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Energetics of running in top-level marathon runners from Kenya

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Abstract On ten top-level Kenyan marathon runners (KA) plus nine European controls (EC, equivalent to KA), we measured maximal oxygen consumption ($\dot{V}O_{2max}$) and the energy cost of running (C_r) on track during training camps at moderate altitude, to better understand the KA dominance in the marathon. At each incremental running speed, steady-state oxygen consumption ($\dot{V}O_2$) was measured by telemetric metabolic cart, and lactate by electro-enzymatic method. The speed requiring $\dot{V}O_2 = \dot{V}O_{2max}$ provided the maximal aerobic velocity (v_{max}). The energy cost of running was calculated by dividing net $\dot{V}O_2$ by the corresponding speed. The speed at lactate threshold ($v_{\Theta AN}$) was computed from individual La_b versus speed curves. The sustainable $\dot{V}O_{2max}$ fraction (F_d) at $v_{\Theta AN}$ ($F_{\Theta AN}$) was computed dividing $v_{\Theta AN}$ by v_{max}. The F_d for the marathon (F_{mar}) was determined as $F_{mar} = 0.92\ F_{\Theta AN}$. Overall, $\dot{V}O_{2max}$ (64.9 ± 5.8 vs. 63.9 ± 3.7 ml kg^{-1} min^{-1}), v_{max} (5.55 ± 0.30 vs. 5.41 ± 0.29 m s^{-1}) and C_r (3.64 ± 0.28 vs. 3.63 ± 0.31 J kg^{-1} m^{-1}) resulted the same in KA as in EC. In both groups, C_r increased linearly with the square of speed. $F_{\Theta AN}$ was 0.896 ± 0.054 in KA and 0.909 ± 0.068 in EC; F_{mar} was 0.825 ± 0.050 in KA and 0.836 ± 0.062 in EC (NS). Accounting for altitude, running speed predictions from present data are close to actual running performances, if $F_{\Theta AN}$ instead of F_{mar} is taken as index of F_d. In conclusion, both KA and EC did not have a very high $\dot{V}O_{2max}$, but had extremely high F_d, and low C_r, equal between them. The dominance of KA over EC cannot be explained on energetic grounds.

Keywords Maximal oxygen consumption · Energy cost · Running performance · Ethnic groups · Altitude

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Introduction

A remarkable evolution in marathon running performance has occurred in recent years. In 1990, the 50th best performer of the year ran in 2 h 13 min and 1 s, implying an average running speed over the distance of 5.287 m s^{-1} or 19.03 km h^{-1} (source: http://digilander.libero.it/atletica2/Stagionali/WRL/1990/Mar). The equivalent performance in 2010 was 2 h 8 min and 25 s, for an average running speed of 5.476 m s^{-1} or 19.72 km h^{-1} (source: http://www.iaaf.org/statistics/toplists), representing a 3.58% improvement with respect to 20 years earlier. Impressively enough, this unusual performance improvement has been

largely due to marathon runners from Kenya. In 1990, there was only one athlete from Kenya in the top 50 list, and he was a Kikuyu. This number never stopped increasing ever since. In 2010, there were 30 Kenyans in the top 50 performers in the marathon, and 108 in the top 200. Similar tendencies can also be reckoned for the half-marathon performance.

Most of the current marathon runners from Kenya belong to the same ethnic group, the Kalenjin. Of the 30 Kenyans in the 2010 top 50 list, 29 were Kalenjin and 1 Kikuyu. The Kalenjins constitute some 3.5 million individuals, divided into 12 tribes that have been dwelling for centuries on the highlands of the Rift Valley, in the western part of Kenya. For more details on the demography and social geography of the Kalenjin tribes, see Larsen (2003). The question is how such an extraordinary achievement by such a small-sized population could take place. Several aspects were looked at, including population genetics (Larsen 2003, 2004; Yang et al. 2007), food intake (Onywera et al. 2004), demography and social organization (Larsen 2003; Onywera et al. 2006), and hematology (Prommer et al. 2010). In the field of exercise physiology, maximal oxygen consumption, lactate threshold and running economy (Billat et al. 2003; Larsen et al. 2004; Saltin et al. 1995b), muscle morphology and muscle fiber typing (Saltin et al. 1995a) were investigated. These studies, however, provided only limited answers to the above question.

Most of previous physiological studies on Kenyan runners were not carried out on top athletes, but on either medium-level or junior athletes and this jeopardized the possibility of identifying differences with respect to athletes from other ethnic groups. This was the first study to be carried out on real top marathon runners: the studied Kalenjin included Martin Lel, multiple winner of London and New York City marathons, and Sammy Korir, who in Berlin ended one second apart from the world record; the control group included Stefano Baldini from Italy, winner of the Olympic marathon in Athens 2004, and Viktor Röthlin from Switzerland, the current European champion.

