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INVITED REVIEW

The energy cost of sprint running and the role of metabolic power in setting top performances

Pietro E. di Prampero · Alberto Botter · Cristian Osgnach

Abstract

Purpose To estimate the energetics and biomechanics of accelerated/decelerated running on flat terrain based on its biomechanical similarity to constant speed running up/down an 'equivalent slope' dictated by the forward acceleration (a_f).

Methods Time course of a_f allows one to estimate: (1) energy cost of sprint running (C_{sr}), from the known energy cost of uphill/downhill running, and (2) instantaneous (specific) mechanical accelerating power ($P_{sp} = a_f \times$ speed).

Results In medium-level sprinters (MLS), C_{sr} and metabolic power requirement ($P_{met} = C_{sr} \times$ speed) at the onset of a 100-m dash attain ≈50 J kg^{-1} m^{-1}, as compared to ≈4 for running at constant speed, and ≈90 W kg^{-1}. For Bolt's current 100-m world record (9.58 s) the corresponding values attain ≈105 J kg^{-1} m^{-1} and ≈200 W kg^{-1}. This approach, as applied by Osgnach et al. (Med Sci Sports Exerc 42:170–178, 2010) to data obtained by video-analysis during soccer games, has been implemented in portable GPS devices (GPEXE©), thus yielding P_{met} throughout the match. Actual O$_2$ consumed, estimated from P_{met} assuming a monoexponential VO$_2$ response (Patent Pending, TV2014A000074), was close to that determined by portable metabolic carts. Peak P_{sp} (W kg^{-1}) was 17.5 and 19.6 for MLS and elite soccer players, and 30 for Bolt. The ratio of horizontal to overall ground reaction force (per kg body mass) was ≈20 % larger, and its angle of application in respect to the horizontal ≈10° smaller, for Bolt, as compared to MLS. Finally, we estimated that, on a 10 % down-sloping track Bolt could cover 100 m in 8.2 s.

Conclusions The above approach can yield useful information on the bioenergetics and biomechanics of accelerated/decelerated running.

Abbreviations

$a(t)$	Acceleration at time t
a_f	Forward acceleration
aLa	Alactic oxygen debt
C_0	Energy cost of running at constant speed on flat terrain (J kg^{-1} m^{-1})
COM	Centre of mass
C_r	Energy cost of running (J kg^{-1} m^{-1})
C_{sr}	Energy cost of sprint running (J kg^{-1} m^{-1})
Ean	Anaerobic energy
ED	Equivalent distance: distance covered running at constant speed on flat terrain, for a given energy expenditure
EDI	Equivalent Distance Index: ratio between ED and actual distance covered
EM	Equivalent body mass
ES	Equivalent slope = tan (90 − α)
F	Force
F_{acc}	Force acting on the subject during accelerated running: $M\,g'$
F_{cost}	Force acting on the subject during constant speed running: $M\,g$
g	Acceleration of gravity
g'	Vectorial sum of af and g: $g' = \sqrt{a_f^2 + g^2}$

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H	Horizontal
i	Incline of the terrain
k	Constant relating mechanical work against the air resistance (per unit body mass) and speed squared (≈ 0.0025 J s^2 kg^{-1} m^{-3})
M	Body mass
P_g	Mechanical power against gravity
P_{req}	Metabolic power requirement (in equivalent oxygen units)
P_{sp}	Specific mechanical power
P_{tot}	Total mechanical power
T	Terrain
$v(f)$	Final velocity
$v(t)$	Velocity at time t
VO_2	Oxygen consumption (ml kg^{-1} min^{-1} or W kg^{-1})
$VO_2(s)$	Oxygen consumption at steady state
$VO_2(t)$	Oxygen consumption at time t
VO_2eff	Actual oxygen consumption
VO_2max	Maximal oxygen consumption
VO_2T	Theoretical oxygen consumption
v_v	Vertical velocity
α	Angle between T and H

Introduction

Direct measurements of energy expenditure during sprint running are rather problematic because of the massive utilisation of anaerobic sources and because of the resulting short duration of any such events which, by their very nature, prevents the attainment of a steady state. Indeed, so far the energy expenditure of sprint running has only been indirectly estimated from biomechanical analyses, on the bases of assumed overall efficiencies of metabolic to mechanical energy transformation (Cavagna et al. 1971; Fenn 1930a, b; Kersting 1998; Mero et al. 1992; Murase et al. 1976; Plamondon and Roy 1984), or else assessed by means of rather indirect approaches (Arsac 2002; Arsac and Locatelli 2002; van Ingen Schenau et al. 1991, 1994; di Prampero et al. 1993; Summers 1997; Ward-Smith and Radford 2000).

An alternative approach, originally proposed by di Prampero et al. (2005), is to assume that sprint running on flat terrain, during the acceleration phase is biomechanically equivalent to uphill running at constant speed, the slope being dictated by the forward acceleration and that, conversely, during the deceleration phase, it is biomechanically equivalent to running downhill. If this is so, since the energy cost of uphill (downhill) running at constant speed is known over a fairly large range of inclines, it is a rather straightforward matter to estimate the energy cost of accelerated (decelerated) running, once the acceleration (deceleration) is determined.

This approach has been subsequently applied to team sports, such as soccer (e.g. Osgnach et al. 2010), the physiological characteristics of which have been, so far, mainly assessed by means of rather indirect methods.

So, we felt that the time has come to summarise under a comprehensive review the theoretical aspects underlying this state of affairs, as well as the practical conclusion that can be obtained therefrom, together with and some possible further developments.

Specifically, the general aim of this review is to (i) summarise the model mentioned above and (ii) show that the model itself can be applied to assess the time course of metabolic power during the initial phase of a 100-m dash. We will then (iii) summarise the study by Osgnach et al. (2010) who showed that this approach can be applied to soccer, specifically to data obtained by video-match analysis during official games. We will also show (iv) that this same approach can be implemented in portable GPS devices, thus greatly simplifying the assessment of the time course of the metabolic power requirement in soccer, whenever the use of these devices is allowed, e.g. training and unofficial matches. This will allow us (v) to estimate the corresponding time course of actual O$_2$ consumption (VO$_2$), assuming a monoexponential VO$_2$ response (Patent Pending). We will also show (vi) that actual VO$_2$, as determined by portable devices, closely matches estimated (by GPEXE ©, Exelio srl, Udine, Italy) VO$_2$ time course. In addition, (vii) we will calculate the peak mechanical acceleration power from the time course of the velocity (and hence of the acceleration) during the first 4 s of an all-out run on medium level sprinters and compare it to the values obtained on the holder of the current 100-m world record (9.58 s; Usain Bolt 2009), as calculated from the data reported by Hernandez Gomez et al. (2013). These data will allow us also (viii) to estimate the overall ground reaction force, its horizontal component as well as its angle of application in respect with the terrain, of medium level sprinters and of Usain Bolt during the very initial phase of the sprint, thus focusing on the different biomechanical characteristics between a world class and a medium-level sprinter. The concluding section will be devoted to an attempt at showing (ix) the crucial role of the maximal metabolic power in the very first phase of the run in setting maximal performances over the 100-m dash.

The energy cost of sprint running

Theory

The analogy briefly mentioned above is described in Fig. 1, as from the original paper by di Prampero et al. (2005) to which the reader is referred for further details.
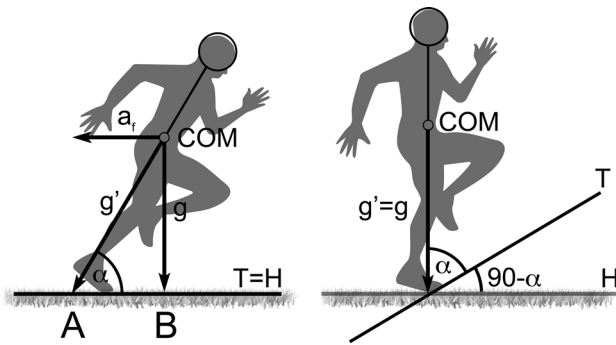
Fig. 1 The subject is accelerating forward while running on flat terrain (*left*) or running uphill at constant speed (*right*). *COM* subject's centre of mass, a_f forward acceleration, g acceleration of gravity, $g' = \sqrt{a_f^2 + g^2}$ vectorial sum of a_f plus g, T terrain, H horizontal, α angle between runner's body and T; $90 - \alpha$ angle between T and H

The subject, whose body mass (M) is assumed to be condensed in his/her centre of mass (COM), is accelerating forward (*left panel*) while running on horizontal (H) terrain (T), the forward acceleration being indicated by the horizontal arrow (a_f). The runner is leaning forward by an amount shown by the angle (α) between his/her body and T. The overall force acting on the runners body (g') is the vectorial sum of the forward acceleration (a_f) and the acceleration of gravity (g): $g' = \sqrt{a_f^2 + g^2}$, wherein both forces are assumed to be applied to the centre of mass.

The subject is running uphill at constant speed (*right panel*), the incline being such that the angle α between his/her mean body axis and the terrain T is the same as in the left panel. It necessarily follows that the angle (deg) between T and the horizontal H is $90 - \alpha$.

Figure 1 shows that accelerated running (left panel) is biomechanically equivalent to uphill running at constant speed (right panel), provided that the up-slope of the terrain is such that the angle between the runner's body and T (α) is the same. It is also immediately apparent that this specific slope, which will here be defined equivalent slope (ES), is given by the tangent of $90 - \alpha$:

$$ES = \tan(90 - \alpha). \tag{1}$$

Indeed, inspection of the left panel of Fig. 1 shows that the angle between a_f and g' is equal to α and that, as a consequence, the angle between g and g' is equal to $90 - \alpha$. Furthermore, since the projection on the terrain of a_f is equal to the segment AB, simple geometric considerations show that

$$\frac{AB}{g} = \frac{a_f}{g} = \tan(90 - \alpha). \tag{2}$$

Hence, from Eqs. (1) and (2)

$$ES = \frac{a_f}{g}. \tag{3}$$

In addition to being equivalent to running uphill, accelerated running is characterised by yet another difference, as compared to constant speed running. Indeed, the force that the runner must develop (average throughout a whole stride), as given by the product of the body mass and the acceleration, is greater in the former ($F_{acc} = M \times g'$) as compared to the latter ($F_{const} = M \times g$), because $g' > g$ (left panel). Thus, accelerated running is equivalent to uphill running wherein, however, the body mass is increased in direct proportion to the ratio F_{acc}/F_{const}.

Since $g' = \sqrt{a_f^2 + g^2}$, this ratio, which will here be defined "equivalent body mass" (EM) is described by

$$EM = \frac{F_{acc}}{F_{const}} = \frac{M \times g'}{M \times g} = \frac{\sqrt{(a_f^2 + g^2)}}{g} = \sqrt{\left(\frac{a_f^2}{g^2}\right) + 1}. \tag{4}$$

It must also be pointed out that during decelerated running, which is equivalent to downhill running, and in which case the equivalent slope (ES) is negative, EM will nevertheless be >1.0, because a_f in Eq. (4) is raised to the power of 2, thus assuming always a positive value.

