Energy Cost and Metabolic Power in Elite Soccer: A New Match Analysis Approach

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ABSTRACT

OSGNACH, C., S. POSER, R. BERNARDINI, R. RINALDO, and P. E. DI PRAMPERO. Energy Cost and Metabolic Power in Elite Soccer: A New Match Analysis Approach. *Med. Sci. Sports Exerc.*, Vol. 42, No. 1, pp. 170–178, 2010. **Purpose**: Video match analysis is used for the assessment of physical performances of professional soccer players, particularly for the identification of "high intensities" considered as "high running speeds." However, accelerations are also essential elements setting metabolic loads, even when speed is low. We propose a more detailed assessment of soccer players' metabolic demands by video match analysis with the aim of also taking into account accelerations. **Methods**: A recent study showed that accelerated running on a flat terrain is equivalent to running uphill at constant speed, the incline being dictated by the acceleration. Because the energy cost of running uphill is known, this makes it possible to estimate the instantaneous energy cost of accelerated running, the corresponding instantaneous metabolic power, and the overall energy expenditure, provided that the speed (and acceleration) is known. Furthermore, the introduction of individual parameters makes it possible to customize performance profiles, especially as it concerns energy expenditure derived from anaerobic sources. Data from 399 "Serie-A" players (mean ± SD; age = 27 ± 4 yr, mass = 75.8 ± 5.0 kg, stature = 1.80 ± 0.06 m) were collected during the 2007–2008 season. **Results**: Mean match distance was 10,950 ± 1044 m, and average energy expenditure was 61.12 ± 6.57 $kJ \cdot kg^{-1}$. Total distance covered at high power (>20 $W \cdot kg^{-1}$) amounted to 26% and corresponding energy expenditure to approximately 42% of the total. "High intensities" expressed as high-power output are two to three times larger than those based only on running speed. **Conclusions**: The present approach for the assessment of top-level soccer players match performance through video analysis allowed us to assess instantaneous metabolic power, thus redefining the concept of "high intensity" on the basis of actual metabolic power rather than on speed alone. **Key Words:** ACCELERATION, DECELERATION, SOCCER ENERGY EXPENDITURE, ACTIVITY PROFILE, PERFORMANCE ANALYSIS

Soccer is an activity involving both aerobic and anaerobic exercises; as such, the physiological demand imposed on soccer players during official matches and training sessions has been the subject of research for many years. Early assessments of metabolic demand, which were conducted through measurements of body temperature (14,23,32), demonstrated that the average metabolic load of a soccer player is close to 70% of $\dot{V}O_{2max}$. These results are confirmed by current energy expenditure estimates; however, they did not lead to the development of techniques for continuous body temperature monitoring owing to practical reasons and to the latency in body temperature changes.

More recently, assessments of energy expenditure have been performed using continuous HR recording, allowing a detailed analysis of aerobic performance (1,8,16,17). However, this approach is not permitted during official matches. In addition, HR recordings do not yield information on high-intensity bouts. Likewise, direct measurement of oxygen uptake is not suitable to provide data on high-intensity exercise, and its use during training sessions or competitions is not feasible (18). Overall, all these methods show that the total estimated energy expenditure during a match ranges from 1200 to 1500 kcal (4,15,23,30,33,36).

The studies conducted so far on anaerobic energy expenditure are rather scant; furthermore, the current procedures are not applicable to official matches and are definitely not suitable for continuous recordings. An example of this approach is the study by Krustrup et al. (19), which measured creatine phosphate concentration on biopsies taken from muscular tissue of athletes immediately after high-intensity exercise bouts during a soccer match. Blood lactate concentration (LA) has also been considered as a marker of anaerobic energy expenditure by several researchers (19); the results of these studies show that its level during matches ranges from 2 to 10 $mmol \cdot L^{-1}$.

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All things considered, the methods described above are sufficiently reliable in estimating the total energy expenditure during a match. However, no method is currently available to either measure or estimate instantaneous metabolic load, and this is particularly true in relation to high-intensity bouts (including accelerations), which are actually the crucial moments in a match.

During the last few years, an increasing number of studies have been devoted to video analysis of soccer matches and to subsequent computer-assisted analysis of the imaging thus acquired. This method has lead to a significant progress in the physical assessments of individual players and is currently being used by many high-level professional soccer teams all over Europe (9). The most up-to-date techniques of video match analysis allow close observation of the movements of players, referees, and ball on the soccer pitch throughout the 90 min of the game. The so-obtained data yield distances covered and relative speeds, football control, and distance from fellow players and from the other pitch areas. The results of these studies (5,6,13,18,27,31,34) show that:

1. The total distance covered in a match (TD) ranges from 10 to 13 km, with differences related to rank and role.
2. The distance covered in the first half of the match is usually 5%–10% greater than that covered in the second half.
3. On average, players spend 70% of the total match duration performing low-intensity activities such as fast walking and jogging, whereas in the remaining 30%, they are engaged in approximately 150–250 actions of 15–20 m of high-intensity exercise.
4. "Sprinting," which, in the different studies, is defined as a running speed above a lower limit ranging from 19 to 25 km·h^{-1}, amounts to 5%–10% of the TD covered during a match, thus corresponding to 1%–3% of the match time; average sprint duration is 2–4 s, and average sprint occurrence is 1 in 90 s.

