UNIVERSITÀ DEGLI STUDI FIRENZE

DOTTORATO DI RICERCA IN
SCIENZE BIOMEDICHE

CICLO XXVII

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Metabolic Power: a new energetic approach in soccer. Match analysis and training evaluation through the use of GPS devices.

Settore Scientifico Disciplinare: **MED09**

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Anni 2012/2014

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INTRODUCTION

Soccer is the most popular sport in the world and is performed by men and women, children and adults with different levels of expertise. Soccer performance depends upon a myriad of factors such as technical/biomechanical, tactical, mental and physiological areas. One of the reasons that soccer is so popular worldwide is that players may not need to have an extraordinary capacity within any of these performance areas, but possess a reasonable level within all areas. However, there are trends towards more systematic training and selection influencing the anthropometric profiles of players who compete at the highest level. As with other activities, soccer is not a science, but science may help improve performance. Efforts to improve soccer performance often focus on technique and tactics at the expense of physical fitness. During a 90-minute game, elite-level players run about 10km at an average intensity close to the anaerobic threshold (80–90% of maximal heart rate). Within this endurance context, numerous explosive bursts of activity are required, including jumping, kicking, tackling, turning, sprinting, changing pace, and sustaining forceful contractions to maintain balance and control of the ball against defensive pressure. The best teams continue to increase their physical capacities, whilst the less well ranked have similar values as reported 30 years ago. Whether this is a result of fewer assessments and training resources, selling the best players, and/or knowledge of how to perform effective exercise training regimens in less well ranked teams, is not known. As there do exist teams from lower divisions with as high aerobic capacity as professional teams, the latter factor probably plays an important role. Distances covered at top level are in the order of 10–12km for the field players, and about 4km for the goalkeeper. Several studies report that the midfield players run the longest distances during a game and that professional players run longer distances than non-professionals. The exercise intensity is reduced and the distance covered is 5-10% less in the second half compared with the first. During a soccer game, a sprint bout occurs approximately every 90 seconds, each lasting an average of 2-4 seconds. Sprinting constitutes 1-11% of the total distance covered during a match corresponding to 0.5-3.0% of effective play time. In the endurance context of the game, each player performs 1000-1400 mainly short activities changing every 4-6 seconds. Activities performed are 10-20 sprints; high-intensity running approximately every 70 seconds; about 15 tackles; 10 headings; 50 involvements with the ball; about 30 passes as well as changing pace and sustaining forceful contraction to maintain balance and control of the ball against defensive pressure. Withers et al. noted that the fullbacks sprinted more than twice as much as the central defenders (2.5 times longer), whilst the midfielders and the attackers sprinted significantly more than central-defenders (1.6 – 1.7 time longer). This is in line with Mohr et al. who reported that fullbacks and attackers sprinted significantly longer than central-backs and midfielders. Strength and power are equally as important as endurance in soccer. Maximal strength refers to the highest force that can be performed by the neuromuscular system during one maximum voluntary contraction (one repetition maximum [1RM]), whereas power is the product of strength and speed and refers to the ability of the neuromuscular system to produce the greatest possible impulse in a given time period. Maximal strength is one basic quality that influences power performance; an increase in maximal strength is usually connected with an improvement of power abilities. A significant relationship has been observed between 1RM and acceleration and movement velocity. This maximal strength/power performance relationship is supported by jump test results as well as in 30m sprint results. By increasing the available force of muscular contraction in appropriate muscles or muscle groups, acceleration and speed may improve in skills critical to soccer such as turning, sprinting and changing pace. High levels of maximal strength in upper and lower limbs may also prevent injuries in soccer. Given this, by identifying some of the aspects affecting physiological traits in soccer (taken from a renowned review published in 2005) the purpose of this study is to highlight a new method of analyzing and evaluating soccer performance parameters from a match analysis point of view and from a training standpoint, based on a different study conducted by Prof. di Prampero on the Theory Model of metabolic power.