The maximal velocity that a long-distance runner can sustain over a given distance (v_d) is equal to:

$$v_d = \frac{\dot{E}_{max}}{C_r} = \frac{F_d \times \dot{V}O_{2max}}{C_r} \qquad (1)$$

where C_r is the energy cost of running (the physical parameter quantifying running economy), $\dot{E}_{max}$ is the maximal sustainable metabolic power, $\dot{V}O_{2max}$ is the maximal oxygen consumption and F_d is the fraction of $\dot{V}O_{2max}$ that can be sustained over the race distance. When $\dot{E}_{max} = \dot{V}O_{2max}$, then $F_d = 1$; when $\dot{E}_{max} < \dot{V}O_{2max}$, then $F_d < 1$. The latter is the case for the marathon, in which F_d

is somehow related to the so-called lactate threshold speed (Ferretti et al. 2011), which Helgerud et al. (1990) defined as the highest speed at which, during a 20-min continuous exercise, blood lactate concentration increases by less than 1 mM in the last 15 min. Because of Eq. 1, the measurement of $\dot{V}O_{2max}$ and C_r and the estimate of F_d is first source of information on potential differences on the sustainable marathon speed between Kalenjin and Caucasians (di Prampero 1986; Ferretti et al. 2011). Other factors may be called upon for a deeper physiological understanding of the phenomenon of Kenyan runners, but if physiological differences exist between Kalenjin runners and runners from other ethnic groups, they can only translate into visible differences in the three terms of the right branch of Eq. 1.

The aim of this study was thus to measure $\dot{V}O_{2max}$, C_r and estimate F_d in a set of top-level marathon runners issued from the Kalenjin ethnic group and compare them with the data obtained on a group of top-level Caucasian athletes. The hypothesis was that the predominance of the Kalenjin in the marathon could be explained by differences in the three terms of Eq. 1 with respect to their Caucasian competitors.

Methods

Subjects

Ten Kalenjin marathon runners (KA) participated in the study. They all had a best performance in the marathon of less than 2 h and 9 min. A control group of nine top European athletes (European controls, EC) was also enrolled, with similar performances to those of KA. The physical characteristics of KA and EC are reported in Table 1, together with the best performances in the marathon and the semi marathon in the 2 years that preceded and followed the performance of the tests. The two groups did not differ among them, except for the fact that EC were significantly older than KA. Body mass was strictly the same (1.7 kg difference, $p = 0.482$). Nevertheless, KA had significantly better performances on both the marathon and the half-marathon than EC, although only four EC athletes had a performance on the marathon.

The athletes were investigated outside the competition period, during winter or summer training stages. This implies that all experiments were carried out at altitude, in winter at Eldoret, Kenya (altitude 2,000 m, inspired oxygen pressure (P_IO_2), 113.2 ± 0.6 mmHg), in summer either at Saint Moritz, Switzerland (altitude 1,800 m, P_IO_2 116.7 ± 0.5 mmHg) or at Ortisei, Italy (altitude 1,300 m, P_IO_2 127.3 ± 0.5 mmHg).

Table 1 Basic characteristics of the subjects and their performances on the marathon and the half-marathon

Subjects	Age (yy)	Height (cm)	Body mass (kg)	Resting $\dot{V}O_2$ (ml min^{-1} kg^{-1})	Resting fh (min^{-1})	Marathon time (s)	Half-marathon time (s)
KA							
Mean	29	172	59.4	5.7	59	7,637	3,640
SD	4	7	5.8	1.4	4	87	31
EC							
Mean	33	175	61.1	6.7	65	7,704[a]	3,717
SD	4	5	4.5	2.3	11	75	47

Concerning performances, as expressed in IAAF official timing rules, the average marathon times corresponded to 2 h 7 min and 17 s (SD 1 min 27 s) in KA, and 2 h 8 min 24 s (SD 1 min 15 s) in EC, whereas the average half-marathon times corresponded to 60 min and 40 s (SD 31 s) in KA and 61 min 57 s (SD 47 s) in EC

$\dot{V}O_2$ oxygen consumption, *fh* heart rate, *KA* top-level Kalenjins ($n = 10$), *EC* European controls ($n = 9$)

[a] $n = 4$

Study designs and methods were approved by the ethical committee of the local health agency of Brescia, Italy, where Rosa Associati, the athletes managing company, is located. All the subjects were informed about the aims of the investigation and the methods applied in the experiments, and they all signed a written informed consent form.

Protocol

This was a field study and the experiments were performed on an athletic camp. In Eldoret, we operated at the Kipchoge Keyno Stadium, whose track is in red clay. In Europe, experiments were performed on training camps, whose track was covered with synthetic material. The length of the track on the inner circle was measured and in all cases resulted to be within 2 m from the official length of 400 m. Starting from the goal line, plastic cones were positioned 50 m apart, to give a precise reference of the distance covered. An investigator, who cycled 10 m ahead of the athlete following the rhythm imposed by a metronome, paced the running velocity. The frequency of the metronome at each speed was set in such a way as to have a beep each time the bicycle had to pass beside a cone. The distance between the bicycle and the athlete, who ran in the innermost track, was such as to avoid any reduction of the air resistance encountered by the athletes while running.