However detailed, such analyses do not take into account an essential element of soccer, e.g., accelerations and decelerations. As a matter of fact, a massive metabolic load is imposed on players not only during the maximally intensive phases of the match (intended as high running speed) but every time acceleration is elevated, even when speed is low.

The scientific literature provides a significant number of studies on the energetics and biomechanics of constant speed running, although the number of studies on accelerated (or decelerated) running are very scant because of the difficulty in using an energy approach in evaluating this kind of exercise. The few works available on the subject focus exclusively on specific mechanical features of sprinting (10,21,26) or consider indirect estimates of its energetics (2,3,11,37,38). However, a new interesting approach is provided by a recent study of di Prampero et al. (12), which shows elements that can be integrated in video match analysis system.

Theoretical Model

The purpose of this section is to describe briefly the approach proposed by di Prampero et al. (12) in estimating the energy cost (EC) of accelerated and decelerated running with the general aim of incorporating the resulting algorithms into video match analysis. Specifically, di Prampero et al. (12) have shown that, as a first approximation, accelerated running on a flat terrain is energetically equivalent to uphill running at constant speed, the upslope being dictated by the forward acceleration, as described below.

During sprinting, the runner's body leans forward forming an angle (α) with the terrain, which is smaller the greater the acceleration. If the terrain is tilted upward to bring the runner's body vertical (Fig. 1), accelerated running can be considered equivalent to running at a constant speed up an "equivalent slope" (ES) where:

$$\mathrm{ES} = \tan(90 - \alpha) \qquad [1]$$

In addition, the average force exerted by the active muscles during sprinting is greater than the subject's body weight by the ratio g'/g (Fig. 1A). This ratio is called "equivalent mass" (EM) and represents an overload imposed on the athlete by the acceleration itself.

$$\mathrm{EM} = \frac{g'}{g} \qquad [2]$$

Therefore, if the forward acceleration is known, ES and EM can be readily determined. According to Minetti et al. (22), the energy cost (EC, J·kg^{-1}·m^{-1}) of running uphill at constant speed is described by:

$$\mathrm{EC} = 155.4i^5 - 30.4i^4 - 43.3i^3 + 46.3i^2 + 19.5i + 3.6 \qquad [3]$$

where i is the incline of the terrain, and 3.6 (J·kg^{-1}·m^{-1}) is the EC of running at constant speed on flat compact terrain;

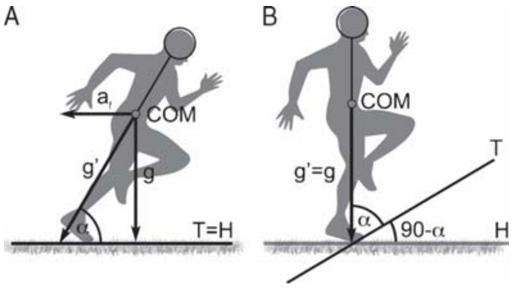

FIGURE 1—Simplified view of the forces acting on a subject during accelerated running (modified from di Prampero et al. (12), with permission). The runner's body is represented by a segment of straight line. COM, center of mass; T, terrain; H, horizontal; *g*, acceleration of gravity; a_f, forward acceleration; g', vectorial sum of a_f and *g*. Accelerated running on flat terrain *(A)* is equivalent to constant speed uphill running *(B)* wherein the angle of the terrain *T* with the horizontal *H* (90 − α) is such that the angle of the subject's body with the terrain (α) is unchanged (see text for further details).

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therefore, the EC of accelerated running can be easily obtained as:

$$\mathrm{EC} = (155.4\mathrm{ES}^5 - 30.4\mathrm{ES}^4 - 43.3\mathrm{ES}^3 + 46.3\mathrm{ES}^2 + 19.5\mathrm{ES} + 3.6)\mathrm{EM} \quad [4]$$

where i has been replaced by ES, and the overall cost is multiplied by EM.

Metabolic power (P) can be then calculated multiplying EC by running speed (v):

$$P = \mathrm{EC}v \quad [5]$$

Therefore, once speed and acceleration are known, the metabolic power output of each athlete in any given moment can be easily obtained.

The aim of this study was to propose a new approach for the assessment of metabolic demands of soccer player by the algorithms described above and to compare the results thus obtained with those of traditional video match analysis.

MATERIALS AND METHODS

Subjects

Data were gathered from 56 matches of the Italian "Serie A" (first division) in the 2007–2008 season, using a multiple camera match analysis system in Meazza Stadium (Milan) and Franchi Stadium (Florence). Altogether, 399 players from 20 teams were evaluated (age = 27 ± 4 yr, mass = 75.8 ± 5.0 kg, and stature = 1.80 ± 0.06 m), all "guest" playing against the three "host" teams in the home stadium of which the video match analysis devices were installed. Consequently, each player can appear a maximum of three times. Substitutes and goalkeepers were excluded from the analysis. The experimental protocol was approved by the Ethical Committee of the University of Udine (Italy). Before the study began, the purpose and objectives were carefully explained to each subject. Written informed consent was obtained from all subjects.