1.1 Metabolic Demands

Because of the game duration, soccer is mainly dependent upon aerobic metabolism. The average work intensity, measured as percentage of maximal heart rate (HRmax), during a 90-minute soccer match is close to the anaerobic threshold (the highest exercise intensity where the production and removal of lactate is equal; normally between 80–90% of HRmax in soccer players). It would be physiologically impossible to keep a higher average intensity over a longer period of time due to the resultant accumulation of blood lactate. However expressing game intensity as an average over 90 minutes, or for each half, could result in a substantial loss of specific information. Indeed, soccer matches show periods and situations of high-intensity activity where accumulation of lactate takes place. Therefore, the players need periods of low-intensity activity to remove lactate from the working muscles. In relative terms, there is little or no difference between the exercise intensity in professional and non-professional soccer, but the absolute intensity is higher in professionals. No-one has yet managed to provide accurate and valid data when measuring oxygen uptake (VO2) during a soccer match. The values measured are probably underestimated, since the equipment most likely inhibited the performance. Ogushi et al. used Douglas bags (the equipment weighing 1200g), measuring VO2 in periods of about 3 minutes in two players. They found an average VO2 of 35 and 38 mL/kg/min in the first half and 29 and 30 mL/kg/min in the second. This corresponded to 56–61% and 47–49% of maximal oxygen uptake (VO2max) for the two players in the first and second half, respectively, which is substantially lower than reported in other studies. The distances covered during the VO2 recordings were 11% shorter when compared with those not wearing the Douglas bags, which partly explain the low VO2 values observed. There is good reason to believe that the use of Douglas bags, due to their size (and limited time for gas sampling), reduced the involvement in duels, tackles and other energy-demanding activities in the match, and, thus, underestimated the energy demands in soccer. New portable gas analysers (~500g) allow valid results, but at present no such study has been performed. Establishing the relationship between heart rate (HR) and VO2 during a game allows accurate indirect measurement of VO2 during soccer matches. Establishing each player's relationship between HR and VO2 (the HR–VO2 relationship) may accurately reflect the energy expenditure in steady-state exercise. However, some authors question the HR–VO2 relationship in intermittent exercise. Static contractions, exercise with small muscle groups and psychological and thermal stresses, will elevate the HR at a given VO2; i.e. changing the HR–VO2 line. However, in soccer, with dynamic work with large muscle groups, one might expect the HR–VO2 line to be a good estimate of energy expenditure. Balsom et al. suggested that HR increases disproportionately to the VO2 after sprinting activities. This accounts only for a minor overestimation of the VO2 in soccer, since sprinting accounts for about 1% of the total game time. Bangsbo showed that HR–VO2 line is valid, in intermittent exercise, by comparing intermittent exercise and continuous exercise in a laboratory test on a treadmill. The same HR–VO2 relationship was found over a large range of intensities and is supported by recent data. If we assume that the HR–VO2 line may be used for an accurate estimation of VO2 in soccer, an average exercise intensity of 85% of HRmax will correspond to about 75% of VO2max. This corresponds to an average VO2 of 45.0, 48.8 and 52.5 mL/kg/min for a player with 60, 65 and 70 mL/kg/ min in VO2max, respectively, and probably reflects the energy expenditure in modern soccer. For a player weighing 75kg this corresponds to 1519, 1645 and 1772 kcal expended during a game (1L oxygen/min corresponds to 5 kcal) assuming the following values of 60, 65 and 70 mL/kg/min in VO2max, respectively. In a previous study, we found a difference of about 5 mL/kg/min in running economy between seniors and cadets during treadmill running at 9 km/hour (unpublished data). Running economy is referred to as the ratio between work intensity and VO2. At a given work intensity, VO2 may vary considerably between subjects with similar VO2max. This is also evident in highly trained subjects. In elite endurance athletes with a relatively narrow range in VO2max, running economy has been found to differ as much as 20% and correlate with performance. The causes of inter-individual variations in gross oxygen cost of activity at a standard work-intensity are not well understood, but it seems likely that anatomical trait, mechanical skill, neuromuscular skill and storage of elastic energy are important. In practical terms, 5 mL/kg/min lower VO2 at the same exercise intensity means that the senior players exercised with approximately 10 beats/min less relative to individual HRmax compared with cadets. Alternatively, seniors could exercise at the same relative HR but at a higher absolute exercise intensity. The senior players reached the same relative HR (in percentage of HRmax) as cadets when exercising at approximately 10 km/hour. Thus, a change in exercise intensity of 1 km/hour lead to a change in metabolism of about 5 mL/kg/min and increased the HR by approximately 10 beats/min to cope with the increased energy/oxygen demand. Translating the differences in running speed between seniors and cadets into differences in distance covered during a 90-minute game, yield a difference of about 1500m per player. Although this is a theoretical consideration, Hoff and Helgerud estimated that a 5% improvement in running economy could increase match distance by approximately 1000m. As can be seen from table I there is a large variation in distances covered at different intensities. There are also notable differences between leagues and playing divisions in different countries. This may partly be explained by vague definitions of the intensities described in some studies. To avoid this, game intensity should be expressed as a percentage of HRmax as well as by describing the number and duration of sprints performed and number of involvements with the ball per game, which should be reasonably easy to define regardless of the players' level. To test each player's HRmax, we recommend uphill running either on a treadmill or outdoor. The players should perform a thorough warm-up for about 20 minutes before running two to three 4-minute runs close to maximum effort; in the last run they should run to exhaustion starting from the second minute of submaximal running. The highest HR recorded, by a HR monitor, should be used as the individual's HRmax. For us, this was achievable regardless of age (<12 years) and sex. We highly recommend measuring each player's HRmax, and don't use different available equations as we frequently experience players >35 years and <20 years with HRmax >220 and <180 beats/min, respectively. Using the traditional formula, 220 – age, will in most cases be very misleading. Recently, Strøyer et al. reported that HRs during soccer matches were higher in young elite soccer players than in non-elite counterparts of the same age (12 years). The average HR during games was similar in young elite players in early puberty (177 beats/min in the first half vs 174 in the second half) and end of puberty (178 vs 173 beats/min). Early puberty elite players had higher VO2 related to body mass (mb) [mL/kg/min] than non-elite players during both match halves. The elite players at the end of puberty showed higher absolute VO2 values during match play than young elite players, but identical relative aerobic loads. Finally, with respect to time–motion analysis, the main difference found was that the frequency of standing activity was significantly higher among the non-elite players compared with the elite players. There is a lack of studies addressing the issue of possible cultural and/or geographical differences in distance covered and time spent in different intensity zones, as most research published so far concerns European teams. In this context, Rienzi et al. reported that English premier league players covered about 15km more as a team compared with South American international players. Whether this reflected differences in aerobic capacity or in playing style/tactics is not known. Measuring the exercise intensity and distance covered in several teams from different continents during a world cup in soccer, as well as assessing teams at similar levels from different leagues, could add important knowledge to the physiology of international soccer.

Study	Level/country	Position	n	Distance covered (m) according to mode of movement (numbers/text in parentheses indicate speed)				
				walk	jog	stride/cruise	sprint	back
Bangsbo et al.[7]	Division 1 and 2/Denmark		14	3600^a	5200^b	2100	300	
Castagna et al.[47]	Young/Italy		11	1144^a	3200	986	468	114
Knowles and Brooke[14]	Professional/England		40	1703	2610		520	
Mohr et al.[4]	Division 1/Denmark		24			1900	410	
	Top team/Italy		18			2430	650	
	Combining both teams	FB	9			2460	640	
		CD	11			1690	440	
		M	13			2230	440	
		A	9			2280	690	
Ohashi et al.[15]	League/Japan		4	7709 (0–4 m/sec)		2035 (4–6 m/sec)	589 (6–10 m/sec)	
Reilly and Thomas[9]	Division 1/England	FB	8	2292	2902	1583	783	668
		CB	7	1777	2910	1598	830	651
		M	11	2029	4040	2159	1059	510
		A	14	2309	2771	1755	1066	495
Rienzi et al.[8]	International/SA		17	3251^a	4119^b	923	345	
	EPL/England		6	3068^a	6111^b	887	268	
	International/EPL	D	9	3256^a	4507^b	701	231	
		M	10	3023^a	5511^b	1110	316	
		A	4	3533^a	2746^b	900	557	
Saltin[16]	Non-elite/Sweden		5	2340	5880		2880	
Thatcher and Batterham[18]	EPL first team/England	D	4				253	
	EPL first team/England	M	4				387	
	EPL first team/England	A	4				306	
	EPL U-19/England	D	4	2572	3956		360	1114^c
	EPL U-19/England	M	4	2442	5243		247	1301^c
	EPL U-19/England	A	4	2961	4993		222	803^c
Van Gool et al.[6]	University players/Belgium	D	2	4449 (low)	4859 (medium)		595 (high)	
		M	3	4182 (low)	5704 (medium)		823 (high)	
		A	2	4621 (low)	4333 (medium)		867 (high)	
Wade[20]	Professional/England			1372–3652		229–1829^d		
Whitehead[2]	Division 1/England	M	1	2150	4604	2281	1894	
		D	1	2593	3545	2753	2593	
	Division 2/England	M	1	4910	4183	1096	1007	
		D	1	4190	2966	2079	1591	

