Introduction

The overall energy expenditure during team sports can be rather high, reaching ≈ 47.5 kJ · kg⁻¹ (11.3 kcal · kg⁻¹) for a 90-min soccer match, which corresponds to an average O₂ consumption of ≈ 25.2 ml O₂ · kg⁻¹ · min⁻¹, as obtained from data gathered during the Italian 2014/2015 “Serie A” over 497 players [Osgnach et al., in preparation]. Therefore, successful players must be characterized not only by elevated technical abilities, but also by an appropriate physical fitness level, which can be achieved only through correct training strategies. To optimize these strategies, we previously developed a set of algorithms that allows the user to estimate the instantaneous metabolic power and overall energy expenditure during a match or training drill together with the fractions derived from aerobic and anaerobic sources. In the original approach, however, walking and running were aggregated and energetically considered as running, thus leading to an overestimate of the overall energy expenditure. This approach has recently been extended to take into account the different energy expenditure of the walking (versus running) episodes and the effects of air resistance on instantaneous metabolic power and overall energy expenditure (see accompanying paper [7]).

The present study shows that this upgraded approach, as incorporated into portable GPS devices, allows one to estimate with reasonable accuracy the time course of metabolic power (Ė) and actual O₂ uptake (V˙O₂). Indeed, overall energy expenditure as estimated from the time integrals of Ė or actual V˙O₂ during constant-speed walking or running and short spells of accelerated/
decelerated running, are rather close to each other and similar to that obtained from direct $\dot{V}O_2$ assessment by means of a portable metabolic cart. We will also show that the information obtained can be utilized to assess overall energy expenditure, fractions derived from aerobic and anaerobic sources, and the duration and metabolic power of high- and low-intensity episodes, thus yielding a more accurate picture of the time course of the metabolic load during a soccer match than can be obtained from speed and/or acceleration alone. Finally, the simplified assumptions that underlie the updated version of our approach will be summarized in the concluding section, together with possible reasons for the discrepancies between the energetic parameters estimated from GPS data and the corresponding values obtained via portable metabolic carts as reported by several recently published studies [1, 2, 4, 10].

The approach described in the accompanying paper [7] has been implemented on a 18, 18 Hz GPS system (GPEXE®) that can be positioned on the player’s back. Hence the player’s speed and instantaneous acceleration can be monitored throughout a soccer match or drill (via the Doppler effect), from which the corresponding instantaneous energy cost and metabolic power can be obtained as described in the present study.

### Metabolic Power and Oxygen Consumption

The section that follows shows that once the metabolic power, as given by the product of the energy cost of transport and speed, is obtained, this system makes it possible to estimate: (i) the corresponding time course of the actual $O_2$ uptake, as well as (ii) the overall energy expenditure and the fractions thereof derived from aerobic and anaerobic sources, thus yielding (iii) a much more accurate picture of the metabolic load than can be obtained from speed and/or acceleration alone.

Metabolic power is a measure of the instantaneous rate of ATP utilization regardless of actual oxygen consumption, which may be equal to, greater than, or less than metabolic power itself. This is so because: (i) with respect to metabolic transients, the kinetics of oxidative processes is rather sluggish in so far as they adapt to the theoretical $O_2$ consumption (VO$_2$ max) at a rate constant of which, at the muscle level, is on the order of 20 s. In addition, (ii) during very strenuous exercise of short duration, the metabolic power requirement can attain values greatly surpassing the subject’s maximal $O_2$ consumption (VO$_2$ max). These considerations show that, in contrast to typical “square wave” aerobic exercises, during which actual VO$_2$ and metabolic power coincide after about 3 min, the characteristics of soccer and 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 the metabolic power requirement.

However, as discussed in detail elsewhere [5], knowledge of the time course of the metabolic power allows one to estimate the corresponding actual VO$_2$ as described below.