Match Analysis

The players' movements on the soccer pitch were monitored using a semiautomatic system supplied by SICS® (Bassano del Grappa, Italy) with four 25-Hz sample frequency cameras. Rampinini et al. (28) determined the reliability of this device with a typical error of 1.0% for TD. Coordinates given by the system and referred to the position of each athlete on the pitch were processed as described below.

Distance Processing

Defining $x(n)$ and $y(n)$ in the Cartesian coordinates of a given player after $n/25$ s from the beginning of the match and the total distance $d(n)$ covered by the player in question from the beginning of the match can be computed as follows:

$$\begin{aligned} \delta(n) &= \sqrt{[x(n) - x(n-1)]^2 + [y(n) - y(n-1)]^2} \\ d(n) &= d(n-1) + \delta(n) \\ d(0) &= 0 \end{aligned} \quad [6]$$

where $\delta(n)$ is the distance covered between $n/25$ and $(n - 1)/25$ s. The speed $v(n)$ at time $n/25$ can then be computed as:

$$v(n) = \frac{1}{T}[d(n) - d(n-1)] \quad [7]$$

where $T = 1/25$ s. Thus, the acceleration $a(n)$ at time $n/25$ is given by:

$$a(n) = \frac{1}{T}[v(n) - v(n-1)] \quad [8]$$

Unfortunately, the noise affecting the position values $x(n)$ and $y(n)$ is greatly amplified because it is multiplied by $1/T$. Actually, if σ is the SD of the noise affecting $d(n)$, it is possible to show that $v(n)$ is affected by a noise with a SD equal to:

$$25\sqrt{2}\sigma \cong 35\sigma \quad [9]$$

and that $a(n)$ is affected by a noise with SD equal to:

$$(25\sqrt{2})^2\sigma = 1250\sigma \quad [10]$$

Therefore, to make the estimates of $v(n)$ and $a(n)$ more reliable, the position data were filtered with the equation:

$$\hat{d}(n) = \textstyle\sum_{k=0}^{186} h(k)d(n-k) \quad [11]$$

where the coefficients $h(k)$ were chosen to remove from the sequence $d(n)$ the components corresponding to position changes too fast to be physiologically significant. Therefore, as from the values $d(n)$, we estimated the velocity ($\hat{v}(n)$) and the acceleration ($\hat{a}(n)$) with the following two equations:

$$\hat{v}(n) = \frac{1}{T}[\hat{d}(n) - \hat{d}(n-1)] \quad [12]$$

$$\hat{a}(n) = \frac{1}{T}[\hat{v}(n) - \hat{v}(n-1)] \quad [13]$$

Match Activities

Performance of each athlete was assessed through three parameters: speed, acceleration, and estimated metabolic power.

Speed. The following six speed categories were used: walking (from 0 to 8 km·h^{-1}), jogging (from 8 to 13 km·h^{-1}), low-speed running (LSR; from 13 to 16 km·h^{-1}), intermediate-speed running (ISR; from 16 to 19 km·h^{-1}), high-speed running (HSR; from 19 to 22 km·h^{-1}), and max-speed running (MSR; >22 km·h^{-1}). Unlike most studies, we voluntarily replaced the category "sprinting," which

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TABLE 1. T (s) and D (m) during the entire match in each speed category (mean ± SD).

Speed Category	T (s)	D (m)
Walking (from 0 to 8 km·h^{-1})	3895 ± 333	4421 ± 322
Jogging (from 8 to 13 km·h^{-1})	1089 ± 169	3111 ± 497
LSR (from 13 to 16 km·h^{-1})	357 ± 89	1423 ± 356
ISR (from 16 to 19 km·h^{-1})	191 ± 56	919 ± 270
HSR (from 19 to 22 km·h^{-1})	97 ± 31	546 ± 178
MSR (>22 km·h^{-1})	77 ± 31	531 ± 214
Total	5705 ± 100	10,950 ± 1044

is normally used for maximal intensities, with a merely quantitative evaluation of running speed (MSR). As a matter of fact, maximal metabolic intensity in "sprinting" occurs even when running speed is not necessarily elevated or maximal. For each of the speed categories, time and distance were quantified.

Acceleration. The following eight acceleration categories were used: max deceleration (MD; <-3 m·s^{-2}), high deceleration (HD; from -3 to -2 m·s^{-2}), intermediate deceleration (ID; from -2 to -1 m·s^{-2}), low deceleration (LD; from -1 to 0 m·s^{-2}), low acceleration (LA; from 0 to 1 m·s^{-2}), intermediate acceleration (IA; from 1 to 2 m·s^{-2}), high acceleration (HA; from 2 to 3 m·s^{-2}), and max acceleration (MA; >3 m·s^{-2}). For each of these acceleration categories, time and distance were quantified.

Power. The following five power categories were used: low power (LP; from 0 to 10 W·kg^{-1}), intermediate power (IP; from 10 to 20 W·kg^{-1}), high power (HP; from 20 to 35 W·kg^{-1}), elevated power (EP; from 35 to 55 W·kg^{-1}), and max power (MP; >55 W·kg^{-1}). For each of these power categories, time, distance, and estimated net energy expenditure (above resting) were quantified.