Table 1. *Activity profile distances covered in different intensities in male soccer players*

1.2 External load

Match-analysis studies reported that, during a competitive match, a referee can cover a mean distance of 11.5km, with ranges from 9 to 14Km. Of this distance, 16–17% is performed at high intensity or at speeds >15–18 km/hour. Standing is reported to account for 14–22% of match duration. Distances performed sprinting have been shown to range from 0.5% to 12% of total match distance covered by an elite-level soccer referee during actual match play. Analysis of between-halves distance coverage is of great interest as it can reveal the occurrence of fatigue and/or refereeing strategies With respect to this interesting aspect of soccer refereeing performance, there exist conflicting results in the available literature. D'Ottavio and Castagna reported a significant 4% decrease in total distance across halves in Serie A (Italy) soccer referees. In contrast, Krustrup and Bangsbo found no significant difference in total coverage between halves in Danish top-level referees. However, total distance should be considered as only a gross measure of match activity. In this regard, analysis of those activities performed at high intensity during the match may reveal more relevant information in the attempt to assess the likelihood of possible fatiguing processes during the game. High-intensity performance analysis revealed the occurrence of a sort of 'sparing behaviour' in referees who officiated at high competitive level (Italian Serie A championship). In fact, in the study by D'Ottavio and Castagna, no between-half differences in high-intensity coverage were detected despite a significant decrease of total distance. This sort of 'sparing behaviour' has been confirmed in longitudinal studies in the same population of elite-level soccer referees. In contrast, Krustrup and Bangsbo reported a second-half decrement in high-intensity activity, but no between-halves difference in total distance. These findings seem to show that referees officiating at elite level may use different refereeing strategies in order to conserve energy during the game. From a refereeing strategy point of view, it would be advisable to have referees with a well developed ability to perform at high intensity throughout the match. This ability is particularly important for soccer referees as it has been demonstrated that the most crucial outcome-related activities may be revealed at the end of each half, where the likelihood of mental and physiological fatigue is higher. Similar to what was reported for elite-level soccer players, elite-level soccer referees have been reported to change their motor behavior every 4 seconds, performing approximately 1270 activity changes by the end of an average match. Recently, Helsen and Bultynck found that international-level soccer referees, in the attempt to regulate the behaviour of players, undertake 137 observable decisions per match. These results clearly show that elite-level soccer refereeing constitutes a demanding physical and cognitive task.

A NEW MATCH ANALYSIS APPROACH

2.1 Di Prampero's Study: Sprint running: a new energetic approach

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, demonstrated that the average metabolic load of a soccer player is close to 70% of VO2max. 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. 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. Overall, all these methods show that the total estimated energy expenditure during a match ranges from 1200 to 1500 kcal. 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. 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; the results of these studies show that its level during matches ranges from 2 to 10 $mmol \cdot L^{-1}$. 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. 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 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 kmIhj1, 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 or consider indirect estimates of its energetics. However, a new interesting approach is provided by a recent study of Di Prampero et al.,

which shows elements that can be integrated in video match analysis system.

The Study

Since the second half of the 19th century, the energetics and biomechanics of running at constant speed have been the object of many studies, directed towards elucidating the basic mechanisms of this most natural form of locomotion; but the results of these studies have also had direct practical applications, e.g. for the assessment of the overall metabolic energy expenditure, or for the prediction of best performances (e.g. see Alvarez-Ramirez, 2002; Lacour et al., 1990; Margaria, 1938; Margaria et al., 1963; Péronnet and Thibault, 1989; Di Prampero et al., 1993; Ward-Smith, 1985; Ward-Smith and Mobey, 1995; Williams and Cavanagh, 1987). In contrast to constant speed running, the number of studies devoted to sprint running is rather scant. This is not surprising, since the very object at stake precludes reaching a steady state, thus rendering any type of energetic analysis rather problematic. Indeed, the only published works on this matter deal with either some mechanical aspects of sprint running (Cavagna et al., 1971; Fenn, 1930a,b; Kersting, 1998; Mero et al., 1992; Murase et al., 1976; Plamondon and Roy, 1984), or with some indirect approaches to its energetics (Arsac, 2002; Arsac and Locatelli, 2002; van Ingen Schenau et al., 1991, 1994; di Prampero et al., 1993; Summers, 1997; Ward-Smith and Radford, 2000). The indirect estimates of the metabolic cost of acceleration reported in the above-mentioned papers are based on several assumptions that are not always convincing. In the present study we therefore propose a novel approach to estimate the energy cost of sprint running, based on the equivalence of an accelerating frame of reference (centred on the runner) with the Earth's gravitational field. Specifically, in the present study, sprint running on flat terrain will be viewed as the analogue of uphill running at constant speed, the uphill slope being dictated by the forward acceleration (di Prampero et al., 2002). Thus, if the forward acceleration is measured, and since the energy cost of uphill running is fairly well known (e.g. see Margaria, 1938; Margaria et al., 1963; Minetti et al., 1994, 2002), it is a rather straightforward matter to translate the forward acceleration of sprint running into the corresponding up-slope, and thence into the corresponding energy cost. Knowledge of this last and of the instantaneous forward speed will then allow us to calculate the corresponding metabolic power, which is presumably among the highest values attainable for any given subject.

Theory

In the initial phase of sprint running, the overall acceleration acting on the runner's body (g') is the vectorial sum of the

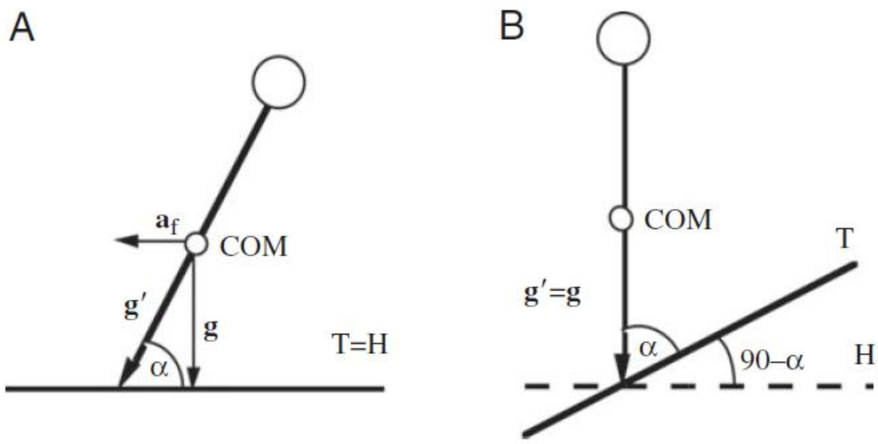


Fig.·1. Simplified view of the forces acting on a runner. The subject is accelerating forward while running on flat terrain (A) or running uphill at constant speed (B). The subject's body mass is assumed to be located at the centre of mass (COM); af=forward acceleration; g=acceleration of gravity; $g'=(a_f^2+g^2)^{0.5}$ is the acceleration resulting from the vectorial sum of af plus g; T=terrain; H=horizontal; α (=arctan g/a_f) is the angle between runner's body and T; the angle between T and H is α'=90–α. (Modified from di Prampero et al., 2002.)