We will first consider a square wave aerobic exercise, in which case the actual VO$_2$ follows the metabolic power transients according to mono-exponential functions described by:

$$\dot{V}O_2(t) = \dot{V}O_2(s) \cdot (1 - e^{-t/\tau})$$  \hspace{1cm} (1)$$

and by:

$$\dot{V}O_2(t) = \dot{V}O_2(s) \cdot e^{-t/\tau}$$  \hspace{1cm} (2)$$

for on and off transients, respectively, where $\dot{V}O_2(t)$ and $\dot{V}O_2(s)$ represent the net VO$_2$ (above resting) at time $t$ and at steady state, respectively, and $\tau$ is the time constant of the process. \(\text{Eq. (1, 2)}\) show also that after a time $t = 4 \tau$, $\dot{V}O_2(t)$ attains the asymptotic value, thus becoming equal to $\dot{V}O_2(s)$, or to zero, in the on or off responses, respectively. Thus, from this time onwards, actual $O_2$ consumption and metabolic power coincide.

\(\text{Eq. (1, 2)}\) describe the VO$_2$ kinetics both at the muscle and upper airway level. However, the process is faster ($t = 20 s$) at the muscle than at the mouth ($t = 35 s$) because the body $O_2$ stores (mainly $O_2$ bound to hemoglobin 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 that at the muscle level. In addition, even if the VO$_2$ kinetics during metabolic transients could be appropriately described by means of more refined algorithms including “cardiodynamic phases” and/or “slow components” (e.g., see [3]), for the sake of simplicity we will here assume that, in all cases, the VO$_2$ on and off responses at the muscle level are described by mono-exponential functions with a time constant of 20 s.

When the exercise intensity exceeds the subject’s maximal oxygen consumption, 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 rate of $O_2$ consumption required to sustain the appropriate exercise intensity on the basis of oxidative processes only, i.e., with the corresponding metabolic power ($\dot{E}$), expressed in equivalent $O_2$ units. In addition (ii) once VO$_2$ max is attained, the actual VO$_2$ cannot increase any further. It follows that, whereas the theoretical $O_2$ consumption (VO$_2$ T) would keep increasing towards $\dot{E}$, the actual $O_2$ consumption (VO$_2$ eff) cannot exceed VO$_2$ max. Similarly, as long as the theoretical $O_2$ consumption is greater than VO$_2$ max in the recovery, the actual $O_2$ consumption cannot decrease below VO$_2$ max.

So far, we have considered square wave exercises whose intensity remains unchanged for relatively long periods of time, thus permitting the attainment of the steady state, or, for supra-maximal exercise, VO$_2$ max. We will now address the more realistic situations in which the metabolic power requirement varies rapidly as a function of time, as is always the case in team sports such as soccer. To this aim, \(\text{Eq. (1, 2)}\) can be generalized as follows:

$$\dot{V}O_2T_{n(0)} = (\dot{E}_n - \dot{V}O_2T_{n(0)}) \cdot (1 - e^{-t/\tau}) + \dot{V}O_2T_{n(0)}$$  \hspace{1cm} (3)$$

where $\dot{V}O_2$ $T_{n(0)}$ and $\dot{V}O_2T_{n(0)}$ are the theoretical VO$_2$ values at time $t$ of each metabolic power interval and at its very onset (end of the preceding one), respectively. Thus, \(\text{Eq. (3)}\) allows one to describe the actual VO$_2$ kinetics provided that the time course of the metabolic power requirement is known (patent N.0001425417). It is immediately apparent that, in this specific example, whenever $\dot{E} \leq$ VO$_2$ max, the actual (VO$_2$ eff) and theoretical (VO$_2$ T) $O_2$ consumption coincide, whereas when $\dot{E} >$ VO$_2$ max, once VO$_2$ max is attained, VO$_2$ eff cannot increase further (since VO$_2$ T > VO$_2$ max), nor
can it decrease below $\dot{V}O_2 \text{max}$ (as long as $\dot{V}O_2 \text{T} > \dot{V}O_2 \text{max}$). It should also be noted that the attainment, or not, of $\dot{V}O_2 \text{max}$ depends on the metabolic power and the duration of the appropriate high metabolic power period.

It seems important to stress here that Eq. (3) applies regardless of the duration of the metabolic power intervals. Therefore it can also be applied to exercises whose intensity changes randomly throughout any given time period.