Energy Cost and Metabolic Power

The described analysis allowed us to estimate EC and metabolic power, as described in the Theoretical Model section. However, the data provided by Minetti et al. (22) and considered by di Prampero et al. (12) refer to running on a treadmill. For this reason, the values of EC obtained by equation 4 were multiplied by a constant (KT = 1.29) to take into account the fact that running on a football field is approximately 30% more costly than running on compact homogeneous terrain (25).

Besides distance, speed, acceleration, metabolic power, and energy expenditure, to reach a better understanding of the performance of soccer players, the following parameters were also calculated.

Equivalent distance (ED). This represents the distance that the athlete would have run at a steady pace on grass using the total energy spent over the match:

$$\mathrm{ED} = \frac{W}{\mathrm{EC}_C \mathrm{KT}} \qquad [14]$$

where ED is the equivalent distance (m), W is the total energy expenditure (J·kg^{-1}), EC$_C$ is the EC of running at a constant pace on flat compact terrain assumed to be 3.6 J·kg^{-1}·m^{-1} (equation 4), and KT is the grassy terrain constant.

Equivalent distance index (EDI). This represents the ratio between ED and TD in the period considered:

$$\mathrm{EDI} = \frac{\mathrm{ED}}{\mathrm{TD}} \qquad [15]$$

where ED is the equivalent distance (m) and TD is the total distance (m).

Anaerobic index (AI). This represents the ratio between the energy expenditure above a certain metabolic power threshold (TP) selected by the investigator (e.g., power output corresponding to $\dot{V}O_{2\max}$ or to anaerobic threshold) and the total energy expenditure over the whole match or in the period considered:

$$\mathrm{AI} = \frac{\sum W_{\mathrm{TP}}}{\sum W} \qquad [16]$$

where AI is the anaerobic index, W_{TP} is the energy expenditure over the selected TP (J·kg^{-1}), and W is the total energy expenditure (J·kg^{-1}). In this study, TP was considered equal to 20 W·kg^{-1}, thus corresponding to a $\dot{V}O_2$ of approximately 57 mL·kg^{-1}·min^{-1}, above resting.

Statistical Analyses

Results are shown as mean ± SD.

RESULTS

The mean match time of the players was 95 min 5 s ± 1 min 40 s compared with the standard duration of an

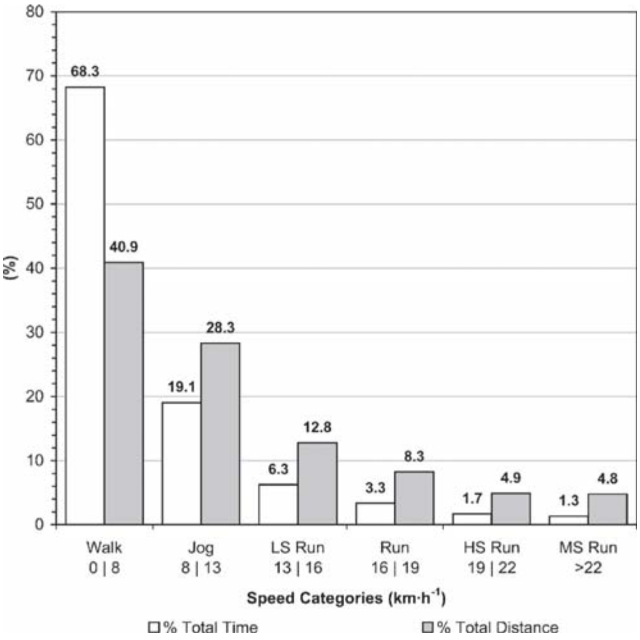

FIGURE 2—T and D (%) during the entire match in each speed category.

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TABLE 2. *T* (s), *D* (m), and corresponding EC ($J \cdot kg^{-1} \cdot m^{-1}$) during the entire match in each acceleration category (mean ± SD).

Acceleration Category	*T* (s)	*D* (m)	EC ($J \cdot kg^{-1} \cdot m^{-1}$)
MD ($<-3\ m \cdot s^{-2}$)	50 ± 16	188 ± 65	>3.41
HD (from −3 to $-2\ m \cdot s^{-2}$)	128 ± 29	411 ± 98	From 2.38 to 3.41
ID (from −2 to $-1\ m \cdot s^{-2}$)	448 ± 68	1176 ± 206	From 2.38 to 2.77
LD (from −1 to $0\ m \cdot s^{-2}$)	2282 ± 120	3821 ± 335	From 2.77 to 4.64
LA (from 0 to $1\ m \cdot s^{-2}$)	2152 ± 102	3587 ± 328	From 4.64 to 7.81
IA (from 1 to $2\ m \cdot s^{-2}$)	461 ± 59	1176 ± 184	From 7.81 to 12.03
HA (from 2 to $3\ m \cdot s^{-2}$)	133 ± 29	411 ± 95	From 12.03 to 17.28
MA ($>3\ m \cdot s^{-2}$)	51 ± 18	180 ± 67	>17.28

As detailed in the Theoretical Model section, the EC of accelerated and decelerated running was obtained from the individual acceleration values, and the corresponding ES and EM was obtained with equation 4; the so-obtained results were then multiplied by the grassy terrain constant (KT = 1.29).

TABLE 3. *T* (s), *D* (m), and EEE ($kJ \cdot kg^{-1}$ or $kcal \cdot kg^{-1}$) during the entire match in each power category (mean ± SD).