A progressive step protocol was applied. Starting from a velocity of 12 km h^{-1}, the velocity was progressively increased by steps of 2 km h^{-1}, up to 20 km h^{-1}. Each step lasted 4 min. Successive steps were separated by 5-min intervals, during which micro blood samples were taken from an earlobe for the measurement of blood lactate concentration. In most cases, the athlete sustained the 20 km h^{-1} step without signs of exhaustion. If this was so, then a final step was performed, consisting of an all-out trial over the 800-m distance. This effort was slightly supramaximal for all athletes. At the end of this last trial,

peak blood lactate concentration (L$\hat{a}_b$) was determined with micro blood samples taken at min 1, 3 and 5 during recovery. Arterial oxygen saturation (SaO_2) was also measured before and immediately after the end of the test.

Measurements

Oxygen consumption ($\dot{V}O_2$) at the exercise steady state was determined by means of a portable telemetric metabolic cart (Cosmed K4, Rome, Italy) at rest and during each running trial. The system comprised a turbine flowmeter (instantaneous flow between 0.03 and 20 l s^{-1}; precision ±2%), a zirconium oxygen analyzer (precision ±0.02%, response time <150 m s) and an infrared carbon dioxide analyzer (precision ±0.01%, response time <150 m s). The metabolic system was calibrated before and after each experimental session by means of certified gas mixtures and a 3-l syringe (Hans Rudolph, Kansas City, MO, USA). R was calculated from $\dot{V}CO_2$ and $\dot{V}O_2$ data. Heart rate was measured continuously by a cardiometer (Polar, Finland). Peak blood lactate concentration was measured by an electro-enzymatic method (Lactate Pro, Biomedic Labs, USA). Arterial oxygen saturation was measured by infrared spectrometry (Siemens MicrO$_2$, Denvers, MA, USA).

The individual $\dot{V}O_{2max}$ was determined from the plateau attained by the $\dot{V}O_2$ versus speed relationship above a given speed. This plateau was observed in all tests. The corresponding maximal aerobic velocity (v_{max}) was calculated as the minimal speed requiring a $\dot{V}O_2$ equal to $\dot{V}O_{2max}$, or, in other terms, as the velocity at the crossing of the $\dot{V}O_{2max}$ plateau with the $\dot{V}O_2$ versus speed line. C_r was computed at all speeds lower than v_{max} (submaximal speeds) as the ratio between the net (measured minus upright resting) steady state $\dot{V}O_2$ at each speed and the corresponding speed. The speed at the lactate threshold ($v_{\Theta AN}$) was computed from the L$\hat{a}_b$ versus speed curves,

with the same procedure used by Helgerud (1994). The sustainable fraction of $\dot{V}O_{2max}$ at $v_{\Theta AN}$ ($F_{\Theta AN}$) was computed as the ratio of $v_{\Theta AN}$ to v_{max}. The F_d for the marathon (F_{mar}) was then determined as (Helgerud 1994):

$$F_{mar} = 0.92 F_{\Theta AN} \tag{2}$$

Statistics

Mean values are reported along with their standard deviations (SD). Data comparison among groups was done by means of a student t test for unpaired observations. Although the level of significance was formally set at $p < 0.05$ (two-tailed test), actual p values are reported. Concerning C_r, comparison of C_r changes with increasing speed within each group was done by means of a one-way analysis of variance for repeated measures. When applicable, a Tukey post hoc test was used to locate significant differences. The level of significance was set at $p < 0.05$ (two-tailed test). Linear regression equations were computed with the least-squares method. The slope was considered significant when $p < 0.05$. Slopes and y-intercepts were compared by means of analysis of covariance (Kleinbaum et al. 1987). In figures, values are given as mean and standard deviation, whereas lines are regression lines computed on individual data.

Results

The $\dot{V}O_{2max}$ is reported in Table 2 for both KA and EC, together with the related parameters. p values indicate that $\dot{V}O_{2max}$ was indeed the same in KA as in EC, as were all other reported parameters, despite the observed significant differences in marathon performance. Of course, a tendency toward lower $\dot{V}O_{2max}$ values at Eldoret or St. Moritz than at Ortisei was observed, for both KA (63.1 ± 6.9 vs. 67.5 ± 2.6 ml kg^{-1} min^{-1}) and EC (62.3 ± 5.2 vs. 65.2 ± 1.6 ml kg^{-1} min^{-1}). The mean C_r was 3.64 ± 0.28 J kg^{-1} m^{-1} (174 ± 13 ml kg^{-1} km^{-1}) in KA and 3.63 ± 0.31 J

kg^{-1} m^{-1} (174 ± 15 ml kg^{-1} km^{-1}) in EC, again practically the same in the two groups ($p = 0.963$).

However, when the effects of speed on C_r is analyzed, as in Table 3, it appears that the C_r at the speed of 18 km h^{-1} was significantly higher than at the speed of 12 km h^{-1} in both groups ($p = 0.046$ for KA and 0.042 for EC), although no differences between groups were observed at any speed. If we plot C_r as a function of the square of submaximal running speeds, as in Fig. 1, significant linear relationships are found for each group. The two regression lines, also reported on the same figure, had no significant differences in slopes and y-intercepts, partly because of inter-individual variability within groups (coefficient of variations for C_r 7.7% in KA and 8.6% in EC). The y-intercepts, corresponding to the non-aerodynamic component of C_r (C_{na}) were indeed very close, equal to 3.288 J kg^{-1} m^{-1} in KA and 3.234 J kg^{-1} m^{-1} in EC, as were the slopes, corresponding to the aerodynamic constant k, which were equal to 0.0180 and 0.0191 J s^2 kg^{-1} m^{-3} in KA and EC, respectively.

