption ($\dot{V}O_{2max}$) and the maximal fraction of it that can be sustained throughout the duration of effort (F):

$$v_{end} = F \dot{V}O_{2max} C_r^{-1} \qquad 1$$

Obviously, in Eq. 1 all variables must be expressed in compatible units, e.g., if $\dot{V}O_{2max}$ is given in $ml \cdot kg^{-1} \cdot min^{-1}$ and C_r in ml $O_2 \cdot kg^{-1} \cdot m^{-1}$, then v_{end} will be expressed in $m \cdot min^{-1}$. (If, in accordance with SI units, C_r is expressed in $J \cdot kg^{-1} \cdot m^{-1}$ and $\dot{V}O_{2max}$ in $W \cdot kg^{-1}$, then the v_{end} will be in $m \cdot s^{-1}$).

The relationship between the v_{end} predicted from Eq. 1 and the actual average speed over a marathon, or semi-marathon (21 km), of 36 subjects was quite good. Indeed, r^2 amounted to 0.72, indicating that 72% of the speed variability could be explained by the combination of the variables in Eq. 1. In addition, the average ratio of the actual speed to v_{end} was 0.978, SD 0.079. However, even though the average ratio was not significantly different from 1, for speeds in excess of 14 $km \cdot h^{-1}$, v_{end} overestimated the actual speed. As mentioned by di Prampero et al. (1986), part of this difference may have been due to the effects of fatigue on C_r. Indeed, in that study, C_r was determined, 1-3 weeks after the competition, during treadmill running at a speed equal to the average speed maintained by the individual during the race. Thus, the possibility could not be discounted that, as the time went by during the race, C_r had increased progressively, thus leading to an actual speed lower than that predicted on the basis of the value of C_r determined in nonfatigued subjects.

We, therefore, set out to determine C_r before and after 15, 32, and 42.195 km of running at a constant speed.

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Methods

Experimental procedure. The experiments were performed on 14 trained amateur runners who ran 15, 32 and 42.195 km on the indoor tartan running track (340 m) of the Institut National Supérieur d'Education Physique in Paris. The subjects were asked to run each of the above distances twice, at a speed which was set according to the previous experience and expectations of the individual. As described in detail elsewhere (Rieu et al. submitted for publication), in all the trials the fluid and energy intake were carefully controlled. The speed was checked at each lap, 80-90 s apart, and the subjects were encouraged to accelerate or decelerate whenever they deviated from the predetermined. The intervals between successive trials were 15, 13 and 30 days after the 15 km, 32 km and the marathon run, respectively. The oxygen consumption ($\dot{V}O_2$) and CO_2 output were determined by standard laboratory procedures (Oxycon-4, Mijnhard, Bunik, Holland; previously calibrated using gases of known composition) at rest before the trial (subject standing) and while running on a treadmill immediately before and after (without interruption) the trial. The treadmill speed was 3% less than that at which the subject was supposed to run (before) or was actually running (after). In all cases metabolism during the treadmill run was entirely aerobic, as shown by the fact that the venous blood lactate concentration immediately at the end of the exercise amounted on average to 2.7 $mmol \cdot l^{-1}$, SD 1.3 (Åstrand et al. 1963). Ambient temperature, relative humidity and barometric pressure during the runs were 12-23° C, 44%-56% and 752-758 mmHg (100.23-101.06 kPa), respectively.

The C_r was calculated from the measured steady-state $\dot{V}O_2$ above resting (standard temperature and pressure, dry), divided by the running speed, and has been expressed in $ml\ O_2 \cdot kg^{-1} \cdot km^{-1}$.

The subjects' $\dot{V}O_{2max}$ during treadmill running was determined on a separate occasion by a conventional direct open circuit method as follows. After a warming-up period of about 5 min, the speed was increased by 1 $km \cdot h^{-1}$ every 4 min until the subject became exhausted. The $\dot{V}O_2$ was determined over the last 30 s of each running period. The largest measured $\dot{V}O_2$ value was assumed to represent $\dot{V}O_{2max}$ when:

1. It was less than 1 $ml\ O_2 \cdot kg^{-1} \cdot min^{-1}$ larger than the value observed at the previous lower speed (to be compared with an expected increase of the order of 3 $ml\ O_2 \cdot kg^{-1} \cdot min^{-1}$)
2. It was associated with a blood lactate concentration of 10 $mmol \cdot l^{-1}$ or more and/or with a heart rate equal to or greater than the predicted maximum for the subject's age.