forward acceleration (af) and the Earth's acceleration of gravity (g), both assumed to be applied to the subject's centre of mass (COM; Fig.·1A):

$$g' = (a_f^2 + g^2)^{0.5}. \qquad (1)$$

To maintain equilibrium, the angle α between g' (which is applied along a line joining the point of contact foot–terrain with the runner's body COM) and the terrain must be given by:

$$\alpha = \arctan g / a_f. \qquad (2)$$

This state of affairs is analogous to that applying if the subject were running uphill at constant speed, in which case the overall average acceleration (g') is assumed to be applied vertically (Fig. 1B). Indeed, if g' is tilted upwards, so as to render it vertical, to maintain constant the angle of g' with the terrain (α), the latter must also be tilted upwards, with respect to the horizontal, by the same amount. Inspection of Fig.1 makes it immediately apparent that the angle between the horizontal and the terrain (α'), due to the forward acceleration yielding the angle α between g' and the terrain, is given by:

$$\alpha' = 90 - \alpha = 90 - \arctan g / a_f . \qquad (3)$$

The slope equivalent to the angle α' (equivalent slope, ES) is therefore given by the tangent of the angle α' itself:

$$ES = \tan (90 - \arctan g / a_f). \qquad (4)$$

In addition, during sprint running, the average force exerted by active muscles during the stride cycle (F'=equivalent body weight) is given by:

$$F' = M_b g', \qquad (5)$$

where M_b is the runner's body mass. When running at constant speed, the average force (F) corresponds to the subject's body weight:

$$F = M_b g \,. \qquad (6)$$

The ratio of Eq.·5 to Eq.·6

$$F' / F = g' / g \qquad (7)$$

shows that, during sprint running, the equivalent body weight (F′=the average force generated by the active muscles) is equal to that required to transport, at constant speed on the Earth, the same mass (M_b) multiplied by the ratio g′/g. This ratio will here be called 'equivalent normalised body mass' (EM). Thus, from Eq.·1:

$$EM = g' / g = (a_f^{\,2} / g^2 + 1)^{0.5} \,. \qquad (8)$$

Summarising, sprint running can be considered equivalent to constant speed running on the Earth, up an equivalent slope ES, while carrying an additional mass $\Delta M = M_b(g'/g-1)$, so that the overall equivalent mass EM becomes $EM = \Delta M + M_b$. Both ES and EM are dictated by the forward acceleration (Eq.·4, 8); therefore they can be easily calculated once a_f is known. The values of ES and EM so obtained can then be used to infer the corresponding energy cost of sprint running, provided that the energy cost of uphill running at constant speed per unit body mass is also known. It should be pointed out that the above analogy is based on the following three simplifying assumptions, which will be discussed in the appropriate sections. Fig. 1 is an idealized scheme wherein the overall mass of the runner is assumed to be located at the centre of mass. In addition, Fig. 1

refers to the whole period during which one foot is on the ground, as such it denotes the integrated average applying to the whole step (half stride). The calculated ES and EM values are those in excess of the values applying during constant speed running, in which case the subject's body is not vertical, but leans slightly forward (Margaria, 1975).

Aims

The aim of the present study was that to estimate the energy cost and metabolic power of the first 30·m of an all-out run from a stationary start, from the measured forward speed and acceleration.

Methods and calculations

The experiments were performed on an outdoor tartan track of 100·m length, at an average barometric pressure and temperature of about 740·mmHg and 21°C, using 12 medium-level male sprinters. The subjects were informed on the aims of the study and gave their written consent to participate. The instantaneous speed of the initial 30 m of an all-out run from regular starting blocks was continuously determined by means of a radar Stalker ATS System™ (Radar Sales, Minneapolis, MN, US) at a sampling frequency of 35 Hz. Raw speed data were filtered (by a fourth order, zero lag, Butterworth filter) using the ATS System™ acquisition software. The radar device was placed on a tripod 10 m behind the start line at a height of 1 m, corresponding approximately to the height of the subject's center of mass. To check the reliability of the radar device, the 12 subjects performed an entire 100 m run. The times obtained on each 10 m section (t_{radar}) were compared to those obtained over the same sections by means of a photocell system (t_{cells}). The two sets of data were essentially identical:

$$t_{radar} = 1.01t_{cells} - 0.06;\ r^2 = 0.99;\ N{=}120;\ P{<}0.01, \qquad (9)$$

thus confirming a previous validation carried out by Chelly and Denis (2001) on moving objects. The speed–time curves were then fitted by an exponential function (Chelly and Denis, 2001; Henry, 1954; Volkov and Lapin, 1979):

$$s(t) = s_{max} * (1 - e^{-t/\tau}), \qquad (10)$$

where s is the modelled running speed, s_{max} the maximal velocity reached during the sprint, and τ the time constant. Typical tracings of the measured or modelled speeds so obtained are reported in Fig. 2 as a function of time. Since the exponential model described the actual running speeds accurately (see Discussion and Fig. 3), the instantaneous forward acceleration was then calculated from the first derivative of Eq. 10:

$$a_f(t) = ds / dt = [s_{max} - s_{max} * (1 - e^{-t/\tau})] / \tau\ . \qquad (11)$$

This is plotted in Fig.·4 as a function of the distance (d, m) of the run, as obtained from the time integral of Eq. 10:

$$d(t) = s_{max} * t - [s_{max} * (1 - e^{-t/\tau})] * \tau\ . \qquad (12)$$

The individual values of speed and acceleration were calculated for each subject over one run. The values so obtained were then pooled and the means calculated. Values are reported as means ± 1 standard deviation (S.D.), where N=12. The individual values of ES (Eq. 4) and EM (Eq. 8) were also obtained for all subjects from the forward acceleration. This allowed us to calculate the energy cost of sprint running with the aid of the data of literature. Indeed, as reported by Minetti et al. (2002) for slopes from –