To verify this assumption, as reported in a previous study [5], a preliminary set of data was collected on a group of 9 subjects during 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 2 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, Stalker Radar, Richardson, TX, USA); the corresponding instantaneous acceleration, energy cost, and metabolic power were then calculated by means of the same set of equations as implemented in the GPEXE® (see above).

Finally, the time course of the actual $\dot{V}O_2$ was estimated according to Eq. (3) as reported in Fig. 1 for a typical subject. In addition, the subjects wore a portable metabolic cart (K4, Cosmed, Rome, Italy) allowing us to assess the actual $\dot{V}O_2$ consumption on a breath-by-breath basis. The data thus obtained are represented for a typical subject in Fig. 2, which reports the time integral of: (i) metabolic power requirement, (ii) $\dot{V}O_2$ estimated from Eq. (3) on the basis of a time constant of 20 s, and (iii) $\dot{V}O_2$ actually measured. This figure shows that: (i) the time integrals of estimated and measured $\dot{V}O_2$ are very close, and (ii) they follow fairly well the time course of the total energy expenditure (i.e., the time integral of the metabolic power requirement). It should also be noted that: (iii) the horizontal time difference between the two functions ($\dot{V}O_2$ measured or estimated, on the one hand, and time integral of metabolic power on the other) is the time constant of the $\dot{V}O_2$ kinetics. As pointed out above, (iv) this turns out to be longer ($\approx 35$ s) at the measuring site (the upper airways) than that assumed to hold at the muscle level ($\approx 20$ s).

These data strongly support the theoretical approach described above. However, in view of the many critical observations and conflicting experimental outcomes reported by several authors [1, 2, 4, 10], an additional series of experiments were performed in which the running speed and the corresponding instantaneous acceleration were continuously monitored by GPEXE® (Cassirame et al., in preparation). The energy cost of both running and walking episodes, as well as the metabolic power and the $\dot{V}O_2$ time course, were then estimated by means of the same set of equations described in the accompanying paper [7]. In addition, as was the case for the preliminary set of experiments described above (Fig. 1, 2), the subjects wore a portable metabolic cart (Metamax® 3B, Cortex, Leipzig, Germany) so that the actual $\dot{V}O_2$ consumption was also determined on a breath-by-breath basis. The experimental protocol is briefly described below.

After 3 min of rest, the subjects walked (4.5 km·h⁻¹) and ran (10 km·h⁻¹) at constant speed in a straight line, for 4 and 5 min, respectively. This was followed by 5 min of rest and by 3 sprint protocols (A, B and C) of 5 min duration (as described below) separated by 5 min of rest. A final rest period of 5 min concluded the session. Throughout all rest periods the subjects maintained a standing position.

Protocol A (straight-line sprints) consisted of ten 50 m straight runs, each performed in 10 s and followed by 20 s of rest.

Protocol B (L-shaped sprints) consisted of ten runs of 25 + 25 m performed in 5 + 5 s with a 90-degree change of direction in between and followed by 20 s of rest.

Protocol C (shuttle sprints) consisted of ten runs of 25 + 25 m performed in 5 + 5 s with a 180-degree change of direction in between and followed by 20 s of rest.

The overall distance and average speed were the same for the 3 protocols, amounting to 500 m and 6 km·h⁻¹.

Blood samples for lactate analysis were taken from the ear lobe at the end of each rest period.

The results obtained from a “standard” trial on a typical subject are reported in Fig. 3 where the time course of $\dot{V}O_2$, as estimated from the instantaneous metabolic power (see above and Fig. 1 Metabolic power ($\dot{E}$, black) and estimated $\dot{O}2$ consumption ($\dot{V}O_2$, grey) (W·kg⁻¹) as a function of time during a series of shuttle runs over 25 m distance in 5 s. See text for details.