Power Category	*T* (s)	*D* (m)	EEE
LP (from 0 to 10 $W \cdot kg^{-1}$)	3818 ± 299	4647 ± 230	19.01 ± 1.21 $kJ \cdot kg^{-1}$ 4.54 ± 0.29 $kcal \cdot kg^{-1}$
IP (from 10 to 20 $W \cdot kg^{-1}$)	1173 ± 161	3435 ± 572	16.41 ± 2.34 $kJ \cdot kg^{-1}$ 3.92 ± 0.56 $kcal \cdot kg^{-1}$
HP (from 20 to 35 $W \cdot kg^{-1}$)	461 ± 91	1718 ± 380	11.89 ± 2.39 $kJ \cdot kg^{-1}$ 2.84 ± 0.57 $kcal \cdot kg^{-1}$
EP (from 35 to 55 $W \cdot kg^{-1}$)	163 ± 38	670 ± 173	6.99 ± 1.63 $kJ \cdot kg^{-1}$ 1.67 ± 0.39 $kcal \cdot kg^{-1}$
MP (>55 $W \cdot kg^{-1}$)	91 ± 28	451 ± 144	6.82 ± 2.22 $kJ \cdot kg^{-1}$ 1.63 ± 0.53 $kcal \cdot kg^{-1}$

official match (90 min). The average distance covered during the matches (all players) was 10,950 ± 1044 m; minimal and maximal distances were 8683 and 13,533 m, respectively.

Speed. Total time (*T*) and distances covered (*D*) in each speed category (averages for all players) are shown in Table 1 (absolute values) and Figure 2 (%).

Acceleration. Total time (*T*) and distances covered (*D*) together with corresponding average EC during accelerated and decelerated running in each category (averages for all players) are shown in Table 2 (absolute values) and Figure 3 (%).

Power. The product of the instantaneous speed and the corresponding EC of running allowed us to estimate the instantaneous values of metabolic power, which, as mentioned above, were grouped into five categories. Total time (*T*), distance covered (*D*), and estimated energy expenditure (EEE) for each power category are shown in Table 3 (absolute values) and Figure 4 (%).

Additional parameters. The mean equivalent distance (ED), that is, the distance that the athlete would have run at a steady pace on grass using the same energy spent in the entire match, was 13,166 ± 1415 m, minimal and maximal distances being 10,067 and 16,845 m, respectively. This corresponds to a mean equivalent distance index (EDI; i.e., the ratio between ED and actual distance covered over the entire match) of 1.20 ± 0.03, the minimal and maximal figures amounting to 1.13 and 1.33, respectively. Finally, mean anaerobic index (AI), that is, the ratio between an energy expenditure exceeding a TP of 20 $W \cdot kg^{-1}$ and total energy expenditure over the entire match, was 0.18 ± 0.03, with minimal and maximal figures of 0.11 and 0.27, respectively.

DISCUSSION

The main aim of this study was to propose a new approach in the analysis of soccer player performance taking into account also the phases of accelerated and

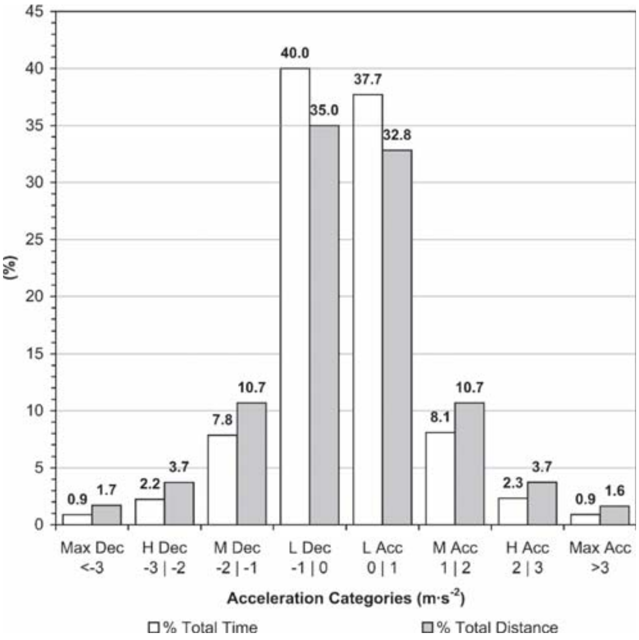

FIGURE 3—*T* and *D* (%) during the entire match in each acceleration category.

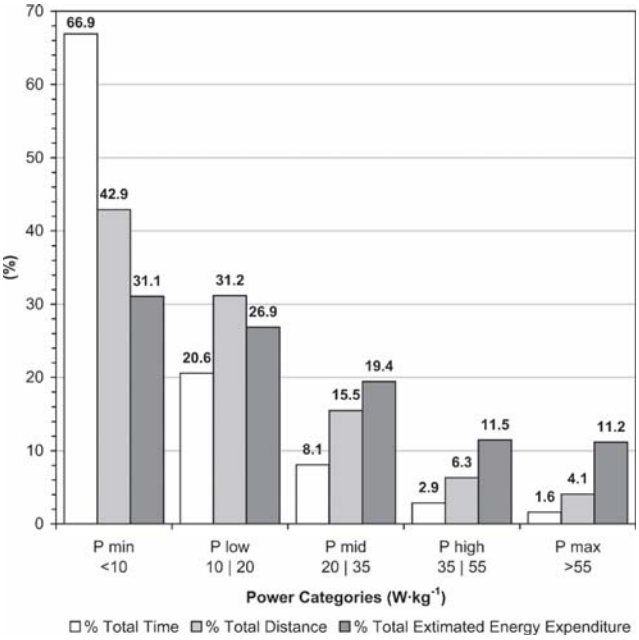

FIGURE 4—*T*, *D*, and EEE (%) during the entire match in each power category.