0.45 to +0.45, the energy cost of uphill running per unit of distance along the running path C (J kg^{-1} m^{-1}), is described by:

$$C = 155.4x^5 – 30.4x^4 – 43.3x^3 + 46.3x^2 + 19.5x + 3.6, \quad (13)$$

where x is the incline of the terrain, as given by the tangent of the angle α' with the horizontal (see Eq. 3 and Fig. 1B). Thus, the estimated energy cost of sprint running (C_{sr}) can be calculated replacing x in the above equation with the calculated values of ES (Eq. 4) and multiplying the sum of the indicated terms by EM (Eq. 8):

$$Csr = (155.4ES^5 – 30.4ES^4 – 43.3ES^3 + 46.3ES^2 + 19.5ES + 3.6)EM. \quad (14)$$

It is also immediately apparent that, when ES=0 and EM=1, C_{sr} reduces to that applying at constant speed running on flat terrain, which amounted to about 3.6 J kg^{-1} min^{-1} (Minetti et al., 2002), a value close to that reported by others (e.g. see Margaria et al., 1963; di Prampero et al., 1986, 1993).

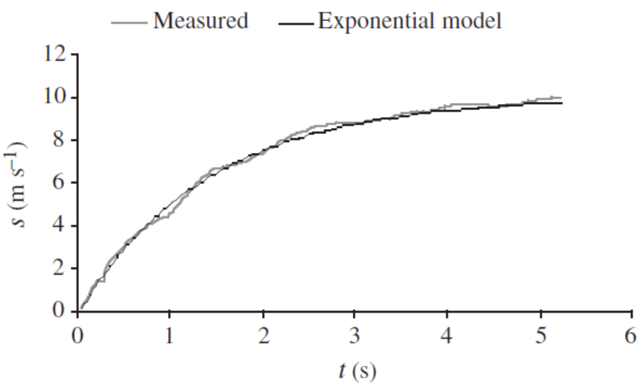


Fig.·2. Actual (gray, thick line) and modelled (black, thin line) forward speed s (m s^{-1}) as a function of time t (s) at the onset of a typical 100 m run for subject 7. Actual speed was accurately described by: $s(t)=10.0*(1–e^{-t/1.42})$. The maximal speed ($s_{max}$) was 10.0·m s^{-1}.

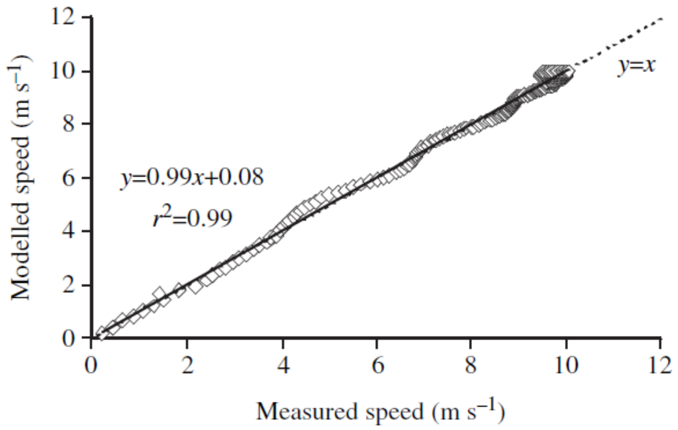


Fig.·3. Running velocity as calculated by the exponential model, as a function of the actual running speed for Subject 7. The linear relationship is reported in the figure (N=234); identity line is also shown.

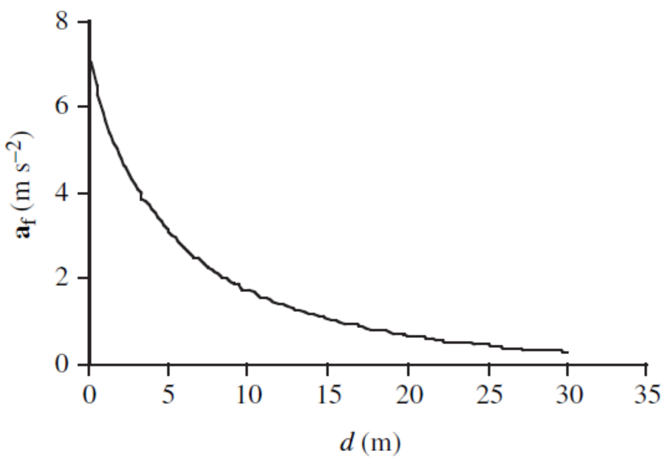


Fig.·4. The instantaneous forward acceleration af (m s^{-2}), obtained as described in the text, is plotted as a function of the distance d (m) for subject 7.

Result

The speed increased to attain a peak of 9.46±0.19 m s^{-1} about 5 s from the start. The highest forward acceleration was observed immediately after the start (0.2 s): it amounted to 6.42±0.61 m s^{-2}. The corresponding peak ES and EM values amounted to 0.64±0.06 and to 1.20±0.03 (Table·2). The behavior of ES and EM, throughout the entire acceleration phase for a typical subject, as calculated from af (see Fig. 4) on the bases of Eq. 4 and 8, is reported in Fig. 5, which shows that, after about 30 m, ES tended to zero and EM to one, which correspond to constant speed running. The energy cost of sprint running (C_{sr}), as obtained from Eq. 13 on the basis of the above calculated ES and EM, is reported in Fig. 6 for a typical subject. This figure shows that the instantaneous C_{sr} attains a peak of about 50 J kg^{-1} m^{-1} immediately after the start; thereafter it declines progressively

	s (m s^{-1})	a_f (m s^{-2})	ES	EM
Mean	9.46	6.42	0.64	1.20
S.D.	0.19	0.61	0.06	0.03
CV	0.020	0.095	0.091	0.025

S.D., standard deviations; CV, coefficient of variation. N=12 throughout.

Table·2. Grand averages of peak values of speed (s), forward acceleration (af), equivalent slope (ES) and equivalent body mass (EM)

to attain, after about 30 m, the value for constant speed running on flat terrain (i.e. about 3.8 J kg^{-1} m^{-1}). This figure shows also that ES is responsible for the greater increase of C_{sr} whereas EM plays only a marginal role. Finally, Fig. 6 also shows that the average C_{sr} over the first 30 m of sprint running in this subject is about 11.4 J kg^{-1} m^{-1}, i.e. about three times larger than that of constant speed running on flat terrain. The product of C_{sr} and the speed yields the instantaneous metabolic power output above resting; it is reported as a function of time for the same subject in Fig. 7, which shows that the peak power output, of about 100 W kg^{-1}, is attained after about 0.5 s and that the average power over the first 4 s is on the order of 65 W kg^{-1}.