The $v_{\theta AN}$ was 4.96 ± 0.15 m s^{-1} in KA and 4.92 ± 0.43 m s^{-1} in EC ($p = 0.774$). As a consequence, the $F_{\theta AN}$ turned out to be equal to 0.896 ± 0.055 in KA and 0.909 ± 0.068 in EC ($p = 0.653$), indicating that EC and KA really had almost equal $F_{\theta AN}$. The F_{mar} was equal to 0.825 ± 0.050 and 0.836 ± 0.062, in KA and EC, respectively (Table 4).

The combination of individual $\dot{V}O_{2max}$, C_r at the speed of 18 km h^{-1} (note that C_r varies with speed) and F_{mar} yielded a prediction of mean sustainable running speed in the marathon, at the altitudes at which the study was carried out, of 4.561 ± 0.246 m s^{-1} in KA and 4.568 ± 0.578 m s^{-1} in EC ($p = 0.972$).

Discussion

According to Eq. 1, three factors determine the maximal sustainable speed during a marathon: the $\dot{V}O_{2max}$, its
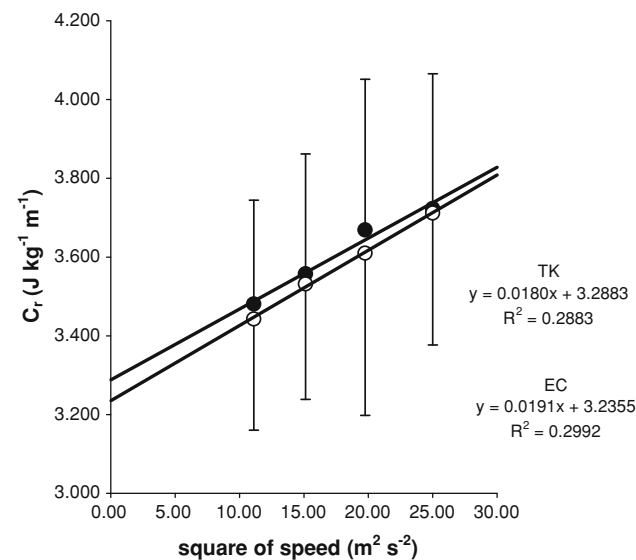
Table 2 Maximal oxygen consumption and related parameters

Subjects	$\dot{V}O_{2max}$ (l min^{-1})	$\dot{V}O_{2max}$ (ml min^{-1} kg^{-1})	$[La]_{max}$ (mM)	v_{max} (m s^{-1})	v_{max} (km h^{-1})	fh_{max} (min^{-1})	R	SaO_2
KA								
Mean	3.83	64.9	8.63	5.55	20.0	181	1.09	0.84
SD	0.36	5.8	3.75	0.30	1.1	9	0.11	0.07
EC								
Mean	3.90	63.9	9.56	5.41	19.5	174	1.06	0.88
SD	0.35	3.7	4.22	0.29	1.0	9	0.07	0.05
p	0.698	0.660	0.617	0.332	0.332	0.111	0.474	0.107

$\dot{V}O_{2max}$ maximal oxygen consumption, $[La]_{max}$ maximal blood lactate concentration, fh_{max} maximal heart rate, R gas exchange ratio at maximal exercise, SaO_2 arterial oxygen saturation, KA top-level Kalenjins ($n = 10$), EC European controls ($n = 9$)

Table 3 Energy cost of running (C_r) (mean and standard deviations) at the various investigated speeds (v)

V (km h^{-1})	C_r (J kg^{-1} m^{-1})		C_r (ml kg^{-1} km^{-1})		p
	KA	EC	KA	EC	
12					
Mean	3.48	3.44	167	165	0.766
SD	0.26	0.28	13	14	
14					
Mean	3.56	3.53	170	169	0.853
SD	0.30	0.29	15	14	
16					
Mean	3.67	3.61	176	173	0.748
SD	0.38	0.41	18	20	
18					
Mean	3.72	3.71	178	178	0.943
SD	0.34	0.34	16	16	

Fig. 1 Mean values of the energy cost of running (C_r) as a function of the square of speed. Data are given as mean and standard deviation. Regressions have been calculated on individual data. *Filled circle* top-level Kalenjin (KA), *open circle* European controls (EC)