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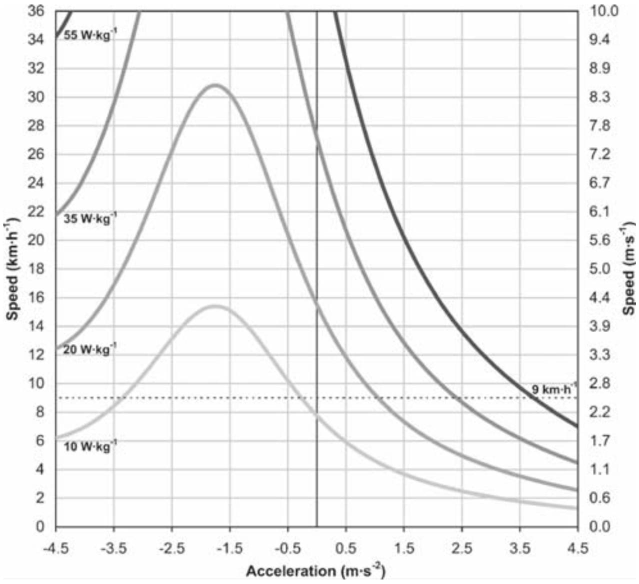

FIGURE 5—Isopower relationships calculated as function of speed (*y*-axis) and acceleration (*x*-axis). A speed of 9 km·h^{-1} (*horizontal sketched line*) yields different power outputs depending on acceleration. For example, at a constant speed (9 km·h^{-1}), the metabolic power would amount to approximately 13 W·kg^{-1}, whereas at the same speed, but with an acceleration of 1 or 2.4 m·s^{-2}, the metabolic power would increase to 20 or to 35 W·kg^{-1}. Conversely, decelerated running would bring about a reduction of metabolic power.

decelerated running, which constitute a large and crucial fraction of every match. The study of di Prampero et al. (12), with proper adaptations, is suitable to be integrated in a video match analysis system. Indeed, the so-obtained results, such as those of numerous other studies (4,7,15,29,33,35), have shown that the average energy expenditure over a match is 61.12 ± 6.57 kJ·kg^{-1} (14.60 ± 1.57 kcal·kg^{-1}). However, compared with the traditional video match analysis, which estimates distances covered at different speeds, the present approach provides a new perspective on player performance on the basis of instantaneous power output. As a matter of fact, the metabolic power output at speeds that are usually classified as high intensity or sprinting is fairly elevated (e.g., when running at a constant speed of approximately 14 km·h^{-1} on grass, the metabolic power is approximately 20 W·kg^{-1}). However, a similar power can also be achieved with low running speeds whenever the acceleration is elevated. As an example, a running speed of 9 km·h^{-1} would be classified as a "low-intensity" activity by traditional video match analysis. By contrast, our approach reveals that this running speed can generate different metabolic demands depending on the acceleration (e.g., Fig. 5).

As a result of this state of affairs, the present approach yields higher performance intensities in soccer than traditional video match analysis. This can be shown as follows. Consider a speed threshold of 16 km·h^{-1}. In this study, as well as in many others, the distance covered at speeds >16 km·h^{-1} amounts to approximately 18% of TD (Table 1). The metabolic power when running on a soccer field at 16 km·h^{-1} amounts to:

$$P = \mathrm{EC}v\mathrm{KT} = 3.6 \times 4.44 \times 1.29 \cong 20\ \mathrm{W \cdot kg^{-1}} \qquad [17]$$

where P is expressed in watts per kilogram (W·kg^{-1}), v is expressed in meters per squared second (m·s^{-2}), EC is expressed in joules per kilogram per meter (J·kg^{-1}·m^{-1}), and the factor 1.29 is introduced to take into account the terrain characteristics (soccer field vs compact terrain). If, as is the case in our approach, instead of the speed threshold as such (16 km·h^{-1}), the corresponding metabolic TP (20 W·kg^{-1}) is considered (thus including also the acceleration and deceleration), then the TD covered at a power exceeding this threshold amounts to 26% and the corresponding energy expenditure to approximately 42% of the total (Table 3).

Furthermore, the profile of a soccer player can be profitably analyzed using the additional parameters identified above rather than the traditional ones. The total energy expenditure can be expressed as ED instead of TD because ED depends both on TD and on "how" TD was performed. Although different players could have covered the same TD, the use of ED allows the identification of different metabolic energy expenditures, thus allowing us to assess the "true" overall energy expenditure regardless of the actual distance covered. As shown in Figure 6, on average, ED is linearly related to TD, being approximately 20% higher.

