Metabolic Power in Team Sports - Part 1: An Update

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ABSTRACT

Team sports are characterized by frequent episodes of accelerated/decelerated running. The corresponding energy cost can be estimated on the basis of the biomechanical equivalence between accelerated/decelerated running on flat terrain and constant speed running uphill/downhill. This approach allows one to: (i) estimate the time course of the instantaneous metabolic power requirement of any given player and (ii) infer therefrom the overall energy expenditure of any given time window of a soccer drill or match. In the original approach, walking and running were aggregated and energetically considered as running, even if in team sports several walking periods are interspersed among running bouts. However, since the transition speed between walking and running is known for any given incline of the terrain, we describe here an approach to identify walking episodes, thus utilising the corresponding energy cost which is smaller than in running. In addition, the new algorithm also takes into account the energy expenditure against the air resistance, for both walking and running. The new approach yields overall energy expenditure values, for a whole match, ≈ 14 % smaller than the original algorithm; moreover, it shows that the energy expenditure against the air resistance is ≈ 2 % of the total.

Introduction

Soccer, as well as many other team sports, is characterized by frequent episodes of accelerated and decelerated running. These bring about a substantial increase in the overall energy cost of any given fraction of a soccer drill or match, as compared to a similar period of running on flat terrain at the same average speed. In recent years, thanks to the advances in player-tracking technology (e.g., Global Positioning System – GPS) in our knowledge of the energetics of accelerated and decelerated running, it has become possible to: (i) estimate the time course of the instantaneous metabolic power requirement of any given player, and (ii) infer therefrom the time course of actual $O_2$ consumption. Hence, (iii) overall energy expenditure and metabolic power, as well as the aerobic and anaerobic fractions thereof, can be assessed for any given time window of a soccer drill or match [2, 4, 5, 13, 14].

However, the time has come to review the theoretical aspects underlying the approach mentioned above, as well as the practical conclusion that can be obtained therefrom. Specifically, in soccer as in many other team sports, several walking episodes are interspersed among running spells; in the original approach, however, walking and running were aggregated and energetically considered as running. Therefore, because the energy cost of walking is less than that of running and it increases with speed, this paper presents an updated version of the model that allows us to more accurately estimate the energy expenditure during the walking phases. In addition, the updated model will also take into account the energy expenditure against the air resistance.

In the accompanying paper [12], we will show that this upgraded approach, as incorporated into portable GPS devices, allows one to estimate with reasonable accuracy the time course of metabolic power and actual $O_2$ uptake. The information thus obtained can be utilized to assess the overall energy expenditure and the fractions thereof derived from aerobic and anaerobic sources, as well as the duration and metabolic power of high- and low-intensity episodes, thus yielding a more accurate picture of the metabolic load than can be obtained from speed and/or acceleration alone.
Energy Cost of Transport and Metabolic Power

In any form of locomotion, the product of the energy cost of transport, per unit body mass and distance (EC), and the speed (v) yields the energy expenditure per unit of time (Ė) necessary to move at the speed in question, given the corresponding energy cost:

\[ \dot{E} = EC \cdot v \] (1)

Of course the quantities in \( \dot{E} \) must be expressed in coherent units, e.g., if EC is expressed in J·kg\(^{-1}\)·m\(^{-1}\) and v in m·s\(^{-1}\), \( \dot{E} \) will result in W·kg\(^{-1}\); if EC is expressed in ml O\(_2\)·kg\(^{-1}\)·m\(^{-1}\) and v in m·min\(^{-1}\), \( \dot{E} \) will result in ml O\(_2\)·kg\(^{-1}\)·min\(^{-1}\). As such, \( \dot{E} \) is the metabolic power required to reconstitute the ATP utilized for work performance regardless of actual oxygen consumption, which may be equal to, greater than, or less than metabolic power itself.