Fig. 2 Time integral (J·kg⁻¹) as a function of time (s) of: (i) metabolic power requirement (black) as determined by GPEXE®; (ii) $\dot{V}O_2$, estimated from equation (3) on the basis of a time constant of 20 s (grey); and (iii) $\dot{V}O_2$, actually measured by means of a portable metabolic cart (dotted line). See text for details [5].
subsequent experimental phases, however, the increase of measured VO₂ is less than estimated from GPEXE®, so that at the end of the 47-min trial, the measured overall amount of VO₂ consumed in this specific subject is about 1500 J·kg⁻¹, i.e., 10% less than the estimated overall energy expenditure. The relationship between estimated (GPEXE®) and measured (Metamax® 3B) VO₂ shows a certain degree of variability among the different protocols. Indeed, whereas the mean estimated VO₂ during constant-speed walking was essentially equal to the one measured directly, it was about 20% more (on average) during constant-speed running and about 15% less during the intermittent running protocols, regardless of whether subjects ran in a straight line, or at a 90- or a 180-degree angle. For a thorough analysis of these data, the reader is referred to Cassirame et al. (in preparation). Nevertheless, it seems noteworthy to point out here that Stevens et al. [13] reported similar discrepancies in 2015.

These discrepancies may be partly due to individual differences in running technique and/or in the VO₂ kinetics. Indeed, it should be stressed here that the estimated metabolic power and O₂ consumption are based on the assumptions that: (i) the energy cost of transport at constant velocity (be it walking or running), (ii) the effect of the acceleration or deceleration phases thereon, and finally (iii) the kinetics of the VO₂ on and off responses, are equal for all subjects. Assumption (i) seems fairly well supported by the experimental data, even if a certain interindividual variability as well as the effects of different types of terrain may indeed play a non-negligible role. In addition, it seems likely that the variability among subjects in the energy cost of sprint running (accelerated and decelerated) may account for part of the difference between estimated and measured VO₂. Finally, as mentioned above, it was also assumed that the time course of the VO₂ responses to metabolic transients at the muscle level is described by a mono-exponential function with a time constant of 20 s, thus neglecting the possible role of cardiodynamic phases and/or slow components that may also play a non-negligible role with increasing the exercise duration (e.g., see [3]).

In conclusion, in spite of the variability between estimated and measured VO₂, these data show that this model is a powerful tool for estimating the energetic characteristics of soccer and for selecting appropriate training strategies (for details, see Cassirame et al., in preparation). Indeed, we would like to stress that although the agreement between the measured and estimated VO₂ reported above could theoretically be improved by determining the individual energy cost of transport both at constant speed and during the acceleration and deceleration phases, as well as the individual VO₂ time constants, neither option seems realistic. Therefore, we think that retaining the necessary simplified assumptions described above and in the accompanying paper [7] is the only reasonable alternative to the use of a crystal ball for assessing the energetics of team sports.

Nevertheless, because several other seemingly more straightforward approaches are often used for this purpose, we have condensed the characteristics of each in ☞ Table 1 and summarized their limits, advantages, and disadvantages.

For a more detailed comparison between the speed and energy-based approaches in hockey, the reader is referred to Polglaze et al. 2017 [12].
Table 1 Summary of the main characteristics of the speed- and energy-based approaches with comments highlighting the principal differences between the two (modified after Polglaze et al. 2017 [11]).