In an attempt to minimize the effect of habituation (H), the following precautions were taken. In a preliminary session, the subjects were familiarized with the experimental procedure and with treadmill running. In a second session $\dot{V}O_{2max}$ was determined, which obviously implied several additional minutes of treadmill running. Hence, the collection of the experimental data commenced only after the subjects had become accustomed to treadmill running and to laboratory procedures.

Only 10 subjects, out of the original 14 taking part in the study, were able to complete the entire series of experiments. The data reported in this study refer exclusively to these 10 subjects whose physical characteristics are reported in Table 1.

Results

The values of C_r, for all subjects under all experimental conditions, are reported in Table 2. Each column refers to the experimental session the order of which in the sequence (N), which was the same for all subjects, is indicated in the upper line. The D after which C_r was assessed is indicated in the second line. The average value of C_r above resting applying to nonfatigued conditions ($D=0$) is reported in the last column for each subject separately, the grand average for all subjects amounting to 174.9 $ml\ O_2 \cdot kg^{-1} \cdot km^{-1}$, SD 13.7 ($n=56$). The average values of C_r for the same N appear in the last two lines. It should also be noted that whereas all averages for odd values of N (last but one line) refer to nonfatigued conditions ($D=0$), the last line reports values of C_r which do not necessarily refer to the same distance. Table 2 shows that the value of C_r determined immediately after 32 km or the marathon (second trial only) was significantly larger than before the run. For the shortest distance ($D=15$ km), however, C_r after the run was not significantly different from the value before the run and in the nonfatigued subjects in general [see di Prampero (1986) for a review]. This latter finding can be attributed to the relatively large intra- and inter-subjects variability, compared to the tiny effect of D (see below), which made it rather difficult to detect significant increases of C_r for the shorter distances.

Discussion

In spite of the precautions taken to minimize the H, the role this appeared to play was not negligible, as indicated by the fact that the value of C_r determined before the run ($D=0$) decreased significantly, albeit at a decreasing rate, with increases in N (Table 2, Fig. 1). Thus, two major factors seemed to affect C_r in the pres-

Table 1. Anthropometric and physiological characteristics of the subjects

Subject	Age (years)	Mass (kg)	Stature (cm)	$\dot{V}O_{2max}$ ($ml \cdot kg^{-1} \cdot min^{-1}$)	Best performance (h:min)
VIG	33	69	172	60.4	2:36
CEN	32	64	178	68.9	2:46
RAT	35	73	169	58.2	2:48
COU	29	73	174	61.9	2:46
LAC	30	67	177	61.7	2:51
BER	29	67	166	55.6	2:55
BUR	36	68	166	63.6	2:56
PEB	36	69	172	63.0	2:53
MAU	29	77	179	57.5	2:54
MON	41	58	165	62.7	3:00

$\dot{V}O_{2max}$ (maximal O_2 consumption), resting included; Best performance, shortest time ever over a marathon

Table 2. Energy cost of running above resting (C_r, in ml $O_2 \cdot kg^{-1} \cdot km^{-1}$) for all subjects under all experimental conditions. The order in the experimental sequence is indicated in the upper line (N). The distance (D) after which C_r was assessed is indicated in the second line. The average value of C_r applying for non-fatigued conditions (D = 0) is reported in the last column for each subject separately, the grand mean for all subjects amounting to 174.9 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$, SD 13.7 ($n = 56$). The average values of C_r for the same N appear in the last two lines. As indicated below the last line, a paired *t*-test showed that after 32 km or the marathon (trial II only), C_r was significantly greater than before the run. See text for details