During constant-speed running on flat, compact terrain, the net energy cost of running (above resting, \( EC_r \)) is independent of the speed and amounts on average to about 4.0 J·kg\(^{-1}\)·m\(^{-1}\) [3, 10]. This is strictly true for treadmill running, in which case the energy to overcome air resistance is nil. For running on the terrain in the absence of wind, the overall \( EC_r \), including the energy expenditure against air resistance, is larger than that applied in treadmill running (\( EC_r\)_TR) by an amount proportional to the square of the air velocity (which in this case is equal to the ground speed, v):

\[ EC_r = EC_r\_TR + k' \cdot v^2 \] (2)

The values of the constant \( k' \) (J·s\(^{-2}\)·m\(^{-3}\)·kg\(^{-1}\)) reported in the literature range from ≈ 0.010 [1, 15] to ≈ 0.019 [16]. This shows that the effects of air resistance are rather small, with the standard deviation ranging between about 5 % [8] and 8 % [3], the individual variability of the energy cost of running is rather small, with values of \( EC_r\_TR \) and \( k' \) shown to have a high reliability [8, 10]. However, in the case of accelerated or decelerated running, which is frequent in soccer, things become more complicated. Under these conditions, direct measurements of energy expenditure are rather problematic because of the massive utilization of anaerobic sources and the resulting short duration of such events, which by their very nature prevent attaining a steady state. Indeed, so far the energy expenditure of accelerated (sprint) running has been estimated only indirectly from biomechanical analyses [4, 10].

An alternative approach, originally proposed by di Prampero et al. in 2005 [5], is to assume that accelerated running on flat terrain is biomechanically equivalent to uphill running at constant speed, the slope being dictated by forward acceleration and that, conversely, during the deceleration phase, it is biomechanically equivalent to running downhill. Indeed, during accelerated running, the runner’s body leans forward so that his/her mean body axis forms an angle (\( \alpha \)) with the terrain that decreases as forward acceleration (\( a_f \)) increases. If the terrain is tilted upwards to bring the runner’s body vertical (\( \alpha = 90\)°), then acceleration becomes equivalent to running at constant speed up an “equivalent slope” (ES), as given by:

\[ ES_{ND} = \tan (90 - \alpha) \] (3)

In fact, the left panel of \( \text{Fig. 1} \) shows that the angle between \( a_f \) and \( g' \) is equal to \( \alpha \), and as a consequence, the angle between \( g \) and \( g' \) is equal to 90 - \( \alpha \). Furthermore, simple geometric considerations show that:

\[ ES_{ND} = \tan (90 - \alpha) = a_f \cdot g^{-1} \] (4)

In \( \text{Eq. (3, 4)} \), the subscript ND (non-drag) indicates that the value thus obtained refers to forward acceleration only without taking into account the effect of air resistance. To overcome the latter, the runner must exert a force proportional to the square of the air velocity. In the absence of wind, in which case air and ground speed are equal, the force is directed horizontally in the forward direction (F):

\[ F = k \cdot v^2 \] (5)

where v is the ground speed and \( k \) is a constant depending on the runner’s frontal area \( (A_f) \), the air density \( (\rho) \) and the drag coefficient \( (C_d) \) (\( k = 0.5 \cdot A_f \cdot \rho \cdot C_d \)), which for subjects of average body size at sea level and 20 °C, amounts to ≈ 0.0037 N·s\(^{-2}\)·kg\(^{-1}\)·m\(^{-2}\) [1, 15]. Also note that the ratio between \( k \) (\( \text{Eq. (5)} \)) and \( k' \) (\( \text{Eq. (2)} \)) yields the mechanical efficiency of work against air resistance; this can therefore be estimated to range between 0.0037/0.010 ≈ 0.37 and 0.0037/0.019 ≈ 0.19.