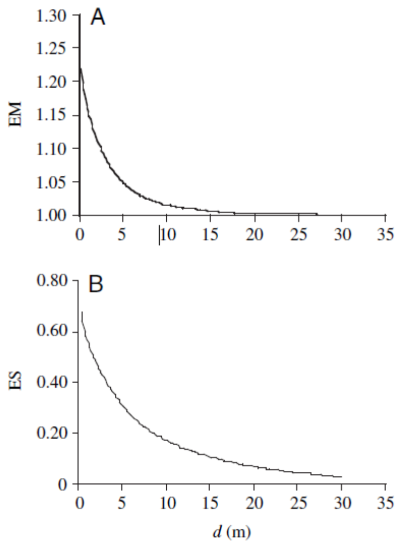


Fig. 5. Equivalent body mass (EM; A) and equivalent slope (ES; B), as a function of the distance d (m) for subject 7.

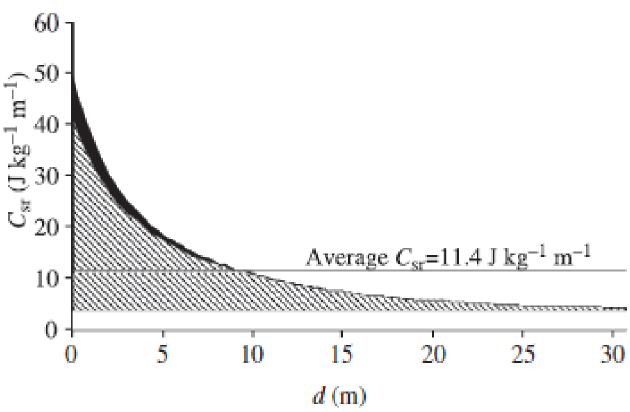


Fig. 6. Energy cost of sprint running C_{sr} (J kg^{-1} m^{-1}), as calculated by means of Eq. 14, as a function of the distance d (m) for subject 7. Energy cost of constant speed running is indicated by the lower horizontal thin line. Black and hatched distances between appropriate lines indicate effects of EM and ES, respectively. Upper horizontal thin line indicates average C_{sr} throughout the indicated distance.

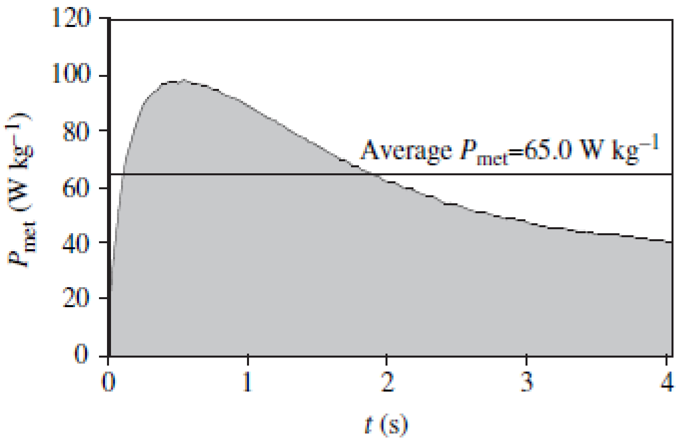


Fig. 7. Metabolic power Pmet (W kg^{-1}), as calculated from the product of C_{sr} (see Fig. 6) and the speed, as a function of time t (s) for subject 7. Average power over 4 s is indicated by horizontal thin line.

Discussion: Critique of methods

The instantaneous values of forward acceleration were obtained from the first derivative of exponential equations describing the time course of the speed. Linear regressions between measured and modelled speed values (Fig. 3) were close to the identity line for all 12 subjects ($r2>0.98$; $P<0.01$), showing the high accuracy of this kind of speed modelling during sprint running (Chelly and Denis, 2001; Henry, 1954; Volkov and Lapin, 1979). Even so, it should be noted that: (i) at the start of the run the centre of mass is behind the start line and (ii) whereas the centre of mass rises at the very onset of the run, the radar device does not; as a consequence, (iii) the initial speed data are slightly biased. However, after a couple of steps this effect becomes negligible, as such it will not be considered further. Finally, it should also be pointed out that filtering the raw speed data, while retaining the general characteristics of the speed vs time curve (Fig. 3), leads to substantial smoothing of the speed swings that occur at each step and are a fundamental characteristic of locomotion on legs. The number of subjects of this study (12) may appear small. However the coefficients of variation of peak speeds and peak accelerations for this population (0.02 and 0.095) were rather limited, and the subjects were homogeneous in terms of performance (Tables 1, 2). Finally, the present approach is directed at obtaining a general description of sprint running, rather than at providing accurate statistical descriptions of specific groups of athletes. The main assumptions on which the calculations reported in the preceding sections were based are reported and discussed below. (1) The overall mass of the runner is assumed to be located at the centre of mass of the body. As such, any possible effects of the motion of the limbs, with respect to the centre of mass, on the energetics of running were neglected. This is tantamount to assuming 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, since the frequency of motion is larger during sprint than during uphill running. If this is so, the values obtained in this study can be taken to represent a minimal value of the energy cost, or metabolic power, of sprint running. (2) The average force applied by the active muscles during the period in which one foot is on the ground is assumed to be described as in Fig. 1B, thus neglecting any components acting in the frontal plane. In addition, the assumption is also made that the landing phase (in terms of forces and joint angles) is the same during uphill as during sprint running at similar ES, a fact that may not be necessarily true, and that may warrant ad hoc biomechanical studies. (3) The calculated ES and EM values are assumed to be in excess of those applying during constant speed running, in which case the subject’s body is not vertical, but leans slightly forward (Margaria,