Table 4 Prediction of marathon average speed at sea level

Sea level	KA	EC
$\dot{V}O_{2max}$ (ml min^{-1} kg^{-1})		
Mean	69.1	67.9
SD	6.0	3.7
C_r at 18 km h^{-1} (J m^{-1} kg^{-1})		
Mean	3.83	3.83
SD	0.35	0.32
F_{mar}		
Mean	0.825	0.836
SD	0.050	0.062
$F_{\Theta AN}$		
Mean	0.896	0.909
SD	0.054	0.068
$F_{d, actual}$		
Mean	0.933	0.919
SD	0.058	0.050
v (F_{mar}) (km h^{-1})		
Mean	17.13	16.85
SD	0.95	1.92
v ($F_{\Theta AN}$) (km h^{-1})		
Mean	18.62	18.31
SD	1.03	2.09
v ($F_{d, actual}$) (km h^{-1})		
Mean	19.39	19.36
SD	1.02	0.77
v_{record} (km h^{-1})		
Mean	19.89	19.72[*]
SD	0.23	0.19

$\dot{V}O_{2max}$ estimated maximal oxygen consumption at sea level, C_r energy cost of running, F_{mar} sustainable fraction of maximal aerobic speed calculated according to Helgerud et al. 1990, $F_{\Theta AN}$ sustainable fraction of $\dot{V}O_{2max}$ calculated after the speed at the lactate threshold, F_d actual, sustainable fraction of maximal aerobic speed calculated after the average speed sustained during the best performance marathon, v velocity, v_{record} average speed attained during best performance marathon by the investigated athletes, KA top-level Kalenjins, EC European controls (*$n = 4$ for this group)

sustainable fraction and C_r (di Prampero 1986; Ferretti et al. 2011). All these factors were determined on KA and EC. This was the first study in which the energetics of running in top-level Kenyan marathon runners was investigated. In fact, the best performances of the KA group were such as to place all the members of this group within the top 50 list of year 2010 or the top 200 best performances of all time in the marathon, according to the records of the International Association of Athletic Federations (see http://www.iaaf.org/statistics/toplists). None of the previous studies of the energetics of running in

Kenyan long-distance runners could be carried out on athletes of similar level to the present ones. In the past, only adolescent or junior athletes, or runners of a lesser level, could be studied (Billat et al. 2003; Larsen et al. 2004; Saltin et al. 1995b). These studies revealed no differences with respect to their European controls. The suspicion existed, however, that energetic differences might have appeared when real top-level athletes were studied. The present results showed that this was not so, since no differences between KA and EC were found for any of the investigated parameters. As a consequence, equal predicted marathon speeds were obtained for both KA and EC at the altitudes where this study was carried out. These results

show that, contrary to the tested hypothesis, the supremacy of Kenyan runners over Caucasians in the marathon is not due to differences in the energetics of running. Yet, we demonstrated a clear effect of speed on C_r in both KA and EC, which we attributed to an effect of speed on the energy cost against aerodynamic forces, C_a. This effect was strictly the same in KA and EC. The three parameters that determine the sustainable mean running speed of a marathon are discussed separately, before putting them together in an attempt at predicting the marathon speed at sea level and compare it with the actual mean speed during competition.

Maximal oxygen consumption

The relatively low $\dot{V}O_{2max}$ values were obviously a consequence of the altitude at which the tests were carried out. Due to logistic constraints, tests had to be made at two different altitudes, so at two inspired PO_2 values, both lower than at sea level, where most marathons take place. This may be viewed as a limitation of our study. The mean $\dot{V}O_{2max}$ value reported in Table 2 accounts for the two altitudes. Luckily enough, the fraction of athletes investigated at 2,000 m was the same in the two groups, which made group comparison possible. An estimate of the equivalent $\dot{V}O_{2max}$ at sea level requires deciding about the occurrence of arterial oxygen desaturation at maximal exercise (Dempsey effect, Dempsey et al. 1984) in these athletes. This occurrence is unpredictable from the measured SaO_2. For the sake of simplicity, we assumed that the present subjects were not affected by the Dempsey effect. Based on this assumption, the individual $\dot{V}O_{2max}$ values at sea level could be calculated from the characteristics of the classical curve describing the $\dot{V}O_{2max}$ decrease at altitude (Ferretti 1990), considering the actual altitude at which each test was done. Then the corresponding SaO_2 values at sea level were estimated after the linear $\dot{V}O_{2max}$ versus SaO_2 relationship reported by Ferretti et al. (1997).

At sea level, estimated $\dot{V}O_{2max}$ turned out equal to 69.1 ± 6.0 ml min^{-1} kg^{-1} in KA and 68.7 ± 4.0 ml min^{-1} kg^{-1} in EC ($p = 0.841$). These $\dot{V}O_{2max}$ values were associated with v_{max} values at sea level of 5.94 ± 0.33 m s^{-1} in KA and 5.78 ± 0.33 m s^{-1} in EC ($p = 0.318$). These sea-level $\dot{V}O_{2max}$ values were coupled with estimated SaO_2 values at maximal exercise of 0.89 ± 0.08 and 0.94 ± 0.05, in KA and EC, respectively ($p = 0.173$). The estimated SaO_2 values of KA are in the range of what Dempsey and Wagner (1999) define as moderate exercise-induced arterial hypoxemia, suggesting that our assumption might have been partially wrong. Nevertheless, in view of the moderate altitude at which the tests were made, the hypothetical error introduced in this