As mentioned above, the quantity \( k \cdot v^2 \) (\( \text{Eq. (5)} \)) is a measure of the horizontal force exerted by the runner against the air drag per unit body mass (in SI units, N·kg\(^{-1}\)). Hence, based on the fundamental quantities mass (M), distance (d) and time (t):
k · v^2 = F · M^{-1} = (F · d) · (M · d)^{-1} = (M · a · d) · (M · d)^{-1} = d · t^2

it is numerically and dimensionally equal to the mechanical work performed per unit of distance and unit body mass ((Force · d) · (M · d)^{-1}, in SI units, J · kg^{-1} · m^{-1}), i.e., to the forward acceleration (a = d · t^2, in SI units, m · s^{-2}).

To overcome the forward acceleration due to air resistance, the runner must lean forward by an additional amount over and above that calculated by means of \(\text{Eq. (4)}\), which, as mentioned, would apply only if the air resistance were equal to zero. Therefore, in calm air, this is equivalent to an additional "equivalent slope" due to the air drag \(E_{SD}\), as given by:

\[E_{SD} = k · v^2 · g^{-1}\]  \(\text{(6)}\)

where \(v\) is the instantaneous velocity. Hence, the overall equivalent slope is set both by forward acceleration and by air velocity, i.e., by the sum of \(E_{SD}\) (\(\text{Eq. (4)}\)) and \(E_{SO}\) (\(\text{Eq. (6)}\)):

\[E_S = E_{SD} + E_{SO} = a_f · g^{-1} + k · v^2 · g^{-1}\]  \(\text{(7)}\)

During uphill running air resistance leads to an increase of ES, whereas the opposite is true in downhill running. In the latter case, forward acceleration \(a_f\) is negative, whereas \(k · v^2\) always has a positive sign, thus acting as "air assistance" that reduces the muscles' decelerating force. It should also be noted that the effects of air resistance are rather minor compared to those due to forward acceleration: indeed, assuming \(k = 0.0037\), at speeds between 2 and 10 m · s^{-1}, the equivalent slope due to air resistance \(E_{SO}\) ranges from 0.15 to 3.8 %. This is consistent with the usual practice of simulating air resistance when running on the treadmill at speeds < 20 km · h^{-1} (5.55 m · s^{-1}) by inclining it upwards by about 1 %.

Also note that during accelerated running the average force developed by the runner throughout a whole stride, as given by the product of his/her body mass \(M\) and the average acceleration along the body axis, \(F_{acc} = M · g'\), is greater than that developed during constant-speed running \(F_{const} = M · g\) because \(g' > g\) (\(\text{Fig. 1}, \text{left panel})\). Thus, accelerated running is equivalent to uphill running wherein, however, the transported mass is increased above that of the runner’s body in direct proportion to the ratio \(g' · g^{-1}\). Because \(g' = (a_f^2 + g^2)^{0.5}\), this ratio, which will be defined here as “equivalent body mass” \(EM\), is described by:

\[EM = F_{acc} · F_{const}^{-1} = (M · g') · (M · g)^{-1} = (a_f^2 + g^2)^{0.5} · g^{-1} = [(a_f^2 · g^{-2}) + 1]^{0.5}\]  \(\text{(8)}\)

It must also be pointed out that during decelerated running, which is equivalent to downhill running, and in which case forward acceleration \(a_f\) and hence equivalent slope \(ES\), as given by \(\text{Eq. (3)}\), are negative, \(EM\) will nevertheless assume a positive value, because \(a_f < 0\) in \(\text{Eq. (8)}\) is raised to the power of 2.

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, \(\text{Eq. (7, 8)}\) 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 the latter is also known, the corresponding energy cost of accelerated/decelerated running can be easily obtained.