However, upon closer inspection of Figure 6, it becomes apparent that the EDI, that is, the ratio between ED and TD (isopleths of Fig. 6), for a given TD varies substantially

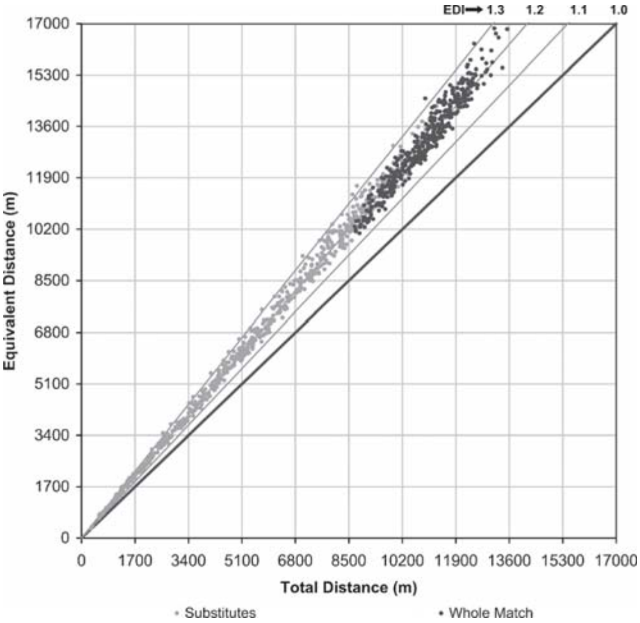

FIGURE 6—ED is plotted as a function of TD. Players who complete the whole match are symbolized in *black circles*, whereas substitutes are symbolized in *gray circles*. Every *straight line* represents a constant ratio between ED and TD defined as EDI.

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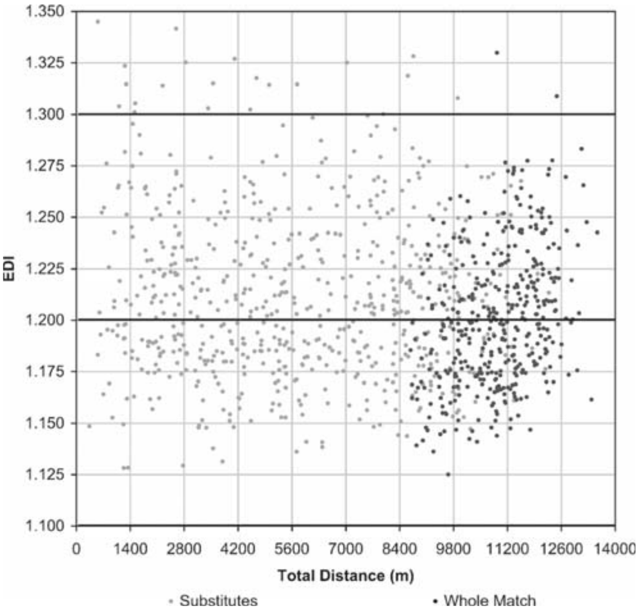

FIGURE 7—EDI is plotted as a function of TD. Players who complete the whole match are symbolized in *black circles*, whereas substitutes are symbolized in *gray circles*.

among players, the "lazy players" being characterized by EDI ≅ 1.15, their more dynamic fellow mates reaching EDI values of approximately 1.30 (Fig. 7).

Finally, the AI can also be rather informative. In the present study, we defined AI as the ratio of the overall energy expenditure above the threshold of 20 W·kg^{-1} (corresponding to a $\dot{V}O_2$ of approximately 57 mL·kg^{-1}·min^{-1} above resting). So defined, AI ranged from 0.15 to 0.25 (Fig. 8), thus indicating that from 15% to 25% of the overall energy expenditure, it was derived at a very high metabolic power. Although, in this study, we assumed a threshold of 20 W·kg^{-1} to define AI, ideally, this parameter ought to be "customized" according to the endurance profile of each athlete, thus allowing the coach to evaluate each player individually.

Figure 8 also shows that, in all groups of players, the increase of total energy expenditure was brought about by a greater use of the anaerobic sources, as shown by the fact that AI becomes progressively larger with increasing overall energy expenditure.

Limits of original method. As reported in the original study (12), the approach used in the present study is based on the following simplifying assumptions:

1. The overall mass of the runner is assumed to be located at the center of mass of the body. As such, any possible effects of the motion of the limbs on the energetics of running were neglected. This is tantamount to assume that the energy expenditure associated with internal work is the same during uphill running as during sprint running at an equal ES. This is probably not entirely correct because the frequency of motion is larger during sprint than during uphill running. If this is the case, the values obtained in this study represent a minimal value of the EC or metabolic power during the match.
2. For inclines greater than +0.45, there are no data on the EC of uphill running. In this study, we did not observe acceleration greater than 5 m·s^{-2}, corresponding to ES = +0.50. Therefore, also because values above this incline were <1.0% of the time of the match (Table 2), we assumed that the same algorithm (22) used for estimating EC (equation 4) was also applicable for ES > +0.50.