estimate would be, practically speaking, negligible. In fact, only slightly higher sea-level $\dot{V}O_{2max}$ values would have been obtained by using the linear relationship that Wehrlin and Hallén (2006) established for desaturating athletes. Moreover, the mean SaO_2 value of KA is affected by the data of two athletes, who were remarkably hypoxemic at maximal exercise (their SaO_2 values were 0.71 and 0.74 at the end of the test, carried out in Eldoret). Saltin et al. (1995b) found a 16.6% higher $\dot{V}O_{2max}$ at sea level than at 2,000 m in a group of young medium-level Kalenjin runners, suggestive of severe exercise-induced arterial hypoxemia in those subjects. This was not the case for the present KA: a 16.6% higher $\dot{V}O_{2max}$ at sea level would have implied SaO_2 values around 1.0, if not above, for the present subjects, a preposterous situation indeed.

The estimated $\dot{V}O_{2max}$ values at sea level are elevated, but not as high as one would expect. They can conveniently be compared with those of Coetzer et al. (1993), who found similar $\dot{V}O_{2max}$ values than the present ones in a group of high-level South-African long-distance runners investigated at sea level. Yet, they appear lower than those found by others on Kenyan runners of lesser level than the present ones (Billat et al. 2003; Saltin et al. 1995b). Even higher $\dot{V}O_{2max}$ values were reported on marathon runners in a farther past. The $\dot{V}O_{2max}$ of two top-level Kalenjins of the 1960s was higher than 80 ml min^{-1} kg^{-1} (Saltin and Åstrand 1967), and similar values were also observed in top-level Caucasians studied in the same period (di Prampero et al. 1970; Pollock 1977; Saltin and Åstrand 1967). Such high $\dot{V}O_{2max}$ values have not been observed anymore in marathon runners in recent years, since values below 75 ml min^{-1} kg^{-1} are most commonly found at sea level nowadays (Billat et al. 2001; Larsen et al. 2004). It is noteworthy, however, that in older studies graded protocols were used and it was reported that the former provide $\dot{V}O_{2max}$ values that are 5% higher than with the latter exercise mode (Hermansen and Saltin 1969). An extremely high $\dot{V}O_{2max}$ is not a distinctive characteristic of contemporary marathon runners, independent of the ethnic group to which they belong.

Sustainable fraction of maximal oxygen consumption

A direct determination of F_d is complex, since it requires running until exhaustion at several submaximal speeds, and no previous study reported measured F_d values, but only estimates. The same was the case for the present athletes. In this study, we relied on the concept that the F_d sustained over a marathon (F_{mar}) is directly related to $v_{\theta an}$ (Helgerud et al. 1990; Helgerud 1994), whose ratio to v_{max} is equal to $F_{\theta AN}$. So, we computed F_{mar} from $F_{\theta an}$, according to Helgerud (1994). An indirect and simple comparison,

however, is possible with the estimates provided by Saltin's linear formula (Saltin 1973), which, for a 2-h duration exercise, predicts F_d values of 0.81, very close to the present F_{mar}. These F_{mar} values, however, are not representative of what occurs during actual competitions. The ratio of the average running speed of the best marathon performance of present athletes to their v_{max} at sea level turns out to be equal to 0.929 ± 0.057 in KA and 0.919 ± 0.050 in EC (those with a marathon performance, $p = 0.670$), which are all significantly higher than the corresponding F_{mar}. This would indicate that top-level marathon runners, whether Kalenjin or European, are capable of sustaining a higher fraction of the v_{max} over a 2-h duration effort than that estimated after previous studies (Costill et al. 1973; di Prampero et al. 1986; Helgerud 1994; Helgerud et al. 1990).

Energy cost of running

The C_r was, as expected (Bunc and Heller 1989; di Prampero 1986; Jones and Doust 1996; Joyner 1991; Minetti et al. 2002), some 15% lower than usually found in the normal population and apparently similar to that reported in other studies on competitive runners (di Prampero et al. 1986; Lacour et al. 1990). Others observed higher Cr values in top-level marathon runners (Billat et al. 2001): those authors did not provide an interpretation of their high C_r, but they reported that they found a positive correlation between $\dot{V}O_{2max}$ and C_r.

The present C_r values were affected by the fact that the present experiments were performed at altitude, where air resistance is less than at sea level, although the effects of air resistance during running are often neglected. In fact, C_r is generally considered invariant in a given individual and thus independent of the running speed (di Prampero 1986; Dill 1965; Hagberg and Coyle 1984; Margaria et al. 1963; McMiken and Daniels 1976; Minetti et al. 2002). On this basis, a simple method for the assessment of C_r in unsteady-state conditions was recently proposed (di Prampero et al. 2009). The concept of invariant C_r with speed stems from data essentially obtained during treadmill running. Pugh (1970) demonstrated that there was a fraction of C_r that increased with the square of wind velocity, although this fraction was quantified as being small (at most, 8% of C_r). Following his study, the concept that an invariant C_r could be slightly higher during track running than during treadmill running was nevertheless admitted (di Prampero 1986; Jones and Doust 1996; Léger and Mercier 1984). If this is so, the effects of air resistance on C_r become larger as the running speed is higher. In this study, we had submaximal running speeds of 18 km h^{-1} in all subjects, of 20 km h^{-1} in some, so that higher submaximal speeds than in previous studies were investigated

during track running, and a larger span of speeds was encompassed. It is thus not surprising that C_r was significantly higher at 18 than at 12 km h^{-1} in both groups. This is a clear effect of increased air resistance: in fact, Helgerud et al. (2010) found no differences in C_r as a function of speed during treadmill running at similar speeds to those of the present study.