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPEED-BASED APPROACH</th>
<th>ENERGY-BASED APPROACH</th>
<th>COMMENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume</td>
<td><strong>YES</strong></td>
<td><strong>YES</strong></td>
<td>The total distance is a correct estimate of the “volume” only if the speed is constant. In the energy-based approach this is expressed by the equivalent distance, thus also taking into account the acceleration/deceleration phases.</td>
</tr>
<tr>
<td></td>
<td>Total distance (m)</td>
<td>Total energy (J·kg⁻¹)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Equivalent distance (m)</td>
<td></td>
</tr>
<tr>
<td>Intensity</td>
<td><strong>YES</strong></td>
<td><strong>YES</strong></td>
<td>The average speed is a correct estimate of the intensity only if the speed is constant. In the energy-based approach, the average metabolic power also takes into account the acceleration/deceleration phases.</td>
</tr>
<tr>
<td></td>
<td>Average speed (m·s⁻¹)</td>
<td>Average metabolic power (W·kg⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Intensity distribution</td>
<td><strong>YES</strong></td>
<td><strong>YES</strong></td>
<td>In the energy-based approach, the metabolic power categories also take into consideration the acceleration/deceleration phases, which is not the case for the speed bands.</td>
</tr>
<tr>
<td>Speed bands:</td>
<td>- Total time (s)</td>
<td>- Total time (s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Total distance (m)</td>
<td>- Total distance (m)</td>
<td></td>
</tr>
<tr>
<td>Peak activities</td>
<td><strong>YES</strong></td>
<td><strong>YES</strong></td>
<td>Peak metabolic power takes into account both acceleration and velocity. Peak eccentric mechanical power, as such, is a good index of the mechanical stress on muscles and joints. This is not discussed in the present review.</td>
</tr>
<tr>
<td>Peak speed (m·s⁻¹)</td>
<td>Peak metabolic power (W·kg⁻¹)</td>
<td>Peak eccentric mechanical power (W·kg⁻¹)</td>
<td></td>
</tr>
<tr>
<td>Peak acceleration (m·s⁻²)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Peak deceleration (m·s⁻²)</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High-intensity phases</td>
<td><strong>YES</strong></td>
<td><strong>YES</strong></td>
<td>The parameters estimated from the energy-based approach take into account the physiological characteristics of the player in question. A brief discussion and a few examples are reported in the two sections that follow.</td>
</tr>
<tr>
<td>High-speed phases based on a fixed/individual speed threshold:</td>
<td>- High-speed running time (s)</td>
<td>Anaerobic phases based on the individual VO₂ max:</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- High-speed running distance (m)</td>
<td>- Total time above VO₂ max (s)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Occurrences at high-speed running (#)</td>
<td>- Total distance above VO₂ max (m)</td>
<td></td>
</tr>
<tr>
<td>High acceleration phases based on a fixed/individual acceleration threshold:</td>
<td>- High acceleration time (s)</td>
<td>- High metabolic power events (#)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- High acceleration distance (m)</td>
<td>- Anaerobic energy (J·kg⁻¹)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Occurrences at high acceleration (#)</td>
<td>- Anaerobic index (%)</td>
<td></td>
</tr>
<tr>
<td>Temporal changes (1st half vs 2nd half, 15 min time periods)</td>
<td><strong>YES</strong></td>
<td><strong>YES</strong></td>
<td>The differences between the two approaches in terms of estimated volume and intensity are discussed above</td>
</tr>
<tr>
<td>Trend of volume and intensity parameters</td>
<td></td>
<td>Trend of volume and intensity parameters</td>
<td></td>
</tr>
<tr>
<td>Cost of acceleration/deceleration</td>
<td>NO</td>
<td><strong>YES</strong></td>
<td></td>
</tr>
<tr>
<td>Acceleration relative to the initial speed</td>
<td>NO</td>
<td><strong>YES</strong></td>
<td></td>
</tr>
<tr>
<td>Erraticness</td>
<td>NO</td>
<td><strong>YES</strong></td>
<td>The quality of being erratic (i.e., the opposite of being constant)</td>
</tr>
<tr>
<td>Equivalent distance index (%)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Changing direction</td>
<td>NO</td>
<td><strong>YES</strong></td>
<td>2</td>
</tr>
<tr>
<td>Backward/lateral locomotion</td>
<td>NO</td>
<td><strong>YES</strong></td>
<td>3</td>
</tr>
<tr>
<td>Vertical actions</td>
<td>NO</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>Static activities</td>
<td>NO</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>Collisions/tackles</td>
<td>NO</td>
<td>NO</td>
<td></td>
</tr>
<tr>
<td>Sport-specific skills</td>
<td>NO</td>
<td>NO</td>
<td></td>
</tr>
</tbody>
</table>

¹ They do not consider the starting speed.

² Only the cost of rotation is not considered, whereas deceleration and acceleration are included in the change of direction’s overall cost.