N	1	2	3	4	5	6	7	8	9	10	11	12		
D (km)	0	15	0	32	0	42	0	15	0	32	0	42	Mean	SD
VIG	187.4	183.7	168.7	174.7	166.9	175.1	165.9	167.3	161.7	168.4	158.6	170.5	168.2	10.1
CEN	203.4	196.6	187.0	184.1	182.6	185.8	194.1	183.5	180.1	193.4	181.1	188.9	188.1	9.1
RAT	184.0	178.7			182.8	174.8	185.7	181.5	175.1	183.6	176.4	182.9	180.8	4.8
COU	186.7	173.7	160.4	175.4			170.9	166.8	161.2	175.1	156.9	179.6	167.2	12.1
LAC	188.4	191.1	185.2	186.3	192.1	200.4	185.0	190.7	187.3	181.4	180.6	192.7	186.4	3.9
BER	176.3	175.6	169.4	177.6	166.1	158.0	159.9	155.3	171.1	167.0	160.3	162.2	167.2	6.4
BUR	188.8	188.1	176.1	188.6			182.2	177.3	179.9	180.8	171.6	179.3	179.7	6.5
PEB	171.2	173.3	167.4	176.0	159.3	186.0	160.3	168.7	162.0	178.0	155.5	171.7	162.6	5.7
MAU	165.5	172.8	159.7	165.5			161.9	162.9	153.0	167.1	144.5	162.5	156.9	8.3
MON	216.6	205.1	186.4	201.5	178.7	207.2	191.3	197.2	177.2	212.3	183.4	196.3	188.9	14.5
Mean	186.8		173.4		175.5		175.7		170.9		166.9		Grand mean 174.9	
SD	14.9		10.8		11.6		13.4		10.9		13.4		13.7	
Mean		183.9		181.1		183.9		175.1		180.7		178.7		
SD		11.1		10.4		16.6		13.2		13.9		11.9		
P				<0.01						<0.05		<0.001		

ent study: D covered and overall N. In an attempt to disentangle the effects of D covered from those of H it was assumed that:

1. The former increased linearly with D, whereas
2. The latter decreased exponentially with increasing N (see Fig. 1):

$$C_r = C_{r0} + aD + He^{-bN} \quad 2$$

where C_{r0} is the "true" energy cost of running in nonfatigued subjects accustomed to treadmill running, the second term is the increase of C_r due the effects of the *D* covered and the third therm takes H into account. The C_{r0} was assumed to be equal to the average value of C_r before the run for N = 7, 9 and 11, i.e. 171.1 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$, SD 12.7 ($n = 30$). The coefficients a and b of Eq. 2 were calculated by a computerized nonlinear regression procedure supplied by Systat (Systat Inc., Evanston, USA). This consisted of an iterative algorithm minimizing the sum of the squared differences between fitted function and experimental data (loss function), as originally proposed by Marquardt (1963). The multiple regression of C_r on *N* and *D* thus obtained was:

$$C_r = 171.1 + 0.235D + 26.0e^{-0.54N} \quad 3$$

($n = 112$), where C_r is given in ml $O_2 \cdot kg^{-1} \cdot km^{-1}$ and *D* in km. In order to reduce the interindividual variability, C_r was expressed as a percentage of the individual means observed before the runs and reported in the last column of Table 2. In this case, $C_{r0} = 98.4\%$, SD 3.7, and the corresponding multiple regression was:

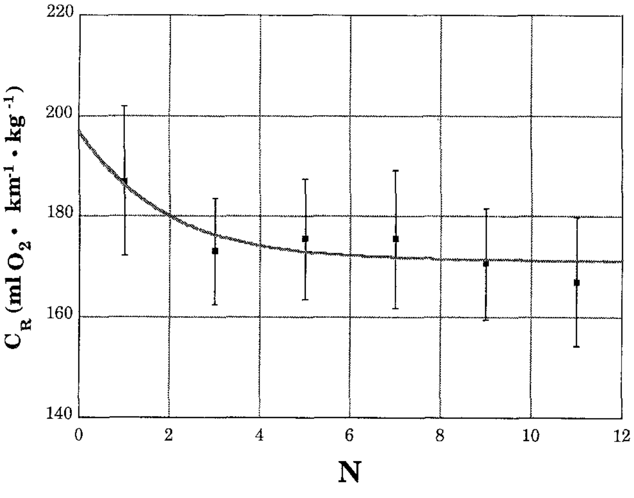

Fig. 1. Energy cost of running on the treadmill (C_r) immediately before the run, for all subjects, as a function of the number of the experimental session (N). The C_r is given in ml $O_2 \cdot kg$ body mass$^{-1} \cdot km^{-1}$ (mean and SD). The continuous line is described by: $C_r = 171.1 + 26.0e^{-0.54N}$

$$C_r = 98.4 + 0.123 \text{ (SEM 0.006)} D + 15.9e^{-0.61 \text{ (SEM 0.034)} N} \quad 4$$

($n = 112$). The residuals of Eqs. 3 and 4, i.e. the differences between actual and expected values, have been plotted in Figs. 2a and b as a function of the calculated values of C_r. These figures show that the statistical approach used in calculating Eqs. 3 and 4 was not biased by unidirectional errors. Thus, from these two equations is appeared that D per se, freed from the effects of H, led to an increase of C_r of the order of 0.21–0.24 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$ per km of D, i.e. about 0.12% per km.

Since H seemed to play a rather minor role for N equal to or greater than 3 (see Fig. 1), the effects of D covered were also calculated by means of a least squares linear regression of C_r on D for N equal to or greater than 3. When expressing C_r as a percentage of the means of individuals observed before the runs (see last column of Table 2), the regression was:

$$C_r = 98.8 + 0.128 D \qquad 5$$

($n = 92$, $r = 0.50$, $P < 0.0001$), where the ordinate intercept for $D = 0$ was C_r in nonfatigued subjects accustomed to treadmill running (C_{r0}). Thus, as from Eq. 5:

1. The C_{r0} was essentially equal to that calculated from the values of C_r before the run for N equal to or greater than 7 which amounted to 98.4%, SD 3.7% of the individual mean before the run
2. Also the effects of D covered were very close to those obtained from Eqs. 3 and 4.

It can, therefore, be concluded that the latter indeed amounted, on average, to about 0.22 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$ per km of D.

Equations 3 and 4 indicated that the constant H amounted to about 16% of C_{r0}. This was the increase in the C_r to be expected in the first trial in subjects not accustomed to treadmill running. However, H seems to have been a rather fast process, since for N equal to 3 the increase in C_r was reduced to only 3% of C_{r0} (see Eqs. 3, 4).

It is well known that, for a given intensity of exercise, the respiratory quotient (RQ) decreases progressively with the effort duration (Saltin and Stenberg 1964; Costill 1970; Costill et al. 1973), thus leading to a lower energy equivalent of $\dot{V}O_2$ (from 21.1 $kJ \cdot l^{-1}$ for RQ = 1, to 19.6 $kJ \cdot l^{-1}$ for RQ = 0.71). In the present study, the time over which the gas exchange was assessed (both at the end and at the beginning of the run) was too short to allow precise estimates of RQ, which, as is well known, is markedly affected by the changes in the large CO_2 stores of the body which may occur during the measurement. In a recent study, however, Bosch et al. (1990) have determined the gas exchange ratio over an entire treadmill marathon, under which conditions the gas exchange ratio may be assumed to have been equal to the metabolic RQ. According to their data, in ten subjects the RQ decreased progressively from 0.95 at the beginning to 0.88 at the end of a treadmill marathon lasting 2 h 58 min (average speed of 14.1 $km \cdot h^{-1}$, SD 1).