The total energy cost of running on flat terrain (C_r) is the sum of the energy cost against aerodynamic forces (C_a) and the energy cost to override non-aerodynamic forces (C_{na}). As in any locomotion mode, the former increases with the square of speed; the latter is independent of speed. So, we can write:

$$C_r = C_a + C_{na} = k v^2 + C_{na} \qquad (3)$$

where constant k is directly proportional to the projection area on the frontal plane, the air density and the drag coefficient, and inversely proportional to the apparent mechanical efficiency of running (di Prampero 1986; Ferretti et al. 2011). According to Eq. 3, if we plot C_r as a function of the square of speed, a linear relation is obtained, with slope equal to k and y-intercept equal to C_{na}. This was done in Fig. 1 for the two investigated groups. The obtained values of k are very close to those reported for traditional cycling (di Prampero 2000). This indicates that the differences in C_a between running and cycling are solely due to differences in speed, which is much higher in the latter than in the former, possibly due to lower C_{na}. Constant k turned out higher than estimated by di Prampero (di Prampero 1986) for running, a difference that may depend on a hypothetical underestimation of projection area in this case.

Non-aerodynamic forces, by contrast, resulted in being much higher than in cycling, as expected (di Prampero 1986; Ferretti et al. 2011), but lower than the estimate made by di Prampero (1986) for untrained non-professional runners. Non-aerodynamic forces should correspond to C_r, independent of speed, determined during treadmill running. This being the case, the similarity of our C_r values with those of Lacour et al. (1990) should be reconsidered, in view of the fact that the latter was a treadmill study. Looking at C_{na} suggests that the present top-level runners might indeed have a lower C_r on the treadmill than the runners investigated by others (Lacour et al. 1990; Padilla et al. 1992).

The C_{na} and k values provided by the regression equations of Fig. 1 are overall mean values for each group. Analysis of covariance showed no differences between the two regression lines, and coherently no significant differences in C_r were found between KA and EC. However, since C_{na} (i) contributes to most of the C_r in running, (ii) is independent of speed and (iii) is affected by large inter-subject variability, we may then assume that the lack of

significant differences in C_r among groups and the relatively low correlation coefficients of the regression lines reported in Fig. 1 are mostly due to variability of C_{na}. Inter-subject variability of C_{na} implies vertical shifts up or down of the individual C_r versus v^2 lines with respect to the corresponding regression line shown in Fig. 1. This shift can be estimated for each speed from the ratio between the individual C_r and the mean C_r at the same speed, when individual C_{na} was obtained. Then the individual C_a was calculated as C_r minus the corresponding C_{na}. These results, however, still include the variability due to the different altitudes at which the experiments were carried out. Thus, C_a was referred to sea-level condition, by correcting it for the effects of lower air density at altitude. To this aim, the relationship between air density and altitude established by Capelli and di Prampero (1995) was used. The results of this analysis are shown in Fig. 2, showing that at each speed KA and EC had also equal C_a values (p ranging from 0.131 at 12 km h^{-1} to 0.378 at 18 km h^{-1}). To sum up, the lack of differences in C_r between KA and EC is not only a result of a confounding effect of the predominance of highly variable C_{na} in determining C_r: KA and EC have the same C_{na} and the same C_a, indeed.

Best performance in marathon running

The knowledge of sea-level $\dot{V}O_{2max}$, C_r and F_d allows an estimate of the mean marathon running speed for a
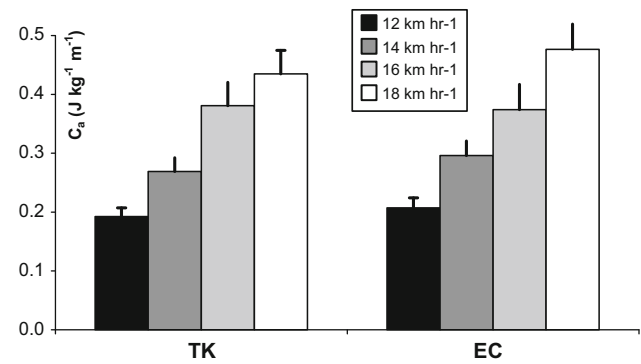
Fig. 2 Estimated aerodynamic energy cost (C_a) of running at the indicated speeds for top-level Kalenjin (KA) and European controls (EC). No significant differences were found between KA and EC

comparison with actual running speeds as attained during competition. The estimated data at sea level used for this prediction are summarized in Table 4. When F_{mar} is used as index of F_d, significantly lower predicted than actual marathon speeds are obtained. When $F_{\theta AN}$ is used instead, predicted speeds are much closer, although still lower, to actual speeds, in both groups. This discrepancy is at least partly related to the fact that athletes run a marathon at their best physical condition, at an even higher F_d than the $F_{\theta AN}$. However, it is of note that we took the individual best performance as actual marathon speed. The above differences are further reduced if we consider the marathon performances that some of the athletes established within 3 months after their participation in the tests. Let us take