It can be concluded that, if the time course of the velocity during accelerated/decelerated running is determined, and the corresponding instantaneous accelerations/decelerations calculated, Eqs. (3) and (4) allow one to obtain the appropriate ES and EM values.

Accelerated/decelerated running can then be easily converted into equivalent constant speed uphill/downhill running. Hence, if the energy cost of this last is also known, the corresponding energy cost of accelerated/decelerated running can be easily obtained.

This point will be addressed in the paragraphs that follow.

The energy cost of uphill/downhill running

The energetics of running, on the level, uphill or downhill, at constant speed have been extensively investigated since the second half of the XIX century (for references see Margaria 1938; di Prampero 1986). We will here base our analysis on the data reported by Minetti et al. (2002) who determined the energy cost of running at constant speed over the widest range of inclines studied so far (at least to our knowledge): from −0.45 to +0.45. These authors showed that throughout this whole range of inclines the net (above resting) energy cost of running per unit body mass and distance (C_r) is independent of the speed and is described by the polynomial equation that follows (Fig. 2):

$$C_r = 155.4 \times i^5 - 30.4 \times i^4 - 43.3 \times i^3 + 46.3 \times i^2 + 19.5 \times i + 3.6, \tag{5}$$

Fig. 2 Energy cost of running at constant speed, C_r ($J\ kg^{-1}\ m^{-1}$), as a function of the incline (i) of the terrain. The function interpolating the *full dots* is described by $C_r = 155.4 \times i^5 - 30.4 \times i^4 - 43.3 \times i^3 + 46.3 \times i^2 + 19.5 \times i + 3.6$ *Straight lines* irradiating from the origin indicate net efficiency of work against gravity, the values of which are indicated in the *inset*. *Open dots* and *diamonds* are data from previous studies (from Minetti et al. 2002)
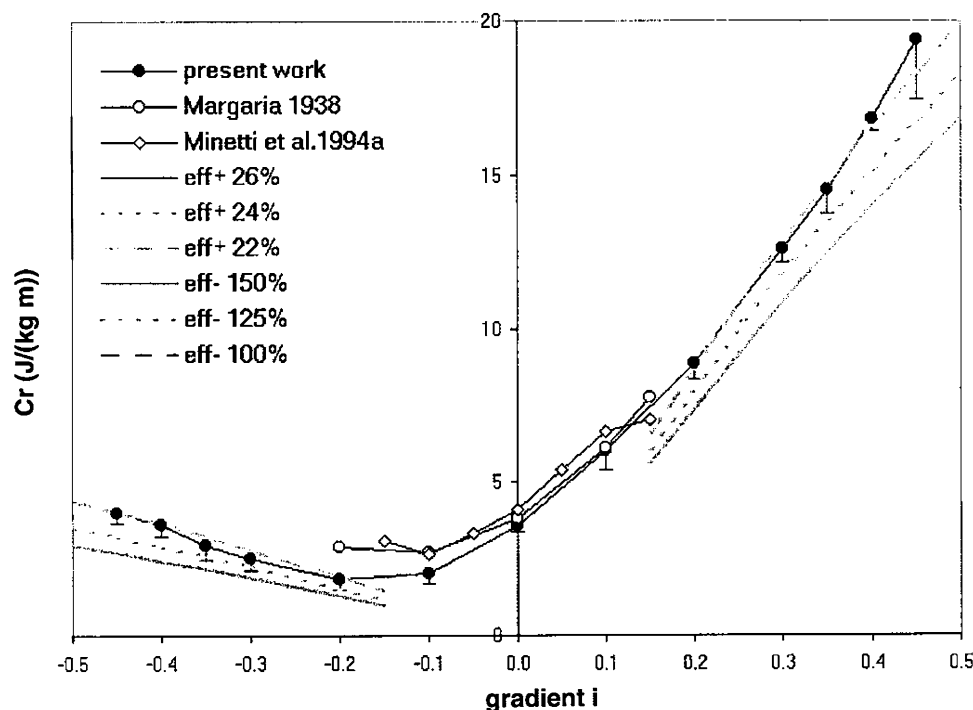
where C_r is expressed in $J\ kg^{-1}\ m^{-1}$, i is the incline of the terrain, i.e. the tangent of the angle between the terrain itself and the horizontal, and the last term ($3.6\ J\ kg^{-1}\ m^{-1}$) is the energy cost of constant speed running on compact flat terrain. Thus, substituting i with the equivalent slope (ES), defining C_0 the energy cost of constant-speed level running, and multiplying by the equivalent body mass (EM), Eq. (5) can be rewritten as

$$C_r = (155.4 \times ES^5 - 30.4 \times ES^4 - 43.3 \times ES^3 \\ + 46.3 \times ES^2 + 19.5 \times ES + C_0) \times EM. \quad (6a)$$

Equation (6) allows one to estimate the energy cost of accelerated/decelerated running provided that the instantaneous velocity, the corresponding acceleration values, and hence ES and EM, are known. This approach was originally proposed by di Prampero et al. (2005) and applied to 12 medium-level sprinters (mean (SD), body mass: 74.2 (7.0) kg; age: 21.0 (2.7) years; stature: 1.80 (0.06) m; best performance time over 100 m: 11.30 (0.35) s), as described below.

From theory to data: the model's output

The time course of the speed of each runner was determined over the first 30 m (about 4 s) of a 100-m dash by means of a radar system placed 10 m behind the starting blocks on a tripod, about 1 m above the ground. The time course of the speed could be appropriately described by an exponential equation:
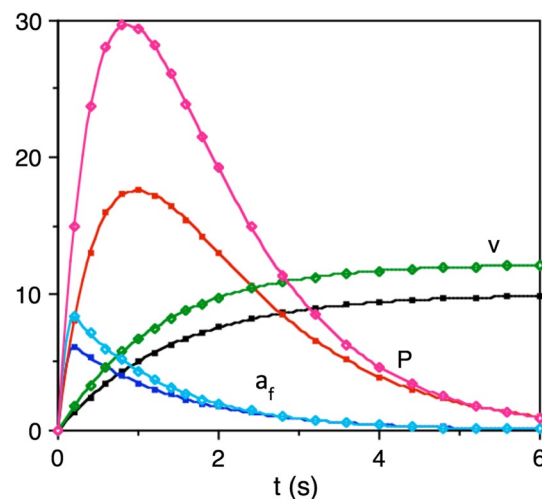

Fig. 3 The velocity ($m\ s^{-1}$) during the first 6 s of Usain Bolt 100-m world record (9.58 s) and of 12 medium-level sprinters (average) is indicated by the *two curves* denoted by v: $v(t) = v(f) \times (1 - e^{-\frac{t}{\tau}})$, the time derivative of which (*curves* denoted by a_f): $a_f(t) = \frac{v(f) - v(f) \times (1 - e^{-\frac{t}{\tau}})}{\tau}$ is the corresponding forward acceleration ($m\ s^{-2}$), where $v(t)$ and $v(f)$ indicate the velocity at time t and the final velocity, $a_f(t)$ is the acceleration at time t, and the time constant $\tau = 1.42$ and 1.25 s for the medium-level sprinters and for Usain Bolt, respectively. The product of the instantaneous acceleration and the corresponding velocity yields the mechanical acceleration power per kg body mass ($W\ kg^{-1}$) (*curves* denoted by P). From the data of di Prampero et al. 2005 and of Beneke and Taylor (2010) and Hernandez Gomez et al. (2013). *Upper curves* refer to Usain Bolt. For further details see text

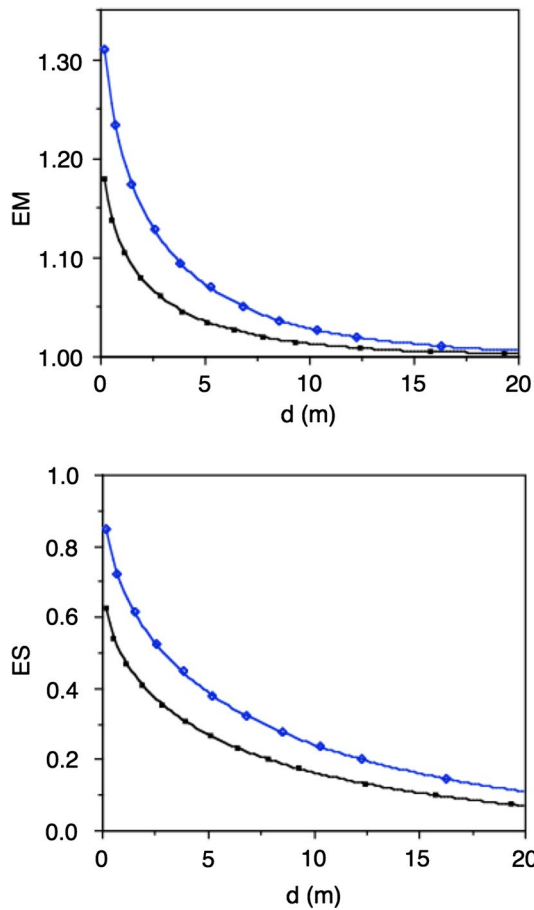$$v(t) = v(f) \times \left(1 - e^{-\frac{t}{\tau}}\right), \quad (7)$$

Fig. 4 Equivalent mass (EM, *upper panel*) and equivalent slope (ES, *lower panel*) as a function of the distance at the *onset* of a 100-m *dash*. Average on 12 medium-level sprinters (*lower curves*, from di Prampero et al. 2005) and on Usain Bolt (*upper curves*, calculated from Taylor and Beneke (2012) and Hernandez Gomez et al. (2013))

Fig. 5 Energy cost of running (C, J kg^{-1} m^{-1}) as a function of distance (*upper*) and metabolic power (P_{met}, W kg^{-1}) as a function of time (*lower*) at the onset of a 100-m *dash* for an average medium-level sprinter (*lower curves*, from di Prampero et al. 2005) and for Usain Bolt (*upper curves*, from the data reported by Taylor and Beneke (2012) and Hernandez Gomez et al. (2013)). P_{met} was obtained from the product of the instantaneous energy cost and the corresponding speed. Average energy cost for constant speed running ≈ 4 J kg^{-1} m^{-1}. The corresponding average values over the first 30 m or 4 s are reported in Table 2

where $v(f)$ and $v(t)$ are the final speed and the speed at time t, respectively, and τ the time constant of the process (Fig. 3). Equation (7) allowed the authors to assess the corresponding instantaneous acceleration ($a_f(t)$), as given by the time derivative of Eq. (7):

$$a_{f}(t) = \frac{v(f) - v(f) \times (1 - e^{-\frac{t}{\tau}})}{\tau}. \tag{8}$$

The so-obtained time courses of the acceleration and of ES and EM (mean of all medium-level sprinters) are reported in Figs. 3 and 4. In addition, in these same figures the corresponding values, as calculated on Usain Bolt during his 100-m world record performance from the velocity profile reported by Hernandez Gomez et al. (2013), are also indicated.