³ The cost of back and lateral locomotion can be corrected for a more accurate estimate of energy expenditure.
The Energy Balance: Aerobic and Anaerobic Energy Yield

Analysis of Fig. 1 allows one to estimate the energy balance over any given time interval of a soccer match or drill. Indeed, the anaerobic energy yield is given by the sum of the dark grey areas, in which the metabolic power requirement (E, black line) is greater than the actual VO₂ (grey line). On the contrary, the aerobic energy yield is given by the time integral below the curve describing the time course of the actual VO₂ (grey line). In turn, this is given by the sum of the white areas, which represent the amount of O₂ consumed whenever the metabolic power requirement (E) exceeds the estimated actual VO₂, and the light grey areas, which represent the amount of O₂ consumed whenever the actual VO₂ exceeds E. As such, the light grey areas indicate time intervals in which a fraction of the O₂ debt is paid at the expense of the oxidative processes that, in these phases, are greater than the metabolic power requirement either during exercise or in the following recovery periods. It can therefore be concluded that the net anaerobic energy contribution during any given time interval is the difference between the dark grey areas representing the aerobic energy deficit (in traditional parlance the O₂ debt incurred) and the light grey areas representing the aerobic energy excess (in traditional parlance the O₂ debt paid).

Whereas the estimate of the overall net anaerobic energy yield seems rather straightforward, its partition into lactic and alactic fractions appears more intricate. Even so, it seems reasonable to suggest that the difference between the O₂ debt incurred and paid, during exercise and in the following recovery period, is proportional to the net amount of lactate produced. An accurate estimate of this difference, on the one hand, together with the assessment of the appropriate blood lactate concentrations on the other, would allow one to verify whether this hypothesis is indeed correct. This seems a formidable task, particularly so because a rough calculation shows that, in view of the large amount of energy spent during a 90-min soccer match, the net energy yield from lactic sources (even assuming a very large lactate accumulation in blood) represents a rather minor fraction of the total. Indeed, the overall energy expenditure during a complete match (average of 497 out of the field players of the Italian “Serie A” during the 2014/2015 season) is on the order of 47.5 kJ·kg⁻¹ (Osgnach et al., in preparation, see also Fig. 4 of the accompanying paper [7]). Hence, even assuming a blood lactate concentration at the end of the match of about 15 mM above resting (a rather extreme possibility), and taking into account the energy equivalent of lactate accumulation in blood (about 65 J·kg⁻¹·mM⁻¹, [6]), the corresponding net energy output can be estimated to be on the order of 1 kJ·kg⁻¹, i.e., about 2% of the total. It goes without saying that, for shorter match spells or drills, things may change substantially.

High-Intensity Versus Low-Intensity Spells

It seems trite to state that soccer, like many team sports, is characterized by frequent high-intensity episodes followed by low-intensity ones. The metabolic power and duration of both high- and low-intensity spells are determined by several factors, such as the role, physical fitness, and technical quality of the player; the time elapsed from match onset; as well as the strategy of the match. The interplay among these different factors is a tangled web and essentially impossible to analyze in detail. Nevertheless, Fig. 1 allows one to quantitatively define the intensity and duration of the high-intensity bouts and the recovery periods that follow, as described below.

Step I (Definition). A given exercise period is considered of “high intensity” (HI) whenever the time integral of the metabolic power curve (black curve in Fig. 1) exceeds a threshold corresponding to the subject’s VO₂ max (18 W·kg⁻¹ above resting, in this specific instance) by a predefined threshold.

Step II (Duration). If these conditions (Step I) are met, the HI bout is assumed to start (and stop) whenever the slope of the metabolic power versus time curve exceeds (or falls below) a predefined value. The time elapsed between these two points sets the HI duration.

Step III (Peak and mean power). Peak and mean power are then easily obtained from the metabolic power curve and the HI duration, as defined above (Step II).

Step IV (Subsequent bouts). Whenever the time interval between two subsequent HI bouts is shorter than a predefined value, they are considered as a single one.

Step V (Low intensity). The intensity and duration of the “low-intensity” (LI) phases are then calculated from the time average of the instantaneous metabolic power of all the periods that do not fall into the HI category and from the corresponding total durations.

In conclusion, the procedure summarized above (Steps I to V), an example of which is graphically represented in Fig. 5, allows one to separate any given period of a soccer match or drill into an appropriate number of HI and LI phases, and to obtain therefrom the corresponding numbers as well as the average duration and metabolic power values.

We would like to stress here that the parameters indicated in Fig. 5 for identifying and characterizing HI and LI bouts must be based on the individual player’s physiological and technical characteristics as well as on his/her role.