Table 5 Individual data obtained on two KA and one EC athletes, who accepted to disclose their data and who ran a marathon within 3 months after testing

	Martin Lel		Elijah Keitany		Viktor Röthlin	
	Eldoret	SL	Ortisei	SL	Eldoret	SL
$\dot{V}O_{2max}$ (l min^{-1})	3.67	3.94	4.40	4.63	3.63	3.90
$\dot{V}O_{2max}$ (ml min^{-1} kg^{-1})	62.8	67.5	64.0	67.4	59.1	63.5
v_{max} (m s^{-1})	5.444	5.854	5.611	5.969	5.556	5.974
C_r at 5 m s^{-1} (J kg^{-1} m^{-1})	3.28	3.39	3.37	3.45	3.49	3.64
$v_{\theta AN}$ (m s^{-1})	5.139	5.526	5.097	5.422	5.361	5.765
$F_{\theta AN}$	0.944	0.944	0.908	0.908	0.965	0.965
v_{mar} at SL (m s^{-1})	Predicted	5.762		5.513		5.550
	Actual	5.508		5.438		5.480
	Record	5.615		5.551		5.521

SL sea level, $\dot{V}O_{2max}$ maximal oxygen consumption, v_{max} maximal aerobic speed, C_r energy cost of running, $v_{\theta AN}$ speed at the lactate threshold, $F_{\theta AN}$ sustainable fraction of $\dot{V}O_{2max}$ calculated after $v_{\theta AN}$, v_{mar} mean speed over a marathon, predicted speed after Eq. 1, actually sustained speed within 3 months after testing, and personal record speed. On 22 April 2007, Lel won the London Marathon in 2 h 7 min and 41 s running at a mean speed of 5.508 m s^{-1}, i.e., 4.4% slower than predicted. According to the prediction, he would have in principle been able to run in 2 h 2 min and 3 s, i.e., faster than the current world record, but he did not need to exploit such a potential to gain the London marathon. On the contrary, on 31 October 2010, Keitany was eighth in Frankfurt, Germany, in 2 h 9 min and 19 s, with a mean speed of 5.438 m s^{-1}, equivalent to only 1.36% less than the predicted speed. His best performance on the marathon (2 h 6 min 41 s) is only 0.69% faster than our prediction (2 h 7 min and 33 s). On 1 April 2007, Röthlin won the Zürich marathon in 2 h 8 min and 20 s. His mean speed was 1.24% less than the predicted speed. His best performance (2 h 7 min and 23 s) is only 0.52% slower than our prediction (2 h 6 min and 43 s)

three examples, from two KA and one EC who authorized disclosure of their individual data, Martin Lel, Elijah Keitany and Viktor Röthlin. Lel and Röthlin were tested in Eldoret, Kenya, in February 2007, Keitany in Ortisei, Italy, in July 2010. Their results are shown in Table 5. Their predicted marathon speeds, calculated using $F_{\theta an}$, were 20.74 km h^{-1} for Lel, 19.85 km h^{-1} for Keitany and 19.98 km h^{-1} for Röthlin, to be compared, respectively, with record speeds of 20.21, 19.98 and 19.87 km h^{-1}.

The present results are not in contrast with the hypothesis that shortly the 2-h record in the marathon may be broken (Capelli and Ferretti 2011), possibly by an athlete with an extremely low C_r (Joyner 1991; Foster and Lucia 2007). In KA, the coefficient of variability of sea-level $\dot{V}O_{2max}$ was 8.62%, that of C_r at 18 km/h was 9.05%, and that of $F_{\theta an}$ 6.08%. Assume a hypothetical athlete with a higher $\dot{V}O_{2max}$ and $F_{\theta AN}$ and a lower C_r at 18 km h^{-1} than the mean values of the KA group by an amount corresponding to one-half of the coefficient of variation of KA for each variable, a very likely case indeed. Well, such an athlete would in theory be able to run the marathon in 2 h 0 min and 14 s, indicating that the goal of the 2-h marathon is close indeed.

Conclusions

In conclusion, top-level Kalenjin marathon runners are characterized by a high, but not very high, $\dot{V}O_{2max}$, an extremely elevated F_d and a low C_r. The same, however, was the case for their European counterparts, so that the dominance of Kenyan marathon runners with respect to Caucasians cannot be explained by differences in the energetics of running. The predictions of mean running speed that can be made from the present data are reasonably close to the actual running performances, if an F_d equal to the $F_{\theta AN}$ is accounted for, although the F_d actually sustained during a competition might be somewhat higher than $F_{\theta AN}$. A precise knowledge of the individual energetic parameters is still a crucial aspect for the evaluation of the physical condition of a marathon runner in view of a competition. The 2-h marathon record is not far from being achieved.

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