As mentioned above, the energy cost of accelerated running can now be estimated from ES and EM, with the aid of Eq. (6a); it is reported in Fig. 5, for the "average"
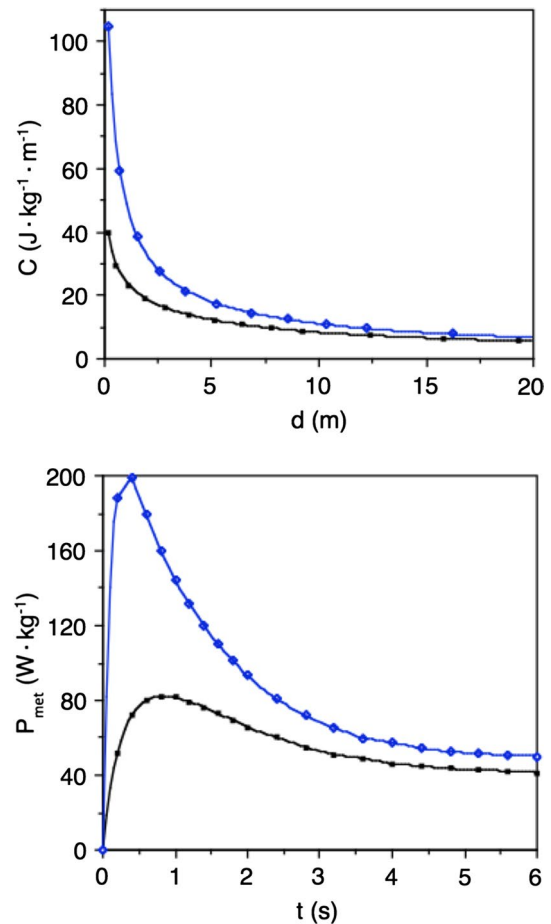
Table 1 Peak values of speed (s), forward acceleration (a_f), equivalent slope (ES) and equivalent body mass (EM)

	s (m s^{-1})	a_f (m s^{-2})	ES	EM
Mean	9.46	6.42	0.64	1.20
SD	0.19	0.61	0.06	0.03
CV	0.20	0.095	0.091	0.025
Usain Bolt	12.20	8.32	0.85	1.31

Means, standard deviations (SD), coefficients of variation (CV) on 12 medium-level sprinters (from di Prampero et al. 2005) and on Usain Bolt, as obtained from the speed profile reported by Taylor and Beneke (2012) and Hernandez Gomez et al. (2013). See text and Fig. 4

Table 2 Peak and mean energy cost of sprint running (C_{sr}, $J kg^{-1} m^{-1}$) and metabolic power (P_{met}, $W kg^{-1}$) over the first 30 m and 4 s of a 100-m dash

	Mean		Peak	
	C_{sr} $(J kg^{-1} m^{-1})$	P_{met} $(W kg^{-1})$	C_{sr} $(J kg^{-1} m^{-1})$	P_{met} $(W kg^{-1})$
Mean	10.7	61.0	43.8	91.9
SD	0.59	4.66	10.4	20.5
Usain Bolt	18.4	105.0	104.4	199.0

Means and standard deviations (SD) on 12 medium-level sprinters (from di Prampero et al. 2005) and on Usain Bolt, as obtained from the speed profile reported by Taylor and Beneke (2012) and Hernandez Gomez et al. (2013). See text and Fig. 5

medium-level sprinter and for Usain Bolt, together with the corresponding instantaneous metabolic power values, as obtained from the product of the instantaneous energy cost of running and the corresponding speed.

The average (over all medium level sprinters) of the peak values of velocity, forward acceleration, ES and EM and of the mean and peak values of energy cost and metabolic power are reported in Tables 1 and 2, together with the corresponding values, as obtained on Usain Bolt during his 100-m world record performance from the velocity profile reported by Hernandez Gomez et al. (2013).

Discussion

Critique of methods

The model proposed by di Prampero et al. (2005) and summarised above is based on several assumptions that will be briefly discussed below, the interested reader being referred to the original paper for further details.

(i) The overall mass of the runner is condensed in his/her centre of mass. This necessarily implies that the energy expenditure due to internal work performance (such as that required for moving the upper and lower limbs in respect to the centre of mass) is the same during accelerated running and during uphill running at constant speed up the same equivalent slope.

(ii) Assumption (i) implies also that the stride frequency of accelerated running is equal to that of constant speed running over the corresponding incline (ES).

(iii) For any given ES, the efficiency of metabolic to mechanical energy transformation during accelerated running is equal to that of constant speed running over the corresponding incline. This also implies that the biomechanics of running, in terms of joint angles and torques, is the same in the two conditions.

(iv) The highest ES values attained at the onset of the run amounted to 0.65–0.70 for the medium-level sprinters and to about 0.85 for U. Bolt, substantially larger than the highest inclines actually studied by Minetti et al. (2002); hence the implicit assumption is also made that even for ES >0.45, the relationship between C_r and the incline is as described by Eq. 6a. However, after about 3 and 6 m for the medium-level sprinters and for U. Bolt, respectively, the actual ES values become <0.45, so that the above assumption is not likely to greatly affect the overall estimate of the energy expenditure, even if it may indeed affect the corresponding time course in the very initial phase of the run. This state of affairs is highlighted by the observation that the peak metabolic power reported in Table 2 for Usain Bolt (about 200 $W kg^{-1}$), is much larger than the values of about 130 $W kg^{-1}$ and of about 150 $W kg^{-1}$ calculated by a similar approach by Beneke and Taylor (2010) for Bolt's 2009 record, and by di Prampero et al. (2005) for the winner of the Gold Medal at the Olympic Games of Seoul (1988) with the time of 9.92 s (C. Lewis). However, the overall average metabolic power, air resistance included (point vi), as calculated for Bolt over the entire 100-m distance turns out to be 87.6 $W kg^{-1}$, i.e. about 14 % larger than that the value of 76.7 reported by Beneke and Taylor (2010). Finally, the metabolic power developed over the last 20 m by U. Bolt turns out to be essentially equal (65 $W kg^{-1}$) to that reported by Beneke and Taylor. These observations support the view that the difference between these sets of data on top-class sprinters can be attributed essentially to the difficulty of estimating precisely the energy cost in the very initial phase of the run.

(v) The calculated ES values are assumed to be in excess of those observed during the constant speed running on flat terrain in which case the runner is lining slightly forward. This, however, can not be expected to introduce large errors, since our reference value was the measured energy cost of constant speed running on flat terrain (C_0).

(vi) As calculated, energy cost and metabolic power do not take into account the energy expenditure against the air resistance. This is described by $k \times v^2$, where v ($m s^{-1}$) is the air velocity, the values of the constant k ($J s^2 kg^{-1} m^{-3}$) reported in the literature ranging form 0.010 (Pugh 1970; di Prampero 1986) to 0.019 (Tam et al. 2012). As such, it can be easily taken into account adding the appropriate quantity to Eq. (6a).

(vii) Finally, the data summarised in Fig. 5 and Table 2 are based on the value of $C_0 = 4.0$ $J kg^{-1} m^{-1}$, slightly larger than that reported by Minetti et al. (2002) which amounted to 3.6 $J kg^{-1} m^{-1}$.

Model validation

Minetti et al. (2012) determined the energy cost of running at "fluctuating speed". Specifically, the subjects ran on the terrain at an average speed of 11 km h^{-1} while the speed was either constant or oscillating in a ramp fashion by ±1, ±2, ±3 or ±4 km h^{-1} every 3 s. The results show that the average (net) energy cost of running (J kg^{-1} m^{-1}) amounted to 4.18 $\pm$ 0.34 at constant speed, and to 4.03 $\pm$ 0.41, 4.32 $\pm$ 0.42, 4.56 $\pm$ 0.49, 4.66 $\pm$ 0.55 (average $\pm$ SD) in the four "fluctuating" conditions mentioned. The authors conclude that, in this acceleration range, the energy cost of running is essentially independent of the acceleration itself.

This is consistent with the observation that the maximal acceleration/deceleration (a_f) amplitude investigated by Minetti et al. (2012) was ±4 km h^{-1} in 3 s, i.e. ±0.37 m s^{-2}, corresponding to an equivalent slope ES $= a_f \times g^{-1} = 0.38/9.81 \approx 0.038$. As shown in Fig. 2, in this range the relationship between the energy cost of running and the incline of the terrain is essentially linear; thus, whatever the gain (in term of energy expenditure) in the downhill phase, it is lost in the following uphill phase. Because the acceleration and deceleration phases are of equal duration, it necessarily follows that the overall average energy cost is essentially equal to that of running at constant speed on flat terrain, as experimentally observed by Minetti et al. (2012).

Buglione and di Prampero (2013) compared the energy cost of shuttle running, as obtained by direct metabolic measurements over distances of $\approx$9 and $\approx$20 m, to the values calculated by means of the approach discussed above over the same distances. The results show that the values obtained by the two approaches over the longer distance are substantially equal. On the contrary, over the shorter distance the indirect approach underestimated significantly (by about 30 %) the directly measured values.

This finding can be attributed to the fact that the indirect approach is based on the assumption that the ratio of the internal to the total (internal + external) work in shuttle running is equal to that applying to constant speed uphill/downhill running (see "Critique of methods"). This also implies that the apparent efficiency (i.e. the ratio of external work to metabolic energy) during accelerated/decelerated running is equal to that of uphill/downhill running at constant speed, over the corresponding ES. While the above assumption seems to hold over the longer distances, it probably breaks down over the shorter ones, in which case the indirect approach underestimates the directly measured one. It should also be pointed out that, because of the 180° speed reversals at each bout, shuttle running may lead to a greater energy expenditure than expected for straight line running on which the above model was developed. In turn this may lead to a greater actual energy cost over the shorter running bouts, as compared to the longer ones, in which case the effect is diluted over a longer distance.

These considerations highlight the need of a thorough discussion of assumptions (i) to (iii) listed under "Critique of methods". Indeed, on the one side, the efficiency of positive work performance during uphill running according to Minetti et al. (2002) data ranges from about 22 to 26 % (see Fig. 2), whereas Hoogkamer et al. (2014) report a 29 % efficiency when running up a 10 % incline. However, in the approach proposed by di Prampero et al. (2005), no explicit efficiency value needs to be assumed, the keystone of the model being the implicit assumption that, for any given equivalent slope (ES), the efficiency of positive work performance is equal to that observed at the corresponding incline (i). This entails also the additional assumption that the ratio of internal to total (internal + external) work in accelerated/decelerated running is equal to that applying at constant speed uphill/downhill running. As briefly discussed above this may not always be the case, so that additional experimental work along these lines seems fully warranted.

In a recent series of experiments to be described below (see Fig. 9), we determined the actual O$_2$ consumption by means of a portable metabolic cart in 8 subjects during a series of shuttle runs over 25 m, each bout being performed in 5 s. The speed was continuously assessed by means of a radar system, thus allowing us to compare the average energy cost of running directly measured over each 25 m bout to that estimated as described above. The two sets of data turned out to be essentially equal, thus confirming the results obtained by Buglione and di Prampero (2013) for 20-m shuttle running.