**The energy cost of uphill/downhill running.**

The energetics of running at constant speed on level terrain, uphill or downhill has been extensively investigated since the second half of the 19th century [1, 9]. In 2002 Minetti et al. [11] 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 gradients, the net (above resting) energy cost of running per unit body mass and distance \(E_{CR}\) is independent of the speed and is described by the polynomial equation that follows:

\[E_{CR} = 155.4 · i^5 – 30.4 · i^4 – 43.3 · i^3 + 46.3 · i^2 + 19.5 · i + 3.6\]  \(\text{(9)}\)

where \(E_{CR}\) 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 expression (3.6 · kg^{-1} · m^{-1}) is the energy cost of constant-speed running on compact, flat terrain as determined from the subjects in their study. Thus, substituting \(i\) with the equivalent slope \(ES\), defining \(E_{EC}\) as the energy cost of constant-speed level running, and multiplying by the equivalent body mass \(EM\), \(\text{Eq. (9)}\) can be rewritten as:

\[E_{CR} = (155.4 · E_S^5 – 30.4 · E_S^4 – 43.3 · E_S^3 + 46.3 · E_S^2 + 19.5 · E_S + E_{EC}) · EM\]  \(\text{(10)}\)

This equation 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. The value thus obtained can then be inserted into \(\text{Eq. (1)}\) to estimate the instantaneous metabolic power.

This approach was originally proposed in 2005 by di Prampero et al. [5], who measured the velocity over the first 30 m of a 100 m dash by means of a radar system on 12 medium-level sprinters. The results showed that at the very onset of the sprint, \(E_{CR}\) attained values on the order of 50 J · kg^{-1} · m^{-1}, i.e., about 12 times larger than for constant-speed running on flat terrain, and that the peak metabolic power attained about 1 s after the start was on the order of 80 W · kg^{-1} (230 ml O_2 · kg^{-1} · min^{-1} above resting), i.e., about 4 times larger than the actual VO_{2max} of their subjects. Thus, accelerated running has a profound effect on the underlying energy expenditure; as such it cannot be ignored when dealing with team sports characterized by frequent acceleration/deceleration episodes.

In 2010 Osgnach et al. [13] applied this same approach to data obtained by video analysis over 50 matches on 399 players during the Italian 2007/2008 “Serie A”. The data obtained showed that the average overall energy expenditure, taking into account the acceleration and deceleration phases, was about 61.1 kJ · kg^{-1} · s^{-1}, i.e., 22 % greater as compared to the traditional approach based on speed only (50.8 kJ · kg^{-1} · s^{-1}). Furthermore, whereas the time spent at speeds greater than 16 km · h^{-1} was about 6.3 % of the total time of the match (about 95 min), the overall amount of energy spent...
above a metabolic power threshold of 20 W·kg⁻¹ (i.e., equal to the metabolic power required to run at a constant speed of 16 km·h⁻¹ on flat terrain), turned 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, metabolic power is crucially dependent on both speed and acceleration (e.g.: (i) at 9 km·h⁻¹, the metabolic power is about 10 W·kg⁻¹ when (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; and (ii) at 3 km·h⁻¹, metabolic power is about 2 W·kg⁻¹ when (walking) speed is constant, whereas for an acceleration of ≈ 4 m·s⁻², it rises by a factor of 10, to ≈ 20 W·kg⁻¹).

Osgnach et al. (2010) condensed these considerations in the concept of “equivalent distance” (ED), i.e., the distance that a given player would have run, based on the overall energy expenditure actually measured, had he been running at constant speed throughout the whole match. They showed that the average ED value was on the order of 13.2 km compared to an actual distance of 11.0 km, with the average ratio between ED and the actual distance (defined for convenience as the equivalent distance index, EDI) ≈ 1.20. They also showed that the EDI was substantially different among players, ranging from ≈ 1.15 to ≈ 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 greater the occurrence of high acceleration bouts leading to energy expenditures over and above that of constant-speed running.

The energy cost of uphill/downhill walking

The approach described so far can be meaningfully applied to running; however, during a soccer match, several walking episodes are interspersed among running bouts. Therefore, to obtain a reliable comprehensive estimate of energy expenditure, the walking phases must also be considered. In the studies published so far, at least to our knowledge, walking and running episodes were aggregated, likely leading to an overestimate of the energy expenditure owing to the greater energy cost of running compared to walking. The aim of the section that follows is to show how walking and running can be separately considered, thus yielding a more accurate estimate of the overall energy expenditure.