Neglected variables. As specified in various sections of the study, this approach considers only the running performance during the match. Therefore, many other typical activities, such as jumping, kicking the ball, tackling, conducting the ball, and so on, have been neglected. Furthermore, the energy spent against air resistance has been neglected. However, the air resistance increases with the square of the speed, amounting to approximately 10% of total EC for a running speed of approximately 21 km·h^{-1}. Because the time spent above this speed represented on average less than 2 min during the whole match, neglecting the fraction of EC because of air resistance cannot be expected to introduce substantial errors. It is also difficult to evaluate climatic and environmental variables: weather and field conditions may influence players' work rate. Incidentally, a value of KT higher than 1.29 (running on grass) may be used for calculating the EC in matches played on fields in bad conditions (muddy, snowy, etc.). Finally, the algorithm used in this study

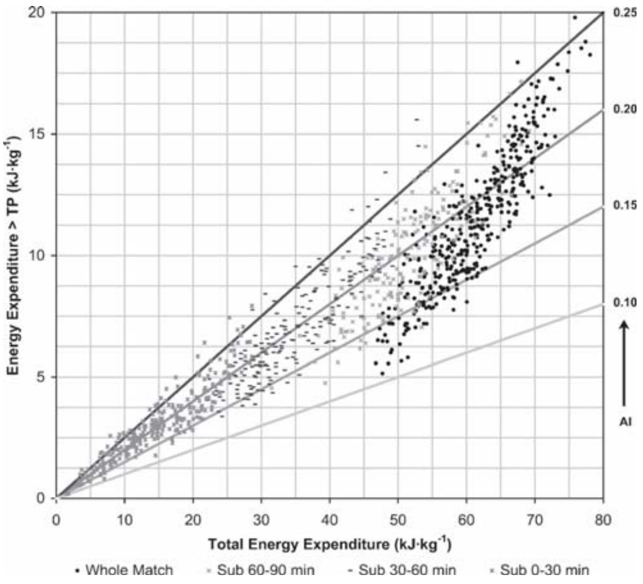

FIGURE 8—Energy expenditure above TP is plotted as a function of total energy expenditure. Players who completed the whole match are symbolized in *black circles*, substitutes who played from 60 to 90 min are symbolized in *gray crosses*, substitutes who played from 30 to 60 min are symbolized in *gray dashes*, and substitutes who played from 0 to 30 min are symbolized in *gray asterisks*. Every *straight line* represents a constant ratio between total energy expenditure and energy expenditure above TP defined as AI.

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represents the EC above resting metabolism. The evaluation of this last is not straightforward; however, it cannot be expected to play a substantial role.

Applications to sports other than soccer. The present approach for evaluating the EC and metabolic power in soccer could be also suitable in other sports characterized by running, such as American and Australian football, rugby, basketball, baseball, field hockey, etc. It goes without saying that the specific characteristics of these sports (e.g., scrums in American football and rugby) should be duly considered to obtain meaningful data. In addition, this approach could be particularly interesting during official competitions in sports where wearing any kind of device is not allowed. When this is not the case (e.g., in Australian football), global positioning system (GPS) technology could be used instead of video match analysis: athletes could wear a GPS receiver defining their position at a frequency of 1 Hz (or 5 Hz with the most recent systems). Further studies will be necessary to investigate whether the temporal accuracy of GPS with the present frequency of acquisition is sufficient to estimate accelerations. Assuming this technology to be reliable, use of GPS could prove very useful during training of all sports on the basis of running. So, ideally, the present approach should be based on two pillars: video match analysis for official competitions and GPS for trainings. Finally, it should be pointed out that, always, it will be mandatory to identify a specific KT defining the effect of the terrain and of the type of shoes worn by athletes on the EC at constant speed.

In conclusion, the approach used in this study allowed us to estimate elite soccer energy expenditure by a video match analysis device also taking into account accelerations and decelerations during the various phases of the match. Energy expenditure (above resting) for a player with an average mass of 75.8 kg turned out to be 4633 ± 498 kJ (1107 ± 119 kcal), comparable to that found by other authors (4,15,23,33,36). The TD covered is only a partial index of the overall energy expenditure. Indeed, because the acceleration and deceleration phases, the variability in energy expenditure for the same TD is approximately 15%. Therefore, we propose the use of ED (the ratio between total energy expenditure and EC at a constant pace on a flat grassy terrain) as a more appropriate index of overall energy expenditure.

Furthermore, the present approach allowed us to assess the metabolic power exerted by the athlete at any instant, thus redefining the concept of "high intensity." The results show that top-class players covered approximately 18% of TD at high speed (exceeding 16 $\text{km}\cdot\text{h}^{-1}$), although they spent more than 42% of the total energy at high-power output (>20 $\text{W}\cdot\text{kg}^{-1}$).

Other parameters make it possible to customize the players' evaluations. A TP can be defined for each player, and the energy derived above this threshold, presumably from anaerobic sources, can be assessed. The use of the same TP for the 399 players involved in this study (20 $\text{W}\cdot\text{kg}^{-1}$) shows that the anaerobic energy yield ranges from 11% to 27% of total energy output.

The EC running on grass was assumed to be 29% higher than that on treadmill (25). However, further data are needed to establish a more precise value of this coefficient, particularly so to take into account the widely different types of terrain. Moreover, as aforementioned, we have only considered the EC of running, excluding any other action typical of soccer.

In conclusion, further development of this model could lead to deeper investigations on the differences related to playing position, ranking, and fatigue during a single match or during the soccer season.

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