A final point to be considered is the choice of the energy cost for constant speed running (C_0), which in Eq. (6a) was taken as that applying on flat terrain. Its net value (above resting) (J kg^{-1} m^{-1}) ranges from 3.6 as determined on the treadmill by Minetti et al. (2002) to 4.32 $\pm$ 0.42 on the treadmill and to 4.18 $\pm$ 0.34 on the terrain, as determined more recently by Minetti et al. (2012) at 11 km h^{-1}, to 4.39 $\pm$ 0.43 ($n = 65$), as determined by Buglione and di Prampero (2013) during treadmill running at 10 km h^{-1}, the great majority of data clustering around a value of 4 J kg^{-1} m^{-1} (Lacour and Bourdin 2015 in press). Thus, whereas on the one side it would be advisable to determine C_0 on each subject, on the other it is often convenient to assume a unique value on the order of 4 J kg^{-1} m^{-1}. It should also be pointed out here that Eq. (6a) can also be used to estimate the energy cost while accelerating/decelerating on a terrain that is not flat, but sloping up/down by a given constant amount. In this case, the C_0 value to be inserted into Eq. (6a) is that applying for constant speed running at the given incline. As such is must be calculated from Eq. (5), assign to i the appropriate value, a fact that

will be discussed later (see "On top performances: the role of metabolic power").

In concluding this section, we think that, in spite of the caveats briefly discussed above, the equivalence between an accelerated frame of reference centred on the runner and the Earth gravitational field is a useful tool for estimating the energy cost of accelerated/decelerated running, at least as long as more sophisticated methods for addressing these questions are not available.

Applications in sport science

The energetics of soccer

The energetics of soccer has been traditionally investigated by means of indirect approaches such as the assessment of body temperature and/or heart rate and/or blood lactate concentration. More recently, video-analysis has been applied to soccer, thus greatly refining the technical evaluation of the players during the match. In addition, thanks to four (or more) video cameras appropriately positioned on the pitch, video-analysis can be utilised to determine the players' position on the field, and hence to derive the corresponding velocities. These are subsequently subdivided into several running categories such as jogging (8–13 km h^{-1}), low speed (13–16 km h^{-1}), intermediate speed (16–19 km h^{-1}), high speed (19–22 km h^{-1}), sprinting (>22 km h^{-1}), thus allowing trainers and coaches to evaluate each players' performances.

Furthermore, the overall energy expenditure during the match is also obtained from the product of the (measured) overall distance and the (assumed) energy cost of running. However, this last is considered to be equal to that applying at constant speed running on the level (≈4 J kg^{-1} m^{-1}); as a consequence the effects of the numerous acceleration and deceleration phases occurring during the match (a crucial ingredient of a soccer game. We therefore subdivided the players' performances in acceleration, rather

than speed categories. This allowed us to calculate time, distance and energy expenditure for each acceleration range, as reported in Table 3. In addition, the product of the instantaneous velocity and of the corresponding energy cost yielded the instantaneous values of metabolic power that were grouped in five categories, as reported in Fig. 6, lower panel.

Two sets of considerations emerge immediately from the data summarised above. On the one side, the overall energy expenditure, when considering the acceleration and deceleration phases, turns out to be about 61.1 kJ kg^{-1}, i.e. 22 % larger, as compared to the traditional approach (50.8 kJ kg^{-1}). On the other, inspection of Fig. 6 shows that, whereas the time spent at speeds greater than 16 km h^{-1} is about 6.3 % of the total, when considering the metabolic power corresponding to constant speed running at 16 km h^{-1} (i.e. about 20 W kg^{-1}), the overall amount of energy spent above this threshold turns out to be 47.1 % of the total energy expenditure.

These discrepancies between the two approaches are due to the fact that the running speed is a correct index of the rate of energy expenditure (metabolic power) if and only if the speed itself is constant. Indeed, as represented graphically in Fig. 7, the metabolic power corresponding to a given speed is crucially dependent on the acceleration (e.g. at 9 km h^{-1}, the metabolic power is about 10 W kg^{-1} when the running speed is constant, whereas for an acceleration of ≈4 m s^{-2}, it rises by a factor of 5.5 to ≈55 W kg^{-1}).

These considerations can be condensed in the concept of "Equivalent Distance" (ED), i.e. the distance that a given player would have run, given the actually measured overall energy expenditure, had he been running at constant speed throughout the whole match. The average ED value emerging from the data reported above is on the order of 13,166 m, to be compared to an actual distance of 10,950 m. Thus, the average ratio between ED and the actual distance was on the order of 1.20. It must be pointed out however, that these individual ratios (defined for convenience Equivalent Distant Index, EDI) were widely different among players, ranging from about to 1.15 to about 1.35, depending, among other things, on the role of the player. Furthermore, it should be pointed out that the EDI is an indirect estimate of the metabolic intensity of the game. Indeed, the higher this index, the higher the occurrence of high acceleration bouts leading to energy expenditures over and above that of constant speed running.

This state of affairs shows that a remarkable fraction of the running time during a soccer match consists of high-speed running, presumably implying a substantial contribution of anaerobic stores to the overall energy expenditure. Even so, the blood lactate concentrations observed at the end of each half of the match (≈45 min) are relatively low, amounting on the average to 3.0–6.5 mM (Stølen et al.

Fig. 6 Overall time (s), distance (m) and energy expenditure (kJ kg^{-1}) during a typical soccer match of the Italian 2007/08 "Serie A" (average values). *Upper* the time spent at the indicated speed categories and the corresponding distance are shown by the *grey* and *black bars*. The distance covered at speeds >16 km h^{-1} is about 6 % of the total. *Lower* the time spent at the indicated metabolic power categories (W kg^{-1}) and the corresponding energy expenditure are shown by the *grey* and *black bars*. The energy spent at powers >20 W kg^{-1} (i.e. at power values greater than that observed when running at 16 km h^{-1} at constant speed on flat terrain) is about 40 % of the total. (Modified after Osgnach et al. 2010)
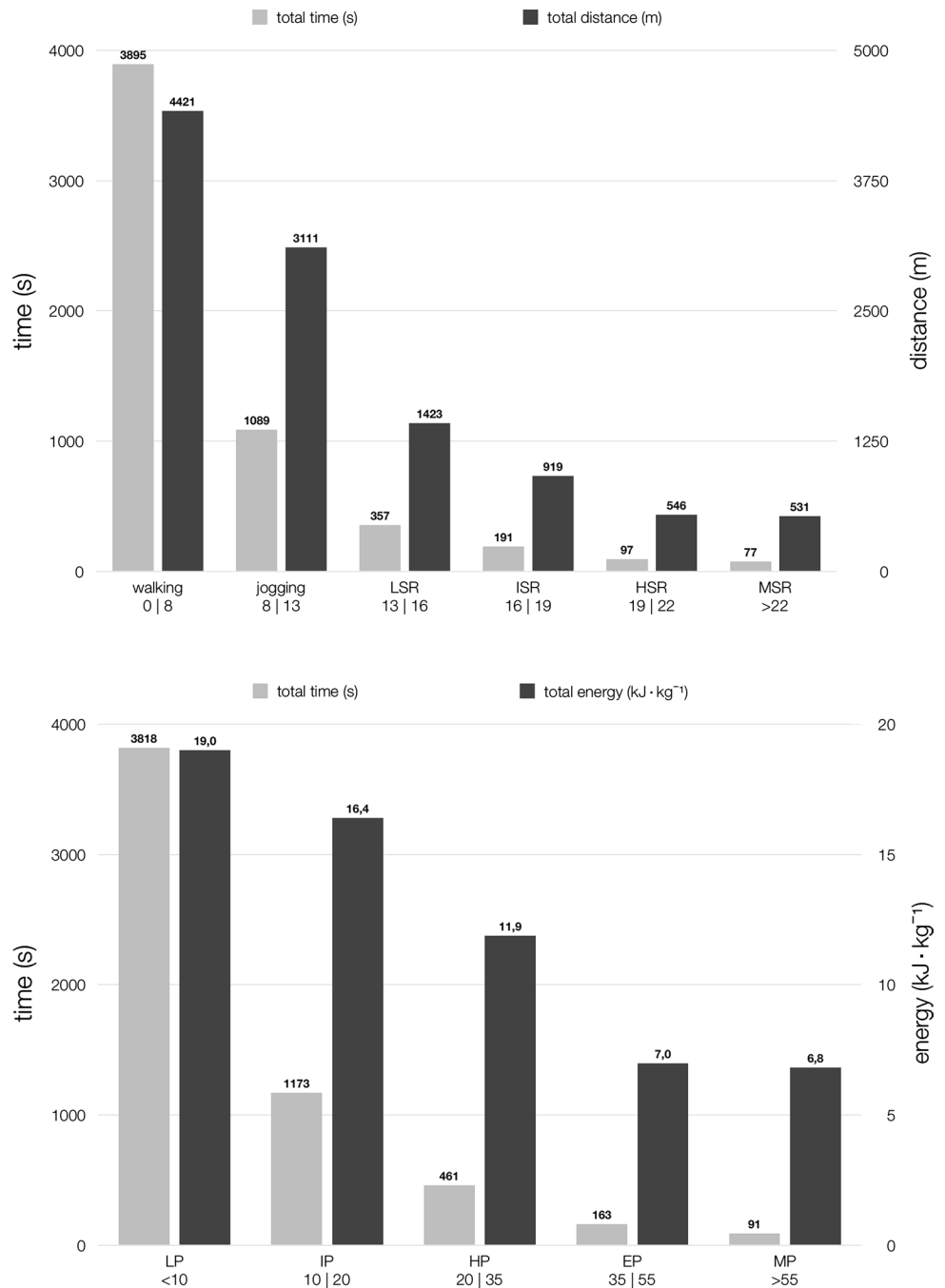
2005). This is probably due to the fact that, by its very character, soccer is a highly intermittent exercise; hence, even if a substantial amount of lactate is liberated from "hypo-aerobic" fibres during high-speed running a large fraction of it can be removed by "hyper-aerobic" fibres during the intervening low-intensity phases (for the definition of hypo- and hyper- aerobic fibres see Antonutto and di Prampero 1995). As a consequence, it can be predicted that the overall net energy utilisation is essentially aerobic with a regular alternating of anaerobic "alactic" stores depletion (essentially phosphocreatine breakdown), followed by

anaerobic "alactic" stores replenishment (essentially phosphocreatine resynthesis). An attempt to disentangle lactic and alactic anaerobic energy sources from one another will be discussed below in some detail (see Fig. 9).

It should be pointed out that the approach proposed by Osgnach et al. (2010), and briefly summarised above, does not take into considerations several specific characteristics of soccer, such as jumps, backwards running, running with the ball, kicking the ball or contrasting an opponent. Nevertheless we think that, in terms of the energetics of a match, it yields a picture closer to the "truth" than that emerging

Table 3 Time (t) and distance (d) during the entire match in each acceleration category; the corresponding energy cost (C_{sr}) is also reported

Acceleration* (W kg^{-1})	t (s)	d (m)	C_{sr} (J kg^{-1} m^{-1})
MD (<-3)	50 (16)	188 (65)	>3.40
HD (-3 to -2)	128 (29)	411 (98)	2.4–3.4
ID (-2 to -1)	448 (68)	1176 (206)	2.4–2.8
LD (-1 to 0)	2282 (120)	3821 (335)	2.8–4.6
LA (0 to 1)	2152 (102)	3587 (328)	4.6–7.8
IA (1 to 2)	461 (59)	1176 (184)	7.8–12.0
HA (2 to 3)	133 (29)	411 (95)	12.0–17.3
MA (>3)	51 (18)	180 (67)	>17.3

Mean and SD (in brackets). (From Osgnach et al. 2010)

* Maximal (M), High (H), Intermediate (I), Low (L), deceleration (D) or acceleration (A)

from more conventional approaches. Finally, we would like to point out that also other team sports, such as basketball, American or Australian football, or rugby could be investigated in a similar manner.