It will be assumed that, as was the case for running, uphill/downhill walking at constant speed is biomechanically equivalent to accelerated/decelerated walking on flat terrain, so that once the acceleration is known, the corresponding equivalent slope (ES) and equivalent mass (EM) can be easily obtained by means of \( \text{Eq. (7, 8)} \). Unlike running, however, where the energy cost is independent of speed, the energy cost of walking depends on both the incline of the terrain and the speed, as described below.

As was the case for running, the energetics of walking at constant speed, on the level, uphill or downhill, has also been extensively investigated since the second half of the 19th century [1, 9]. These data consistently show that, for any given incline, the energy cost of walking (ECw) attains a minimum at an optimal speed,
above and below which it increases. As shown in \( \text{Fig. 2} \), the optimal speed is on the order of 1.25 m · s\(^{-1}\) for level walking to attain 0.40 m · s\(^{-1}\) for \( i = 40\% \) and 1.5 m · s\(^{-1}\) for \( i = –30\% \) or steeper.

The ECw values at optimal speed for the different inclines reported in \( \text{Fig. 2} \) are rather close to those obtained by Minetti et al. in 2002 [11] for slopes between –0.45 and +0.45. Indeed, these authors showed that the net energy cost of walking (above resting) at the optimal speed depends on the incline of the terrain (i), as described by:

\[
\text{ECw} = 280.5 \cdot i^3 - 58.7 \cdot i^4 - 76.8 \cdot i^3 + 51.9 \cdot i^2 + 19.6 \cdot i + 2.5 \quad (11)
\]

where ECw is expressed in J · kg\(^{-1}\) · m\(^{-1}\) and the last expression (2.5 J · kg\(^{-1}\) · m\(^{-1}\)) is the energy cost of walking at the optimal speed on flat terrain, as determined from the subjects in their study.

For any given incline, and hence equivalent slope (ES), there appears to be a speed value (indicated by the dots in \( \text{Fig. 2} \)) above which the energy cost of walking exceeds that of running. These dots correspond to the speed threshold above and below which un-informed subjects shift spontaneously from walking to running or vice versa: it is reported in \( \text{Fig. 3} \), as described by:

\[
v_{\text{trans}} = -107.05 \cdot i^3 + 113.13 \cdot i^4 - 1.13 \cdot i^3 - 15.84 \cdot i^2 - 1.70 \cdot i + 2.27 \quad (12)
\]

where \( v_{\text{trans}} \) is the transition speed in m · s\(^{-1}\) and ES is the equivalent slope as obtained from \( \text{Eq. (7)} \). It seems fair to point out here that, as shown by Thortensson et al. in 1987 [17], the transition speed from running to walking is about 3 % lower than that from walking to running and that it also depends on the subjects’ size. These differences, however, are unlikely to substantially affect the resulting calculations, and they have therefore been discounted.

\( \text{Eq. (12)} \) allows one to select the energy cost of transport pertaining to the appropriate gait (running or walking). So for speeds \( v_{\text{trans}} \), it is assumed that the energy cost of transport is described by \( \text{Eq. (10)} \), whereas for speeds \( < v_{\text{trans}} \), the energy cost of transport is obtained from \( \text{Fig. 2} \), as described below.

The relationship between energy cost and speed in the walking range, i.e., for a speed lower than that corresponding to the dot on the appropriate function, can be described by a set of fourth-order polynomial equations:

\[
\text{ECw} = a \cdot v^4 + b \cdot v^3 + c \cdot v^2 + d \cdot v + e \quad (13)
\]

The constants a to e are reported in \( \text{Table 1} \) for the indicated incline (i) or equivalent slope (ES) values.