1975) and the average force required to transport the runner's body mass is equal to that prevailing under the Earth's gravitational field. Indeed, the main aim of this study was to estimate the energy cost and metabolic power of sprint running, and since our reference was the energy cost of constant speed running per unit body mass, the above simplifying assumptions should not introduce any substantial error in our calculations. (4) The energy cost of running uphill at constant speed, as measured at steady state up to inclines of +0.45, was taken to represent also the energy cost of sprint running at an equal ES. Note that the energy cost of running per unit of distance, for any given slope, is independent of the speed (e.g. see Margaria et al., 1963; di Prampero et al., 1986; 1993). Thus the transfer from uphill to sprint running can be made regardless of the speed. Even so, the highest values of ES attained by our subjects (about 0.70) were greater than the highest slopes for which the energy cost of uphill running was actually measured (0.45). Thus the validity of our values for slopes greater than 0.45 is based on the additional assumption that, also above this incline, the relationship between C_{sr} and ES is described by Eq. 14. Graphical extrapolation of the Minetti et al. (2002) equation does seem to support our interpretation of their data; however, stretching their applicability as we did in the present study may seem somewhat risky. We would like to point out, however, that the above word of caution applies only for the peak C_{sr} and metabolic power values, i.e. to the initial 3 m (Fig. 5), which represent about 1/10 of the distance considered in this study. Thus, the majority of our analysis belongs to a more conservative range of values. (5) Minetti et al. (2002) determined the energy cost of uphill running from direct oxygen uptake measurements during aerobic steady state exercise. In contrast, the energy sources of sprint running are largely anaerobic. It follows that the values of C_{sr} and metabolic power (P_{met}), as calculated in this study, should be considered with caution. Indeed, they are an estimate of the amount of energy (e.g. ATP units) required during the run, expressed in O_2 equivalents. The overall amount of O_2 consumed, including the so-called 'O_2 debt payment' for replenishing the anaerobic stores after the run, may well be different, a fact that applies to any estimate of energy requirement during 'supramaximal exercise'. Finally, the calculated values of C_{sr} and P_{met} represent indirect estimates rather than 'true' measured values. However, the actual amount of energy spent during sprint running cannot be easily determined with present day technology, thus rendering any direct validation of our approach rather problematic. However, in theory at least, computerised image analysis of subjects running over series of force platforms could be coupled with the assessment of the overall heat output by means of thermographic methods. Were this indeed feasible, one could obtain a complete energetic description of sprint running to be compared with the present indirect approach.

Metabolic power of sprint running

The peak metabolic power values reported in Table 3 are about four times larger than the maximal oxygen consumption (V_{O2max}) of elite sprinters which can be expected to be on the order of 25 W kg^{-1} (70 ml O_2 kg^{-1} min^{-1} above resting). This is consistent with the value estimated by Arsac and Locatelli (2002) for sprint elite runners, which amounted to about 100 W kg^{-1}, and with previous findings showing that, on the average, the maximal anaerobic power developed while running at top speed up a normal flight of stairs is about four times larger than V_{O2max} (Margaria et al., 1966). The same set of calculations was also performed on one athlete (C. Lewis, winner of the 100 m gold medal in the 1988 Olympic games in Seoul with the time of 9.92 s) from speed data reported by Brüggemann and Glad (1990). The corresponding peak values of ES and EM amounted to 0.80 and 1.3, whereas the peak C_{sr} and metabolic power attained 55 J kg^{-1} m^{-1} and 145 W kg^{-1}. The overall amount of metabolic energy s pent over 100 m by C. Lewis was also calculated by this same approach. It amounted to 650 J kg^{-1}, very close to that estimated for world record performances by Arsac (2002) and Arsac and Locatelli (2002). However, these same authors, on the basis of a theoretical model originally developed by van Ingen Schenau (1991), calculated a peak metabolic power of 90 W kg^{-1} for male world records, to be compared with the 145 W kg^{-1} estimated in this study for C. Lewis. The model proposed by van Ingen Schenau is based on several assumptions, among which overall running efficiency plays a major role. Indeed, the power values obtained by Arsac and Locatelli (2002) were calculated on the bases of an efficiency (η) increasing with the speed, as described by η_t=0.25+0.25. v_t/v_{max} where η_t and v_t are efficiency and speed at time *t*, respectively, and V_{max} is the maximal speed. However, Arsac and Locatelli point out that, if a constant efficiency of 0.228 is assumed, then the estimated peak metabolic power reaches 135 W kg^{-1}, not far from that obtained above for C. Lewis. Thus, in view of the widely different approaches, we think it is the similarity between the two sets of estimated data that should be emphasized, rather than their difference.

Mean		Peak	
C_{sr}	P_{met}	C_{sr}	P_{met}
(J kg^{-1} m^{-1})	(W kg^{-1})	(J kg^{-1} m^{-1})	(W kg^{-1})
10.7+0.59	61.0±4.66	43.8±10.4	91.9±20.5

C_{sr}, energy cost of sprint running; P_{met}, metabolic power.
Values are means ± S.D. Mean C_{sr} was calculated over 30 m and mean P_{met} over 4 s.

Table 3. Peak and mean energy cost of sprint running and metabolic power for the 12 subjects.

Energy balance of sprint running

It is now tempting to break down the overall energy expenditure of 650 J kg^{-1} needed by C. Lewis to cover 100 m in 9.92 s, into its aerobic and anaerobic components. To this end we will assume that the maximal O_2 consumption (V_{O2max}) of an élite athlete of the caliber of Lewis amounts to 25 W kg^{-1} (71.1 ml O_2 kg^{-1} min^{-1}) above resting. We will also assume that the overall energy expenditure (E_{tot}) is described by:

$$E_{tot} = A_{ns} + V_{O2max} t_e - V_{O2max}(1-e^{-te/\tau})\tau\,, \qquad (15)$$

where t_e is the performance time, A_{ns} is the amount of energy derived from anaerobic stores utilisation and τ is the time constant of the V_{O2} response at the muscle level (Wilkie, 1980; di Prampero, 2003). The last term of this equation is the O_2 debt incurred up to the time t_e, because V_{O2max} is not reached instantaneously at work onset, but with a time constant τ; therefore, the overall amount of energy that can be obtained from aerobic energy sources is smaller than the product $V_{O2max}t_e$, by the quantity represented by the third term of the equation. In the literature, the values assigned to τ range from 10 s (Wilkie, 1980; di Prampero et al., 1993) to 23 s (Cautero et al., 2002). So, since in case of C. Lewis, Etot=650 J kg^{-1} and V_{O2max}=25 W kg^{-1}; A_{ns} (calculated by Eq. 15) ranged from about