The technical procedures on which video-match analysis is based are expensive and available only to few clubs. However, we have now succeeded in implementing a similar approach onto a GPS system, positioned on the player's back, monitoring his/her speed, via the Doppler effect, based on a 20-Hz sampling frequency (GPEXE©). The final output of this system, in terms of distance, speed and acceleration, has been compared with data simultaneously obtained by video-analysis during unofficial matches and by radar tracking during training, the results being rather satisfactory (manuscript in preparation).

This system, as well as any other based on the GPS technology, can not by used during official matches, in which case wearing these devices is not allowed; however, it can be extremely useful for monitoring unofficial matches as well as the players' training. In additional, the algorithms implemented into the GPEXE© can be utilised to analyse off-line the data collected by video-analysis.

Metabolic power and oxygen consumption

As mentioned above, the product of the energy cost per kg body mass and unit distance (J kg^{-1} m^{-1}) and the speed (m s^{-1}) yields the metabolic power (W kg^{-1}) necessary to move at the speed in question, given the corresponding energy cost. As such, the instantaneous metabolic power is a measure of the amount of energy required per unit of time to reconstitute the ATP utilised for the work performance on the bases of oxidative processes only; hence, it

Fig. 7 Iso-metabolic power curves (W kg^{-1}) calculated from speed (km h^{-1}, y axis) and acceleration (m s^{-2}, x axis). A given metabolic power, e.g. 18 W kg^{-1} (corresponding to about 52 ml O$_2$ kg^{-1} min^{-1}) can be obtained running at a constant speed of about 14.4 km h^{-1} or at 7.2 km h^{-1} if the acceleration is 1.25 m s^{-2} or at 27.0 km h^{-1}, if the acceleration is -1.5 m s^{-2} or at any combination of speed and acceleration lying on the corresponding iso-power curve. (Modified after Osgnach et al. 2010)
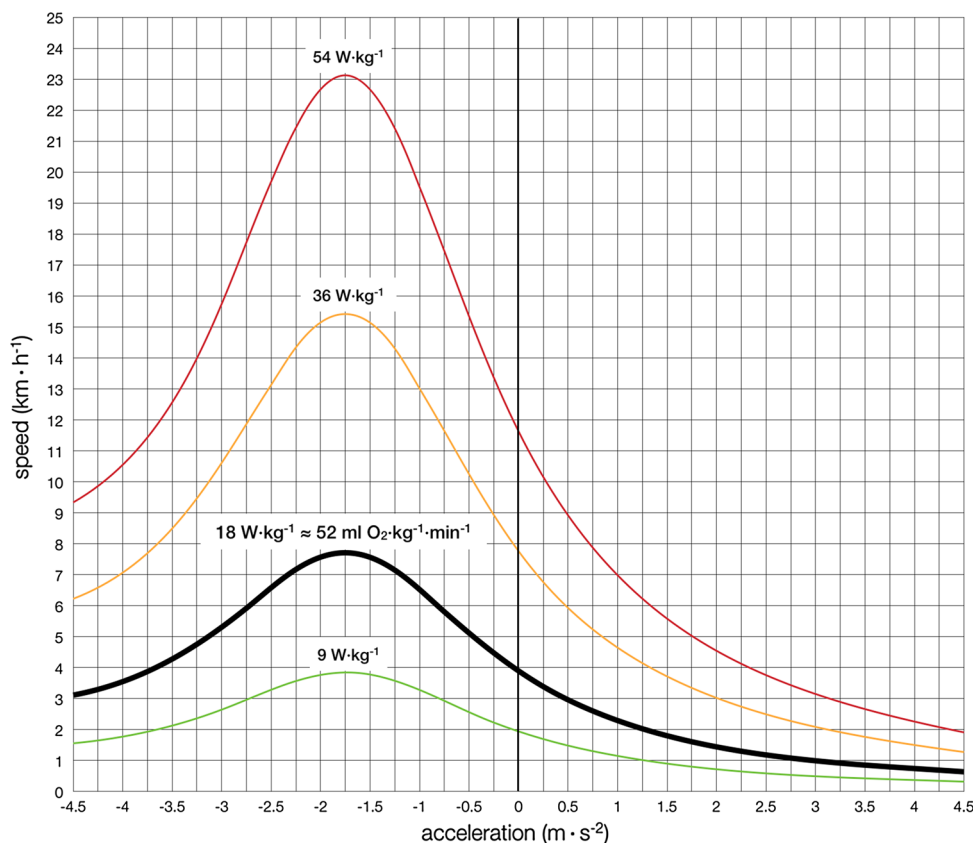
is a measure of the instantaneous rate of ATP utilisation expressed in equivalent O_2 units, regardless of the actual oxygen consumption (VO_2) which may be equal, greater or smaller than the metabolic power itself. (For simplicity, the dot above the symbol for the rate of oxygen consumption (VO_2) has been omitted.)

Indeed, at any given time, the actual rate of O_2 consumption may be different than the corresponding metabolic power requirement for two reasons. On the one side (i) upon metabolic transients, the kinetics of the oxidative processes is rather sluggish in so far as they adapt to the required metabolic power following an exponential process, with a time constant that at the muscle level is on the order of 20 s; in addition, (ii) during very strenuous exercise of short duration, a common feature during soccer, the metabolic power requirement can attain values greatly surpassing the subject's maximal O_2 consumption (VO_2max). These considerations show that, at variance with typical "square wave" aerobic exercises, in which after about 3 min actual VO_2 and metabolic power requirement coincide, the characteristics of soccer as well as of many other team sports are such that in the great majority of instances; the time course of actual VO_2 is markedly different than that of metabolic power requirement.

However, knowledge of the time course of the metabolic power requirement allows one to estimate the corresponding actual VO_2 as follows.

Let us first consider a square-wave aerobic exercise, in which case the actual VO_2 follows the metabolic power requirement according to a monoexponential function described by (Fig. 8a)

$$VO_2(t) = VO_2(s) \times \left(1 - e^{-\frac{t}{\tau}}\right), \tag{9}$$

where $VO_2(t)$ and $VO_2(s)$ represent the net VO_2 at time t and at steady state, respectively, and τ is the time constant of the process. Equation (9) shows also that after a time $t = 4\,\tau$, $VO_2(t)$ attains the asymptotic value, thus becoming equal to $VO_2(s)$. It should also be noted that, in these conditions, $VO_2(s)$ and metabolic power requirement coincide. In recovery, the process is mirror-like:

$$VO_2(t) = VO_2(s) \times e^{-\frac{t}{\tau}}. \tag{10}$$

As a consequence, as was the case above, after a time $t \approx 4\,\tau$, $VO_2(t)$ attains the asymptotic value, which in this case is equal to zero, since both $VO_2(t)$ and $VO_2(s)$ are net values, above resting.

Equations (9) and (10) describe the VO_2 kinetics at the muscle level as well as at the upper airways. However, the process is faster ($\tau \approx 20$ s) at the muscle that at the upper airways level ($\tau \approx 35$ s). Indeed, the O_2 stores of the body (mainly O_2 bound to haemoglobin in the venous compartment of the circulation) act as a capacitance in series, thus slowing down the VO_2 kinetics at the lung as compared to the muscle level.

It should be pointed out here that, even if the VO_2 kinetics during metabolic transients can be appropriately described by means of more refined algorithms including "cardiodynamic phases" and/or "slow components" (e.g. see Capelli et al. 2011), we think that the assumption of a monoexponential function, which corresponds to the primary component (phase II) in a bi-exponential model is justified here. Indeed, on the one side the cardiodynamic phases contribute minimally to the energy balance, on the other, the slow components do not play any significant role in these conditions, essentially because of the short duration of any high-intensity exercise bout (see below and Fig. 9).

When the exercise intensity exceeds the subject's maximal oxygen consumption (VO_2max), the VO_2 kinetics at work onset and offset are formally identical (and with identical time constants) to those reported above, with the following caveats. (i) $VO_2(s)$ must be replaced with the VO_2 that would be necessary to carry it out the on the basis of oxidative processes only, i.e. with the corresponding metabolic power, expressed in equivalent O_2 units (P_{req}), see above. In addition (ii) once VO_2max is attained, the actual VO_2 cannot increase any further. It follows that, whereas the theoretical O_2 consumption (VO_2T) keeps increasing towards P_{req}, the actual O_2 consumption (VO_2eff) cannot exceed VO_2max. Similarly, in the recovery, as long as, VO_2T is greater than VO_2max, VO_2eff cannot decrease below VO_2max. Therefore, whereas the time course of VO_2T is completely described by Eqs. (9) and (10), VO_2eff coincides with VO_2T only if VO_2T $<$ VO_2max; on the contrary, if VO_2T $>$ VO_2max, VO_2eff coincides with VO_2max (Fig. 8b).

So far, we have considered square wave exercises the duration of which permits the attainment of the steady state, or, for supramaximal exercise, VO_2max. It is now necessary to address the more realistic situations in which metabolic power requirement varies rapidly as a function of time, as is always the case in team sports such as soccer. To this aim we will first consider the example represented in Fig. 9a in which metabolic power requirement (P_{req}) varies following "square waves" of the indicated intensity, the duration of which is 10 s (or multiples thereof). In this case, the kinetics of the theoretical O_2 consumption (VO_2T) becomes

$$VO_2T(t) = (P_{req} - VO_2T(t-1)) \times \left(1 - e^{-\frac{t}{\tau}}\right) + VO_2T(t-1), \tag{11}$$

where $VO_2T(t)$ and $VO_2T(t-1)$ are the theoretical VO_2 values at time t of each metabolic power interval and at the end of the preceding one, respectively.