This allowed us to estimate ECw for any given walking speed and the estimated ES values corresponding to the set of inclines reported in \( \text{Table 1} \). In addition, whenever the estimated ES value fell in between any two slopes reported in the table, we estimated the difference between the ECw at the appropriate speed corresponding to the closest higher and lower ES functions. A fraction of this difference (defined as \( \Delta \text{ECw} \)) equal to the fractional difference between the actual and the lower ES was then added to the ECw applying to the estimated lower ES. An example of this set of calculations is reported below.

Assume the instantaneous speed is equal to 1 m · s\(^{-1}\) and ES = 0.24. The ECw values corresponding to the closest lower and higher ES values (0.20 and 0.30) amount to 8.54 and 12.93 J · kg\(^{-1}\) · m\(^{-1}\) (\( \text{Fig. 2} \) and \( \text{Table 1} \)); hence \( \Delta \text{ECw} = 4.39 \) J · kg\(^{-1}\) · m\(^{-1}\). The ECw applicable at the speed of 1 m · s\(^{-1}\) and an ES of 0.24 can now be obtained as follows:

\[
\text{ECw} = 8.54 + 4.39 \cdot (0.24 - 0.20) \cdot (0.30 - 0.20)^{-1} = 10.296 \text{ J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}
\]

In general terms, this equation can be written as follows:

\[
\text{ECw}_{\text{ES}} = \text{ECw}_{\text{ES} + \Delta \text{ECw}} \cdot \text{ES} \cdot (\text{ES} - \text{LES}) \cdot (\text{HES} - \text{LES})^{-1} \quad (14)
\]

where \( \text{ECw}_{\text{ES}} \) and \( \text{ECw}_{\text{ES} + \Delta \text{ECw}} \) are the energy cost of walking at the actual speed and ES, and at the actual speed and lower ES, respectively. \( \Delta \text{ECw} \) has been defined above, and finally, ES, LES and HES represent the actual and the closest lower and higher ES, respectively.

In conclusion, knowledge of the time course of the velocity and the corresponding acceleration allows one to estimate the equivalent slope (ES), from which the appropriate gait can be selected by means of \( \text{Eq. (12)} \). The energy cost of walking can then be estimated for any given speed by inserting the coefficients listed in \( \text{Table 1} \) in \( \text{Eq. (13)} \), and whenever the ES values are different from those reported in the table, by using \( \text{Eq. (14)} \). The ECw value obtained must finally be multiplied by EM (\( \text{Eq. (8)} \)) to obtain the comprehensive value of the energy cost of walking, taking into account speed and acceleration.

\( \text{Fig. 4} \) provides an example. The left panel shows the time course of the speed during 60 s of an actual match; the walking (broken lines) and running (continuous lines) periods are delimited by the open circles that indicate the transitions between the two gaits. The right panel of \( \text{Fig. 4} \) reports the average overall energy expenditure (J · kg\(^{-1}\)) of a whole 90-min match, as obtained from data gathered during the Italian 2014/2015 “Serie A” over 497 players [Osgnach et al., in preparation]. If it is assumed that the players were running throughout, as in the previous versions of the model, the overall energy expenditure (55045 J · kg\(^{-1}\)) turns out to be about 13.7 % greater than that obtained using the updated algorithm that takes into account the different energy cost between the two gaits. Of the total energy expenditure obtained (47492 J · kg\(^{-1}\)), about 74.7 % is due to running and the remaining

\begin{table}[h]
\centering
\begin{tabular}{|c|c|c|c|c|c|}
\hline
\text{i or ES} & a & b & c & d & e \\
\hline
0.00 & 1.25 & -6.57 & 13.14 & -11.15 & 5.35 \\
0.10 & 0.69 & -3.21 & 5.94 & -5.07 & 2.79 \\
0.20 & 0.03 & -0.15 & 0.98 & -2.25 & 3.14 \\
0.30 & 0.28 & -1.66 & 3.81 & -3.96 & 4.01 \\
\hline
\end{tabular}
\caption{The coefficients a to e of \( \text{Eq. 13} \) are reported for the indicated values of the incline (i), or equivalent slope (ES).}
\end{table}