In the present experimental, the average speed (13.85 $km \cdot h^{-1}$, SD 0.66, see Table 3), and hence the performance time (t), were essentially identical to those reported by Bosch et al. (1990). It can, therefore, be assumed that in our subjects also the RQ decrease from the beginning to the end of the marathon followed the same trend, the corresponding energy equivalent of $\dot{V}O_2$ decreasing from 20.9 to 20.5 $kJ \cdot l^{-1}$. These values, as well as intermediate ones applying to D equals 15 and D equals 32 km (RQ equals 0.92 and 0.90; energy

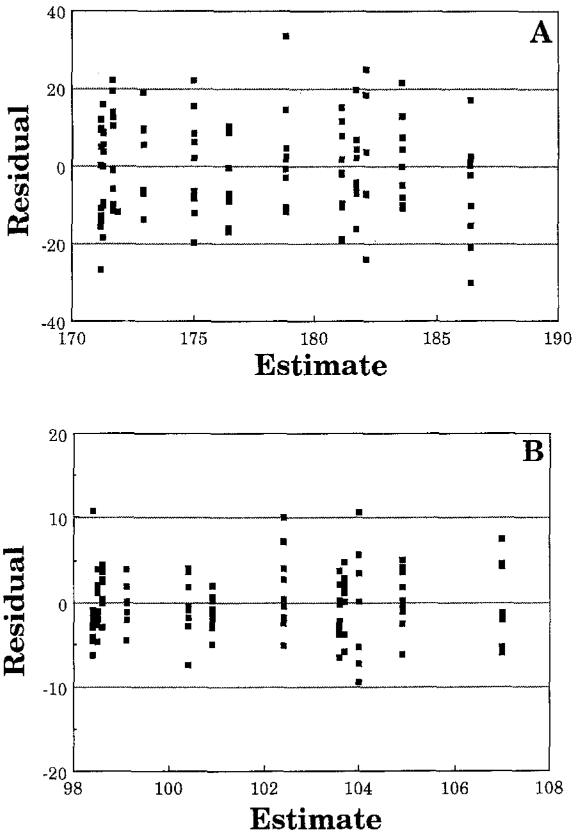

Fig. 2. The differences between the actual and expected values of the energy cost of running (C_r), in ml $O_2 \cdot kg^{-1} \cdot km^{-1}$ (**A**) or in percentage of the means for individuals observed before the runs (**B**) are plotted as a function of the calculated C_r values as obtained from Eqs. 3 and 4, respectively

Table 3. Actual and theoretical speeds over the marathon

Subject	v_{real} ($m \cdot s^{-1}$)	v_{end} ($m \cdot s^{-1}$)	$v_{real} : v_{end}$
VIG	4.008	4.118	0.973
CEN	4.250	4.301	0.988
RAT	3.643	3.609	1.009
COU	3.767	4.193	0.898
LAC	3.794	3.765	1.008
BER	3.868	3.760	1.029
BUR	3.890	4.053	0.960
PEB	3.675	4.365	0.842
MAU	3.908	4.156	0.940
MON	3.670	3.752	0.978
Mean	3.847	4.007	0.963
SD	0.184	0.264	0.057

v_{real}, Speed actually maintained over the two marathon runs; v_{end} was calculated according to Eq. 1, as described in the text. Actual and theoretical speeds were not significantly different equivalent for O_2 of 20.7 and 20.6 $kJ \cdot l^{-1}$, respectively) allow the expression of C_r in $J \cdot kg^{-1} \cdot m^{-1}$, as for the data in Table 2. A least squares linear regression of the data thus corrected for N equal to or greater than 3 (see above) was:

$$C_r' = 98.5 + 0.081\,D \qquad 6$$

($n=92$, $r=0.36$, $P<0.001$), where C_r' was expressed as a percentage of the mean before the run for each individual (corrected for RQ) and D was in km. Thus, also in terms of energy consumption, the C_r increased significantly with the D covered. The increase, however, amounted only to 0.08% (about 0.0029 $J \cdot kg^{-1} \cdot m^{-1}$) per km of D, i.e. about 60% of the value applying when C_r was expressed in terms of $\dot{V}O_2$.