Equation (11) allows one to describe the VO_2 kinetics provided that the time course of the metabolic power requirement is known (see Fig. 9a).
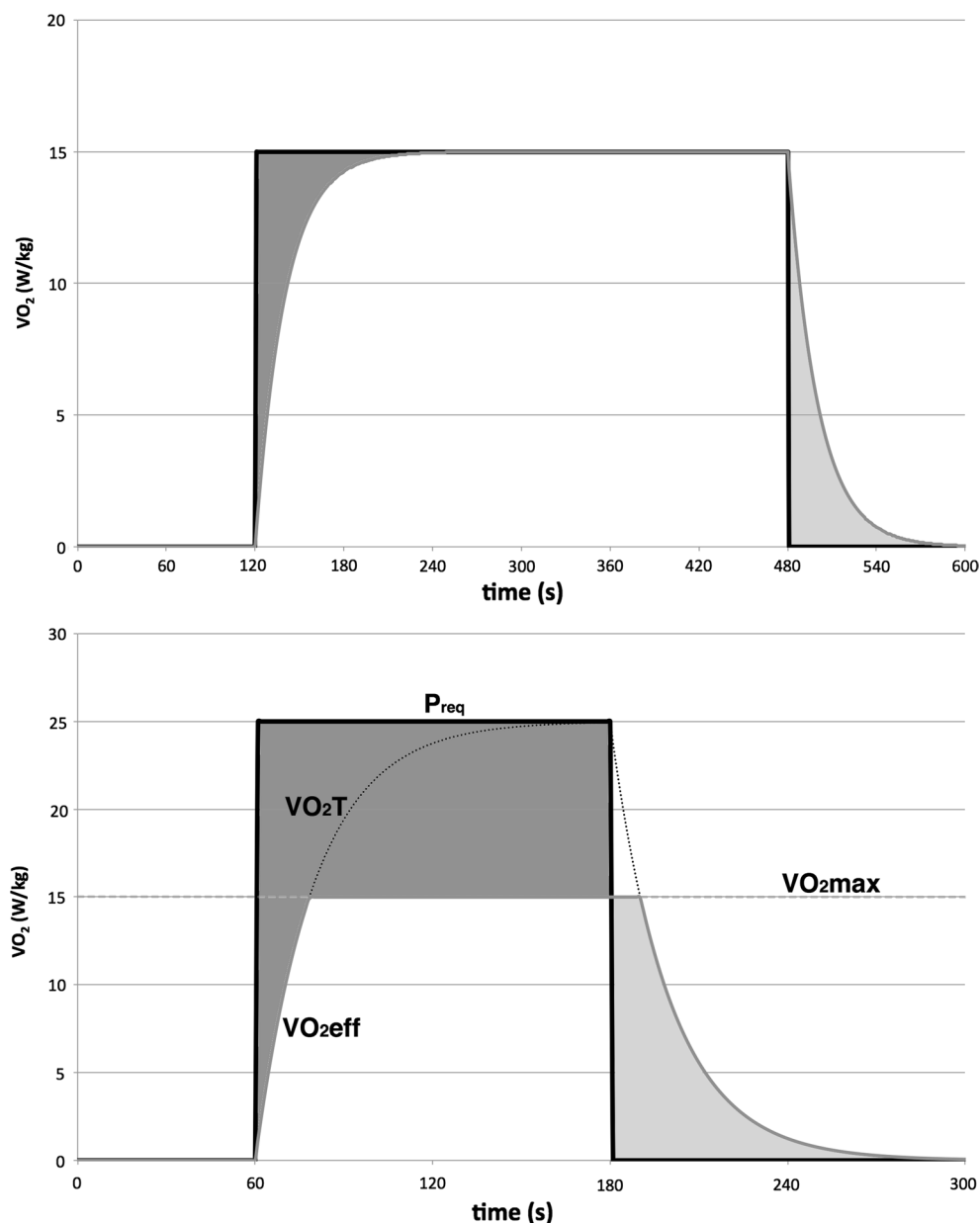
Fig. 8 O_2 consumption (W kg^{-1}) at the onset of square wave exercise. *Upper panel* aerobic exercise of moderate intensity. VO_2 attains the steady state in about 3 min (see text and Eq. 9). *Lower panel* "supramaximal exercise". The metabolic power requirement (P_{req}, *thick black continuous line*) is greater than the subject's VO_2max (*thin grey broken line*). VO_2 increases exponentially towards P_{req}, as described by Eq. 9, until VO_2max is reached (VO_2T). Below VO_2max the actual O_2 consumption (VO_2eff) coincides with VO_2T. (Values are net, above resting). See text for details

Figure 9b illustrates a similar situation in which the metabolic power intervals, while having the same duration as indicated in Fig. 9a, are characterised by a double intensity. In this case, as indicated above, once VO_2max is attained, the actual O_2 consumption (VO_2eff) cannot increase further (if VO_2T > VO_2max) nor can it decrease below VO_2max (as long as VO_2T > VO_2max).

This state of affairs is well illustrated in Fig. 9c, in which case the intensity of the metabolic power intervals

is the same as in Fig. 9b; the corresponding duration, however, is reduced by a factor of 10 (1 rather than 10 s). It follows that VO_2T (as obtained by the same Eq. (11)) stays always below VO_2max and as a consequence coincides with VO_2eff.

The theoretical considerations reported above and in Fig. 9 have been verified by a preliminary series of experiments briefly reported below. VO_2eff estimated on the basis of Eq. (11) was compared to the actually measured

Fig. 9 The metabolic power requirement (P_{req}) follows a step-wise profile: steps intensity and duration are indicated by the *black continuous line*. Three examples are shown in **a**, **b** the step duration is equal (10 s), but the intensity in **b** is twice than that in **a**; in **c** the intensity is the same as in **b**, but the step duration is reduced to 1/10 than that in **a**, **b** (1 s). The O_2 consumption (*grey continuous line*) follows P_{req}, as described by Eq. 11; whether, or not, it attains VO₂max (*grey broken line*) depends on both intensity and duration of the steps. The *dark grey areas* (Ean) indicate the amount of energy (in equivalent O_2 units) derived from anaerobic sources; the *light grey areas* (-aLa) denote the amount of energy utilised during, or after, the exercise for phosphocreatine resynthesis (alactic O_2 debt payment). See text for details
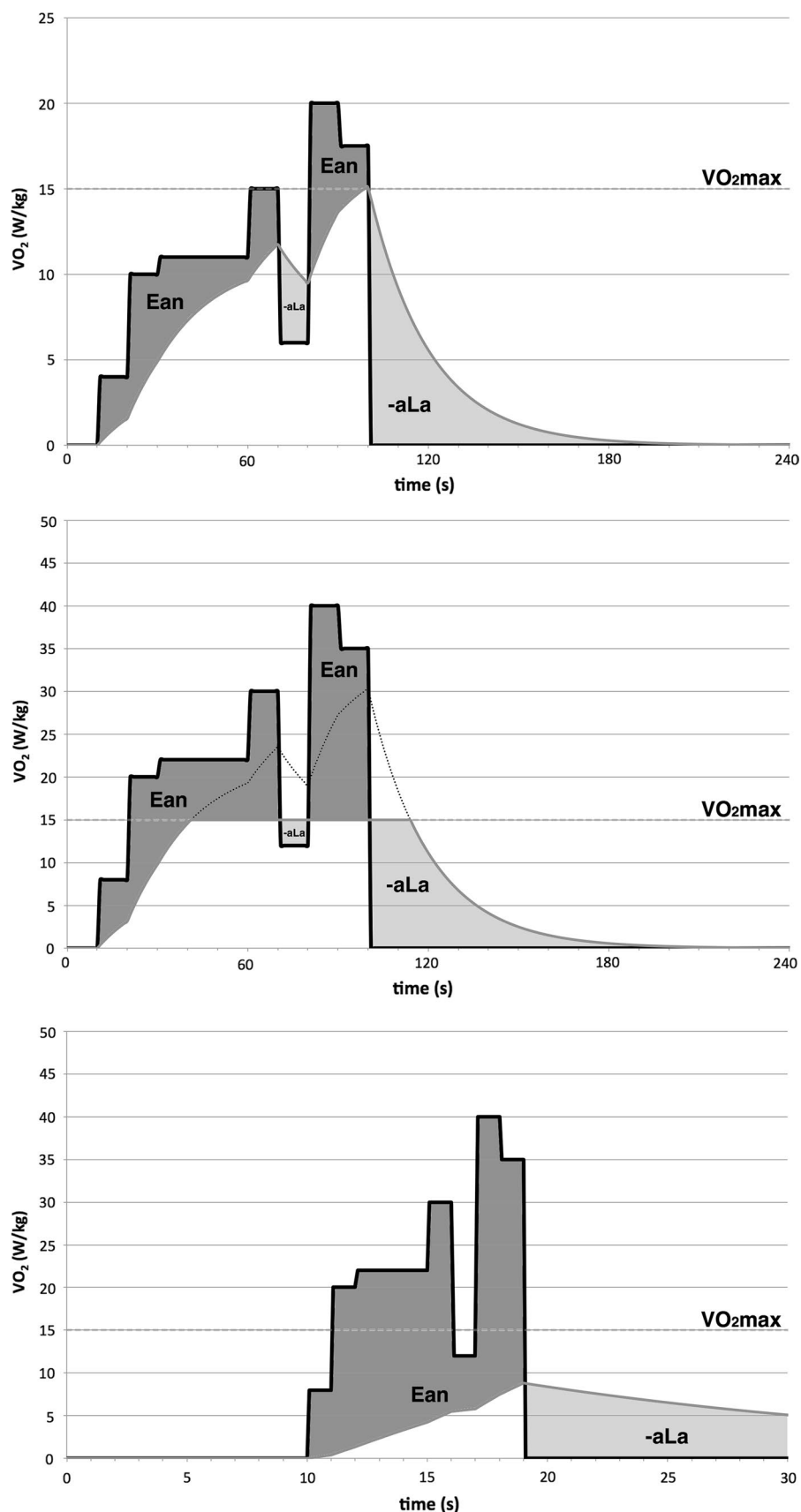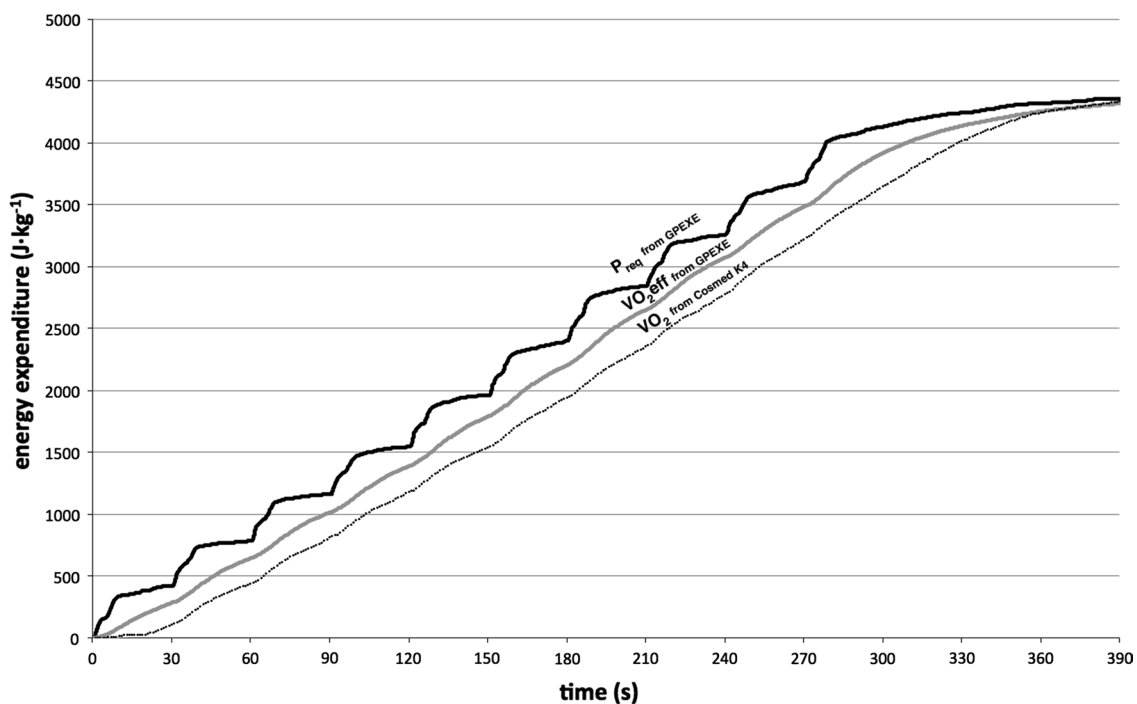
Fig. 10 Time integral (J kg^{-1}) as a function of time (s) of (i) metabolic power requirement (P_{req}, *black continuous line*) as determined by GPEXE ©; (ii) VO$_2$ estimated from Eq. 11 on the basis of a time constant of 20 s (VO$_2$eff, *light grey line*) and (iii) VO$_2$ actually measured by means of a portable metabolic cart (VO$_2$, *black dotted line*) (K4, Cosmed, Rome). See text for details