For a more detailed discussion of this approach and an overview of the data obtained during official matches, the reader is referred to Osgnach et al. (in preparation). For the reader’s convenience, however, Fig. 6 provides an example that reports the average overall energy expenditure during HI (black dots) and LI (grey dots).
over consecutive 15-min intervals of an entire match (data obtained on 497 outfield players of the Italian “Serie A” during the 2014/2015 season on the basis of the same approach graphically represented in \(\text{Fig. 5}\)). The number of HI and LI spells decreased from 30 in the first period to 26 in the following three and to 24 and 23 in the last two periods, respectively, and the corresponding durations are reported above or below the appropriate dots.

\(\text{Fig. 6}\) shows that the energy expenditure during HI decreases markedly from the first to the last 15-min period, in direct proportion to the number of bouts per period without, however, any substantial changes in the corresponding mean metabolic power, which amounted to about 22 W · kg\(^{-1}\). On the contrary, the overall energy expenditure during LI decreased to a lesser extent, whereas the length of each single bout increased substantially, thus leading to a reduction of the mean metabolic power from about 5.8 W · kg\(^{-1}\) in the first 15-min period to about 4.8 W · kg\(^{-1}\) in the last. This behavior underscores the need for longer recovery periods between HI bouts as the match progresses. It should also be pointed out that the power values reported above are mean values during the HI or LI episodes, whereas the corresponding peak values are not reported here. Finally, whereas the HI bouts correspond only to running bouts, the LI phases include both walking and running episodes.

It can be concluded that inspection and analysis of figures similar to those reported here seem fundamental for assessing the physiological performance of any given player in any given situation. For a further discussion, the reader should refer to Osgnach et al. (in preparation). Nonetheless, it is tempting to speculate that an analysis of the LI periods (in terms of power, energy, duration, and number) seems to be as important as, and perhaps more important than, the analysis of the HI bouts.

**General Discussion and Conclusions**

The time integral of metabolic power as obtained from the approach described in the accompanying paper [7] and of the \(O_2\) consumption estimated therefrom, was assessed during constant-speed walking or running as well as during intermittent spells of accelerated/decelerated running under various conditions. It turned out to be rather close to the overall amount of \(O_2\) consumed simultaneously determined by means of a portable metabolic cart. We therefore think that the disagreement between the energetic parameters estimated from GPS data and the corresponding values obtained by means of portable metabolic carts recently reported by several authors [1,2,4,10] may be due, at least in part, to the fact that the preliminary versions of our approach implicitly assumed that, on the pitch, the players’ displacements occur exclusively running. In addition, these previous versions, at variance with the more recent ones, did not take into consideration the effects of air resistance on the energy cost of running, a fact that is likely responsible for an (albeit minor) underestimate of the metabolic power obtained by means of GPEXE® as compared to that directly determined via metabolic carts.

Another source of disagreement may reflect the fact that the metabolic power and \(O_2\) consumption, as obtained by our approach, refer to the net values (above pre-exercise), whereas the directly measured \(V_\dot{O}_2\) values obviously yield overall gross values. If not properly taken into account, this may lead to substantial differences between estimated and measured values, particularly because pre-exercise \(V_\dot{O}_2\) increases substantially throughout a match or a drill period (e.g., see \(\text{Fig. 3}\)).

A typical example of an in-depth evaluation of the energetics of a soccer match, as obtained from the analysis of 71 matches of the Italian “Serie A” during the 2014/2015 season on 497 players, shows that the average duration of the high-intensity spells declines in number from 30 in the first to 23 in the last 15-min period of the match, even if the average spell intensity is essentially unchanged. This is compensated by a corresponding increase in the duration and decrease in the intensity of the recovery intervals between high-intensity spells.

In conclusion, and in contrast to the data recently reported by several authors, we strongly support the general validity of the proposed model, albeit within the limits discussed above, and we think that it provides an appropriate method for assessing the energetic demands of soccer (and other team sports).

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**Conflict of Interest**

The authors declare their interest in the commercial development and utilization of the system GPEXE® (Exelio srl, Udine, Italy). The data on which this study is based were collected in accordance with the IJSM Ethical Standards [8].
References