The data obtained in this study has made possible the comparison of the actual speed maintained throughout the marathon (v_{real}, Table 3) with the theoretical v_{end}. This was calculated inserting the appropriate values for individuals into Eq. 1, as follows:

1. The $\dot{V}O_{2\,max}$ was taken from Table 1 and corrected for the resting value, assumed to be 4 ml $O_2 \cdot kg^{-1} \cdot min^{-1}$.
2. The maximal fraction of $\dot{V}O_{2\,max}$ sustained throughout the run (F) was estimated from the individual's marathon times on the basis of the relationship between F and t in running [$F=0.905-0.91\times10^{-3}t$ (min) obtained in a previous study by di Prampero et al. 1986].
3. Finally, the individual values of C_r were calculated assuming: (1) $C_{r0}=0.984$ of the mean value for individuals before the runs (Table 2, Eq. 5) and (2) adding to C_{r0} the effects of the D for D=21.1, i.e. midway through the marathon: $0.22\times21.1=4.64$ ml $O_2 \cdot kg^{-1} \cdot km^{-1}$. The v_{end} values thus obtained are reported in Table 3 together with the individual's v_{real}:v_{end} ratios. It appeared from Table 3 that the v_{real} and v_{end} were not significantly different from each other, the average ratio amounting to 0.963, SD 0.057, which was not significantly different from 1.0.

We would like to stress at this point that the above calculations of the theoretical speed were not affected by the RQ changes discussed above, provided that both $\dot{V}O_{2\,max}$ and C_r were expressed in terms of $\dot{V}O_2$. In this case in fact, the RQ changes cancelled out since they affected equally the numerator (metabolic power output) and the denominator C_r of Eq. 1. It should also be pointed out that, when dealing with real marathon with uphills, downhills, and horizontal running, the average C_r to be used in the calculations should be the weighted mean of the appropriate C_r values. Therefore, the true average C_r may be rather difficult to assess, a fact that somewhat weakens the accuracy of the predictions.

The data reported in Table 2 show that C_r varied widely among subjects. The following section deals with the calculation of the theoretical effects of the variability of C_r on marathon performance. Assume for simplicity two hypothetical subjects whose C_{r0} amounts to 162.6 and to 188.9 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$ (the two extreme values reported in Table 2). Assume further that, for both subjects: $\dot{V}O_{2\,max}$ equals 70 $ml \cdot kg^{-1} \cdot min^{-1}$ above resting, F equals 0.75 and C_r increases throughout the marathon by 4.64 ml $O_2 \cdot kg^{-1} \cdot km^{-1}$ (see above). Hence, from Eq. 1, the two average speeds amount to 5.23 and 4.52 $m \cdot s^{-1}$, corresponding to performance times of 134.5 and 155.6 min respectively, a remarkable difference indeed. As well as the difference in C_{r0}, the increase of C_r with the D also varied markedly from subject to subject. In fact, the regression coefficient of C on D varied from 0.06% (average minus 1 SD) to 0.19% (average plus 1 SD)$\cdot km^{-1}$ (Eq. 4), which may well have accounted for a difference of 3-4 min on a performance time of about 140 min. It can therefore be concluded that an endurance runner, to achieve excellence, as welt as being characterized by a large $\dot{V}O_{2\,max}$, a high F and a low C_r (see Eq. 1), must also be a "nonaugmenter" i.e. a runner whose C_r increases only minimally with the D. Whereas the role of the first three characteristics (high $\dot{V}O_{2\,max}$ and F, low C_r) in setting marathon performances has been previously pointed out (di Prampero et al. 1986; but see Sjodin and Svedenhag 1985, for review), to our knowledge this is the first study to show quantitatively the importance of being a non-augmenter.

Finally, we would like to point out that, apart from the athletic importance of being a non-augmenter, C_r only seems to be affected to a minor extent by fatigue. Indeed, at the very end of a marathon, the average increase of C_r was only about 5% in terms of $\dot{V}O_2$ and about 3% in terms of energy expenditure (see Eqs. 5, 6). This constancy, or quasi-constancy, of C_r may have been due to the fact that the neuromuscular coordination on which running (and walking) depend are so phylogenetically old that they cannot be easily altered, except in pathological conditions (Olgiati et al. 1986).

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