O$_2$ consumption values as follows. A group of 13 subjects performed a series of shuttle runs over 25-m distance in 5 s. Each bout was immediately followed by an equal run in the opposite direction (again 25 m in 5 s). A 20-s interval was interposed between any two bouts, and the whole cycle was repeated 10 times (for a total running distance of 500 m). The running speed was continuously monitored by a radar system (Stalker ATS II, TX, USA); the corresponding instantaneous acceleration, energy cost and metabolic power were then calculated by means of the same set of equation as implemented in the GPEXE© (see above). Finally, the time course of the actual VO$_2$ was estimated according to Eq. (11). In addition, the subjects wore a portable metabolic card (K4, Cosmed, Rome, Italy) allowing us to assess the actual O$_2$ consumption on a single breath basis.

The so-obtained data are represented for a typical subject in Fig. 10 which reports the time integral of (i) metabolic power requirement; (ii) VO$_2$ estimated from Eq. (11) on the basis of a time constant of 20 s and (iii) VO$_2$ actually measured. Inspection of this figure shows that (1) estimated and measured VO$_2$ are very close, and (2) they follow fairly well the time course of the total energy expenditure (i.e. of the time integral of the metabolic power requirement). It should also be noted that (3) the horizontal time difference between the two functions (VO$_2$ measured or estimated, and metabolic power) is the time constant of the

VO$_2$ kinetics and (4) the ratio between the overall amount of O$_2$ consumed above resting and the total distance covered (500 m) is the average energy cost of this type of intermittent exercise which turns out to be essentially equal to the value estimated from the equations reported above (see section on energy cost).

This brief excursus lends experimental support to the theoretical approach described above.

Analysis of Fig. 9 allows one to estimate the energy yield from anaerobic sources over any given time interval. Indeed, this is proportional to the net area included between the curves describing the time course of the metabolic power requirement (P_{req}, thick black line) and the actual VO$_2$ (VO$_2$eff, grey continuous line). It should be pointed out here that the term "net" denoted the difference between the area above the curve VO$_2$eff, but below the curve P_{req} (areas Ean, dark grey in Fig. 9) and that below VO$_2$eff, but above P_{req} (areas -aLa, light grey in Fig. 9). Indeed, the light grey areas indicate time intervals in which a fraction of the alactic O$_2$ debt is paid at the expense of the oxidative processes which, in these phases are greater than the metabolic power requirement, either during exercise (areas -aLa) or in the following recovery periods.

While the estimate of the overall anaerobic energy yield seems rather straightforward, its partition into the lactic and alactic fractions appears more intricate. Even so, it seems reasonable to suggest that the difference between the sum of

all "dark gray" and the sum of all "light gray" areas (during exercise and in the following recovery) is proportional to the net amount of lactate produced. In addition, it seems also reasonable to suppose that, if VO$_2$eff does not reach VO$_2$max (e.g. during very high intensity bouts of very short duration, such as those represented in Fig. 9c) net lactate production is very small, albeit not necessarily nil. Be this as it may, it does not seem possible here to go into further details, also in view of the paucity of data concerning the kinetics of lactate production at the onset of very strenuous exercise in humans.

The acceleration power

In the preceding sections, we dealt with the metabolic power of accelerated/decelerated running; this section is devoted to the other "half of the sky", the corresponding mechanical power. To this aim, after a brief analysis of the concepts at stake, we will describe the time course of the acceleration power in the 12 medium-level sprinters (di Prampero et al. 2005); we will then compare the peak value obtained in these subjects to more recent data on 13 professional soccer players (unpublished observations), as well as on the present holder of the 100-m world record, Usain Bolt, as calculated from the data reported by Hernandez Gomez et al. (2013) and on top athletic animals (polo horses, racing greyhounds and cheetahs, Williams et al. 2009; Wison et al. 2013).

The (total) mechanical power at time t is the product of force (F) and velocity (v):

$$P_{tot}(t) = F(t) \times v(t) = M \times a_f(t) \times v(t), \tag{12}$$

where M is the subject's body mass. Hence, the instantaneous (specific) acceleration power, per unit body mass, is given by

$$P_{sp}(t) = \frac{P_{tot}(t)}{M} = a_f(t) \times v(t). \tag{13}$$

As mentioned above (see Eqs. 7 and 8), the time course of the velocity at the onset of the 100-m run in the 12 sprinters of our 2005 study could be described by

$$v(t) = v(f) \times \left(1 - e^{-\frac{t}{\tau}}\right), \tag{7}$$

where $v(t)$ is the velocity at time t, $v(f)$ the asymptotic (final) velocity, and τ is the time constant of the process. Hence, the instantaneous acceleration ($a_f(t)$) could be easily obtained:

$$a_f(t) = \frac{v(f) - v(f) \times (1 - e^{-\frac{t}{\tau}})}{\tau}. \tag{8}$$

Since in our subjects the mean values of $v(f)$ and τ were 9.5 m s^{-1} and 1.42 s, respectively, these equations allowed

us to calculate the time course of the acceleration power; its mean value over all sprinters is reported in Fig. 3, together with the corresponding time courses of mean velocity and acceleration.

In the case of the world record performance of Usain Bolt, the velocity data, as reported by Hernandez Gomez et al. (2013) could also be well described by an exponential function of the from of Eq. (7) where, however, $v(f) = 12.2$ m s^{-1} and $\tau = 1.25$ s, thus allowing us to obtain the time course of the corresponding acceleration, as from Eq. (8).

Figure 3 shows that, in the average medium level sprinter, the peak acceleration power was attained after about 1 s and amounted to 17.6 W kg^{-1}, to be compared with a value of 19.2 (1.9, S.D) W kg^{-1} [range 15.5–23.2; $n = 51$)] which we recently obtained by an approach identical to that described above on 13 professional soccer players. It is of interest to point out that, in these subjects, the individual peak acceleration power was obtained from the product of acceleration and velocity over all-out runs of 10 or 15 metres. In all subjects, the peak power was reached after about 1 s from the onset of the all-out runs, no differences in peak values being observed between the two distances. These values on human athletes are on the order of 60 % of that obtained on the holder of the current 100-m world record (9.58 s, Usain Bolt, Berlin, 2009) which amounts to 29.7 W kg^{-1} (Fig. 3).

The results reported above in humans, can be compared to the values obtained by Wilson et al. (2013) in animal athletes. Indeed, these authors determined the peak acceleration power during 367 hunting runs in wild cheetahs. The largest values observed amounted to 100–120 W kg^{-1}, in a few cases being even higher. This is to be compared with 30 and 60 W kg^{-1} in polo horses and racing greyhounds, previously determined by the same group (Williams et al. 2009) (Table 4).

The data reported in Table 4 reveal a fascinating continuum in term of maximal mechanical power in the animal kingdom and, even if it would be highly desirable to have a wider range of data on a greater number of species, they immediately bring to one's mind two main physiological questions dealing with (i) the energetic and (ii) the biomechanical characteristics underlying these extraordinary performances. These two points are briefly sketched below.

The mechanical work performed per mole of ATP split, as determined (or estimated) in the dog gastrocnemius or in exercising humans is on the order of 16–22 kJ mol^{-1} (di Prampero 1981; di Prampero and Piiper 2003). Hence, the mechanical values reported in Table 4 correspond to a rate of ATP splitting from about 1.0–1.6 mmol per kg body weigh per second in humans to about 6.3 mmol per kg body weigh per second in wild cheetahs. When expressing these values per kg of active muscle, they become substantially larger, in a manner that is difficult to assess with reasonable

Table 4 Maximal acceleration power (W kg^{-1}) and maximal vertical velocity (v_v, m s^{-1}) in human and animal athletes

Humans	Male sprinters		Soccer players
	Medium level	Usain Bolt	Elite
Max power (W kg^{-1})	17.6	29.7	19.2 (1.9)
Max v_v (m s^{-1})	1.80	3.11	1.96
Animals	Polo horses	Racing greyhounds	Wild cheetahs
Max power (W kg^{-1})	30	60	100–120
Max v_v (m s^{-1})	3.1	8.6	10.2–12.2

See text for details and references

accuracy, but that can be estimated on the order of 3.3–5.3 mmol kg$_{muscle}^{-1}$ s^{-1} in humans (assuming an active muscle mass of 30 % of total body mass) to $\approx$14 mmol kg$_{muscle}^{-1}$ s^{-1} in wild cheetahs (assuming an active muscle mass of 45 % of total body mass, as reported by Wilson et al. 2013). These values can be expressed in terms of O_2 requirement, assuming that the energy yield from the consumption of 1 mol of O_2 brings about the resynthesis of 6 mol of ATP, i.e. a "textbook" P/O_2 ratio of 6.0. If this is so, the above values correspond to O_2 requirements of 215–350 to 1400 ml O_2 kg$_{body\ mass}^{-1}$ min^{-1} from humans to wild cheetahs, respectively. It goes without saying that these enormous O_2 requirements, because of the intrinsic limits of the aerobic metabolism and of the O_2 transport system, as compared to the essentially instantaneous rate of ATP slitting, will necessarily be delayed after the effort is over.

The mechanical power values reported in Table 4 represent presumably the maximal absolute peak values (averaged over one stride) in the human or animal athletes considered, as applied to the centre of mass and neglecting the "internal" power due to the limbs movements. As such they allow us to estimate the corresponding theoretical maximal vertical velocity, assuming that the overall mechanical power is utilised against gravity. Indeed, this last (P_g) is given by

$$P_g = M \times g \times v_v, \tag{14}$$

where M is the mass of the body (kg), g the acceleration of gravity (9.81 m s^{-2}) and v_v is the vertical velocity (m s^{-1}). Hence, the vertical velocity can be expressed as

$$v_v = \frac{P_g}{M \times g}, \tag{15}$$

where P_g/M is the specific power (W kg^{-1}). Hence, the maximal vertical velocities can be obtained from the corresponding maximal power values; they are also reported in Table 4. For human athletes, these values are close to those obtained during maximal all-out runs up a flight of stairs on 20–30 year-old males, which range from 1.5 to 2.0 m s^{-1} depending on the athletic characteristics of the subjects (e.g. see, Margaria et al. 1965; di Prampero et al. 1970; Margaria et al. 1971).