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25.3 % to walking; finally, the energy spent against air resistance (797 J·kg\(^{-1}\)) comes to about 1.7 % of the total energy spent, most of which is obviously due to running. Finally, in this connection, it should be pointed out that a correct estimate of energy expenditure against air drag ought to be based on the effective air velocity, as given by the algebraic sum of the wind and ground speeds rather than on the basis of ground speed alone (which is strictly true only in the absence of wind), as implicitly assumed in the updated algorithm. However, because in team sports athletes move randomly with, against, or across the wind (if present), the resulting net effect is probably very close to that obtained assuming a wind speed of nil. These considerations show that the error introduced assuming that air and ground speed are equal is indeed small, even more so in view of the fact that the energy expenditure against the wind is a very small fraction of the total (see above and Fig. 4).

**General Discussion and Conclusions**

We have previously shown that the energy cost of accelerated/decelerated running on flat terrain can be estimated on the basis of the biomechanical equivalence between accelerated/decelerated running on flat terrain and uphill/downhill running at constant speed [5] and that this approach can be applied to soccer and other team sports [13]. Indeed, by monitoring the players’ speed at 18.18 Hz by means of a GPS system (GPEXE®), it is possible to estimate energy cost, overall energy expenditure and instantaneous metabolic power of any given player, from which the effective \(O_2\) consumption can also be obtained, as shown in the accompanying paper [12]. However, in soccer as in many other team sports, several walking episodes are interspersed among running bouts. Therefore, the approach mentioned above has been extended to include a set of appropriate algorithms allowing us to also estimate the energy cost and hence metabolic power during accelerated/decelerated walking as well as the energy expenditure against air resistance.

The main assumptions underlying this general approach are briefly mentioned and discussed below. Before addressing these questions, however, we would like to point out that, to obtain reasonable results, a great deal of attention should be devoted to the data acquisition characteristics. To this aim, the following main steps must be carefully verified. (A) The number and distribution of the satellites accessible to the GPS system, as well as the intrinsic characteristics of the antenna and amplifier, must be such as to guarantee appropriate signal quality, i.e., the best possible signal-to-noise ratio. (B) When dealing with accelerations, and hence with the variables derived therefrom, any sampling frequency below 10 Hz is highly questionable. In addition, (C) the filtering of the signal must also be appropriately selected so that the analysis is focused on the average acceleration of the center of mass rather than on the accelerations/decelerations occurring within each single stride. Finally, (D) the algorithms utilized to gain information from the data thus obtained must be appropriately controlled and validated.

The energy cost of accelerated/decelerated running is estimated by determining the so-called equivalent slope (ES), as calculated from the instantaneous acceleration using the fifth-order polynomial equation experimentally obtained by Minetti et al. [11], which relates the energy cost to the slope of the terrain during treadmill running. This equation can be meaningfully applied only within the incline (and hence ES) values from which it was obtained (−0.45 to +0.45). Beyond these limits, it is necessary to utilize a linear extrapolation of the energy cost vs. incline function [6]. Furthermore, this equation implies the assumption of a given value for constant-speed running on flat terrain. Theoretically this should be determined for any given subject on the specific terrain in question. Because this is not a realistic possibility, it is generally assumed to be on the order of 4 J·kg\(^{-1}\)·m\(^{-1}\). In addition, the five coefficients of the polynomial equation may be different among different subjects. Again, because it is not possible to determine these individually, they are assumed to be equal to those determined by Minetti et al. [11] on the treadmill. It should also be pointed out that similar caveats apply when dealing with the energy cost of walking.

Finally, we would like to point out that the approach described above does not take into consideration several specific characteristics of soccer, such as jumps, backwards running, running with the ball, kicking the ball or confronting an opponent. Nevertheless, as discussed in detail in the accompanying paper [12], we think that, in terms of the energetics of a match and provided that it is correctly implemented, this approach yields a picture closer to the “truth” than that emerging from more conventional approaches.
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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 [7].

References