The actual speed along the runner's path depends on the incline of the terrain. If this is assumed to be equal to that of a normal flight of stairs ($\approx$50 %), the maximal speed turns out to be about 6.8 m s^{-1} (24.4 km h^{-1}) for top human athletes, and to about 6.8, 19.3 and 25.0 m s^{-1} (24.5, 69.5 and 90.0 km h^{-1}) for polo horses, running greyhounds and cheetahs, respectively. This shows that, even at the top of his youth and physical splendour, Usain Bolt would have had a hard time saving his life from a hunting cheetah affected by old-age decrepitude!

The values of forward acceleration reported in Fig. 3 allow us to compare the biomechanical characteristics (as calculated over the entire stride cycle) of the average medium-level sprinter, to those of the holder of the present 100-m world record (Usain Bolt). Indeed these data show that the ratio of the horizontal force to the resultant ground reaction force, both expressed per kg body mass ($\frac{a_f}{\sqrt{a_f^2+g^2}}$) decreases with the forward velocity, as previously shown by Morin et al. (2012), at any given velocity being substantially larger in Usain Bolt (Fig. 11a). In addition, the angle α between the resultant ground reaction force and the body axis (α = 90 − arctan ES, see Eq. (1) and Fig. 1) at any given velocity is about 10° smaller in Usain Bolt than in the average medium-level sprinter (Fig. 11b). These data confirm and extend the observations by Morin et al. (2012) on 13 subjects, including a world-class sprinter, running on an instrumented treadmill and support their conclusion that the ability of applying a greater ground reaction force with a greater forward inclination is the main signature of a top-class sprinter.

On top performances: the role of metabolic power

The final paragraphs of the preceding section were devoted to a brief discussion of some crucial biomechanical differences between a world-class sprint runner (Usain Bolt) and
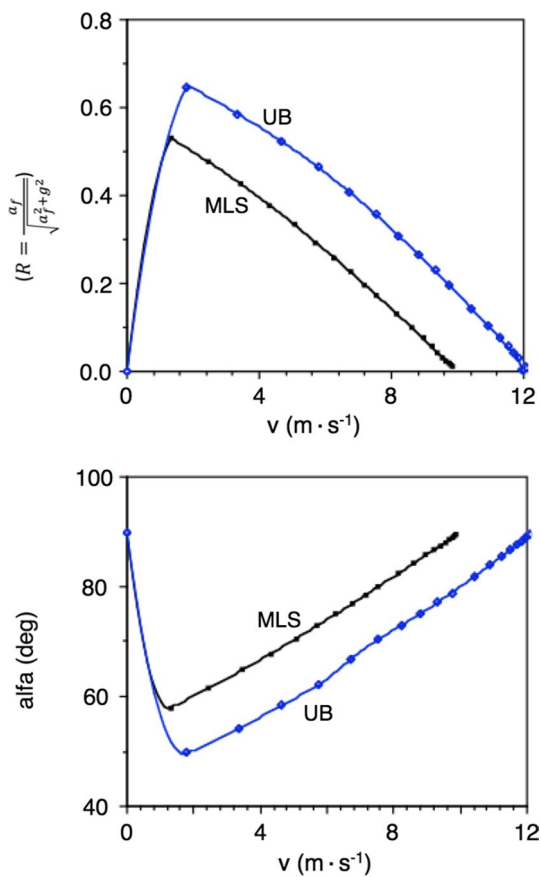
Fig. 11 Ratio of horizontal to overall ground reaction force, both expressed per unit body mass ($R = \frac{a_f}{\sqrt{a_f^2 + g^2}}$) (*upper*) and angle α (deg, see Fig. [1]) (*lower*) as a function of the speed during a 100-m *dash*. Average medium-level sprinter (MLS); Usain Bolt (UB). See text for details

a group of medium-level sprinters. We will now address the role of the maximal metabolic power in setting maximal performances. We will adopt a kind of science fiction approach, the aim of which will be to identify a strategy to allow our "average medium level sprinter" to equalise the current 100-m world record (9.58 s) obtained by Usain Bolt in 2009.

Specifically, we will assume that the maximal metabolic power available to our average medium-level athlete is as reported in Fig. [5]. Hence, since the running speed is set by the ratio metabolic power to the energy cost, the only way to improve the performance of our medium-level sprinter will be to reduce his energy cost. We will therefore ask our hypothetical engineers to construct a track with a constant −10 % incline. So the C_0 value to be inserted into Eq. ([6a]) for estimating the overall energy cost of sprint running will be that applying for $i = -0.10$, i.e. 2.55 J kg^{-1} m^{-1}. The choice of this specific down-slope has been dictated by the desire to be as close as possible to the incline of the terrain yielding the minimum energy cost of constant speed running, but still in a range permitting a safe running technique.
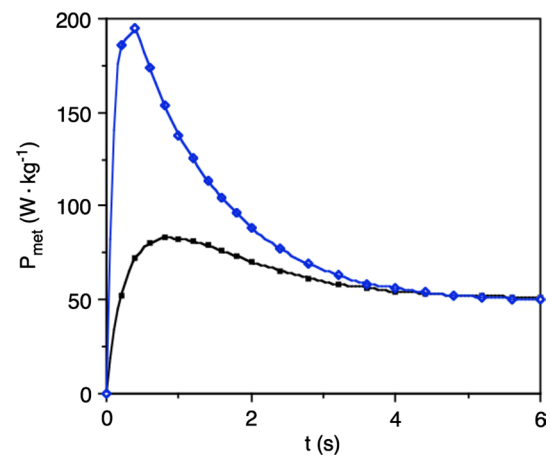

Fig. 12 Total metabolic power (W kg^{-1}), including that against the wind resistance, to cover 100 m in a time equal to Usain Bolt current world record (9.58 s), but on a track with a 10 % down-slope (*upper curve*). *Lower curve* is the actual metabolic power developed by a MLS over the first 6 s of a 100-m *dash*. See text for details

This allowed us to estimate ES and EM (Eqs. ([3]) and ([4])) from the acceleration profile of Usain Bolt during his top performance and hence to estimate the corresponding energy cost as described by Eq. ([6a]), assuming $C_0 = 2.55$ J kg^{-1} m^{-1}, see above) and adding the energy expenditure against the wind, per unit body mass and distance:

$$C_r = \left(155.4 \times ES^5 - 30.4 \times ES^4 - 43.3 \times ES^3 \right.$$
$$\left. + 46.3 \times ES^2 + 19.5 \times ES + 2.55 \right) \times EM + k \times v^2,$$

$$(6b)$$

where $k = 0.01$ J s^2 kg^{-1} m^{-3} (Pugh [1970]; di Prampero [1986]). This allowed us to calculate the time course of the metabolic power required by a hypothetical sprinter to equalise Bolt's performance on a track with a 10 % down-slope. It is reported in Fig. [12] for the first 6 s of the run, together with the actual time course of the metabolic power of our medium-level athlete. This figure shows that whereas after about 3 s metabolic power requirement and actual metabolic power coincide, in the initial phase of the run the power requirement to equalise Bolt record is by far larger that the actual power of a medium-level sprinter.

Finally, these data allowed us to estimate by an iterative procedure the time course of the speed and hence of the acceleration yielding an energy cost value such that when multiplied by the speed yields the actual metabolic power of a medium level sprinter and of Bolt during a first 6 s of a 100-m dash down a −10 % slope. The corresponding distances are reported in Fig. [13], together with the actual evolution of the distance during Bolt world's
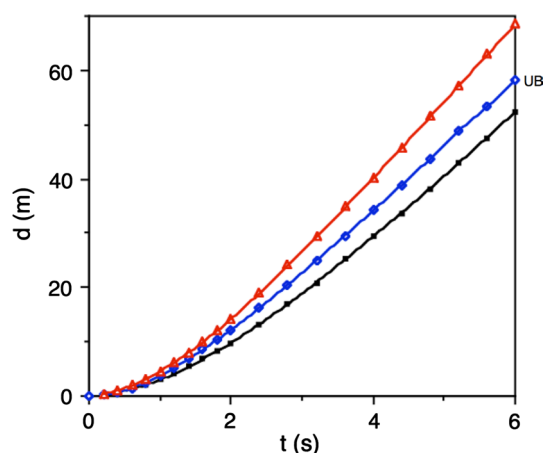
Fig. 13 Medium curve (UB) is the distance covered by Usain Bolt during the first 6 s of his current 100-m world record (from the data reported by Taylor and Beneke (2012) and Hernandez Gomez et al. (2013)). *Upper curve* and *lower curves* are the distances that Usain Bolt or an MLS could cover with the same metabolic power as in Fig. 12, on a track with a 10 % down-slope. See text for details

Concluding remarks

Accelerated/decelerated running by its very nature prevents the attainment of a steady state, thus making it rather difficult to estimate the corresponding biomechanics and energy expenditure. However, we show here that, monitoring the runner's speed it is possible to estimate energy cost, metabolic power requirement and actual O_2 consumption (VO_2), based on the biomechanical similarity between accelerated/decelerated running on flat terrain and uphill/downhill running at constant speed, the slope being dictated by the forward acceleration. In addition, knowledge of the runner's speed, and hence of his/her forward acceleration, yields the horizontal component of the overall ground reaction force, which can also be easily calculated from the vectorial sum of the forward acceleration itself and of the acceleration of gravity. Finally, the angle of application of the ground reaction force in respect with the terrain can also be obtained.

Hence this simple approach, in spite of its numerous and necessary simplifying assumptions, can yield useful information on the bioenergetics of accelerated/decelerated running, as well as on some of its biomechanical characteristics. As such, we think that it can be applied to estimate not only the main characteristics of typical "Track and Field" sprint running, but also to team sports such as soccer.

Conflict of interest The authors declare to be interested in the commercial development and utilisation of the system GPEXE© (Exelio srl, Udine, Italy).

record. This figure shows that even when running down a slope of −10 % a medium level sprinter would lose about 5.7 m over the first 6 s, as compared to Bolt running on a flat track. It seems interesting to note that this loss in terms of distance occurs in the first ≈3 s of the run, i.e. in the high acceleration phase, essentially because the maximal power of the medium-level sprinters in this phase is markedly lower than that necessary to accelerate at a pace comparable to that of Bolt. This is consistent with the biomechanical data reported by Morin et al. (2012) who showed that the mechanical power output was positively correlated to mean 100-m speed. Finally, the data reported in Fig. 14 allowed us to calculate that the mean finishing time in our medium-level sprinter on a −10 % track amounts to 10.0 s, to be compared with 11.3 s on flat terrain (average over the whole group), whereas the theoretical best time of Usain Bolt on a −10 % track amounts to 8.2 s, as compared to his current world record of 9.58 s.

It should also be pointed out that the above considerations are based on the implicit assumption that the biomechanics of running at this high speeds is not per se limiting the performance which is assumed to depend entirely on the bioenergetic factors describe above. To replace this implicit assumption with facts, it would be highly desirable to be on the position of condensing the biomechanics and bioenergetics of running into a comprehensive equation of motion applying over a wide range of speeds, accelerations and inclines. We only hope that the above "wild" speculations may stimulate the scientific community to address experimentally these questions.

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