560 J kg^{-1} (for τ=10 s) to about 600 J kg^{-1} (for τ=23 s). Thus, for an élite athlete to cover 100 m at world record speed the anaerobic energy stores must provide an amount of energy on the order of 580 J kg^{-1}. Unfortunately we cannot partition this amount of energy into that produced from lactate accumulation and that derived from splitting phosphocreatine (PCr). However, we can set an upper limit to the maximal amount of energy that can be obtained from A_{ns} as follows. Let us assume that the maximal blood lactate concentration in an élite athlete can attain 20 mmol l^{-1}. Thus, since the accumulation of 1 mmol l^{-1} lactate in blood is energetically equivalent to the consumption of 3 ml O_2 kg^{-1} (see di Prampero and Ferretti, 1999), the maximal amount of energy that can obtained from lactate is about:

$$20 \times 3 \times 20.9 \approx 1250 \text{ J kg}^{-1}, \qquad (16)$$

(where 20.9 J ml^{-1} is the energetic equivalent of O_2). The maximal amount of PCr that can be split from rest to exhaustion in an all-out effort can be estimated to be about 22 mmol kg^{-1} of fresh muscle (see Francescato et al., 2003). We can assume that the muscle mass involved in the all-out effort in question, for an élite sprinter, is about 25% of his body mass (e.g. about 25 kg of muscle). If this is so, and since to spare 1 mmol O2 the amount of PCr that needs to be split is about 6 mmol, which corresponds to a P/O_2 ratio of 6.0, the amount of energy yielded per kg body mass by complete splitting of PCr in the maximally active muscles can be calculated as:

$$0.25 \times 22 \times 1/6 \times 22.4 \bullet 20.9 \approx 430 \text{ J kg}^{-1}, \qquad (17)$$

where 22.4 is the volume (ml, STPD) of 1 mmol O_2. Thus the maximal amount of energy that can be obtained at exhaustion from the complete utilization of anaerobic stores amounts to:

$$1250 + 430 = 1680 \text{ J kg}^{-1}. \qquad (18)$$

It can be concluded that the amount of energy derived from A_{ns} during a 100 m dash in a top athlete is about 1/3 of the total, which is consistent with the fact that longer events (200 m or 400 m) are covered at essentially the same, largely anaerobic, speed.

Conclusion

The above analysis and calculations allow us to condense the factors affecting the instantaneous energy cost of sprint running into one comprehensive formula:

$$C_{sr} = (155.4ES^5 – 30.4ES^4 – 43.3ES^3 + 46.3ES^2 + 19.5ES + 3.6)EM + k'v^2, \qquad (19)$$

where all terms have been previously defined. The corresponding metabolic power (P_{met}) is described by the product of Eq. 19 and the ground speed (s):

$$P_{met} = C_{sr} * s = (155.4ES^5 – 30.4ES^4 – 43.3ES^3 + 46.3ES^2 + 19.5ES + 3.6)EMs + k'v^2s. \qquad (20)$$

When, as is often the case, the sprint occurs in calm air and hence v=s, these two equations can be easily solved at any point in time, provided that the time course of the ground speed is known.

2.2 Energy Cost and Metabolic Power in soccer

Given what I mentioned above, Di Prampero's equipe have enlarged and improved their study on soccer performance analysis by comparing it with traditional match analysis video footage. 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 T 4 yr, mass = 75.8 T 5.0 kg, and stature = 1.80 T 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. 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.

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 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. and considered by di Prampero et al. 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. 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:

$$\mathrm{ED} = \frac{W}{\mathrm{EC}_C \mathrm{KT}}$$

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}Imj1, and KT is the grassy terrain constant.

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

$$\mathrm{EDI} = \frac{\mathrm{ED}}{\mathrm{TD}}$$

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 V_{O2max} or to anaerobic threshold) and the total energy expenditure over the whole match or in the period considered:

$$AI = \frac{\sum W_{TP}}{\sum W}$$

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 V_{O2} of approximately 57 mL kg^{-1} min^{-1}, above resting.

Result

The mean match time of the players was 95 min 5 s ± 1 min 40 s compared with the standard duration of an 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 4 (absolute values) and Figure 8 (%).

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 5 (absolute values) and Figure 9 (%).

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 6 (absolute values) and Figure 10 (%).

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 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.

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

Table 4. T (s) and D (m) during the entire match in each speed category (mean T SD).

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

Table 5. T (s), D (m), and corresponding EC (J kg^{-1} m^{-}1) during the entire match in each acceleration category (mean T SD). 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).

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

Table 6. T (s), D (m), and EEE (kj kg^{-1} or kcal kg^{-1}) during the entire match in each power category (mean T SD).

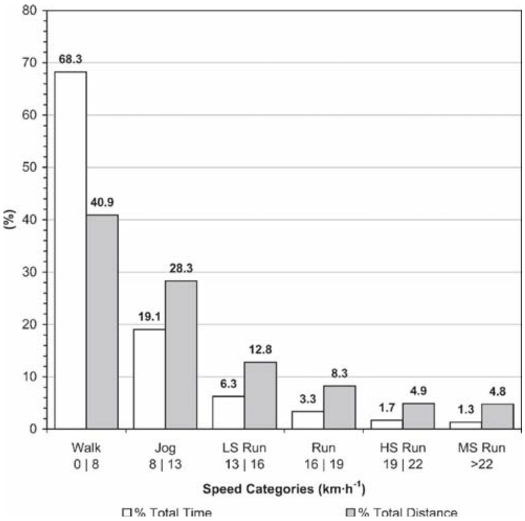


Fig 8. T and D (%) during the entire match in each speed category.

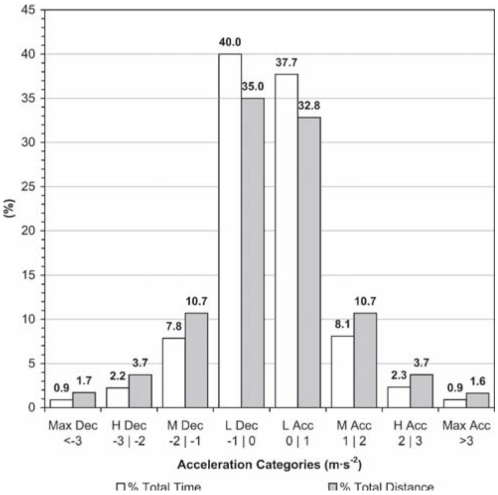


FIGURE 9. T and D (%) during the entire match in each acceleration category.

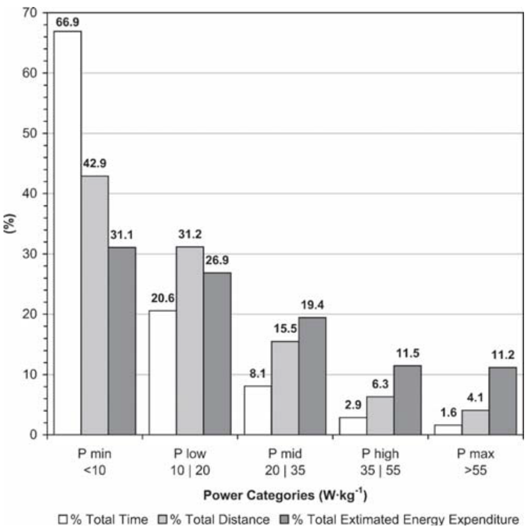


Figure 10. T, D, and EEE (%) during the entire match in each power category.

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

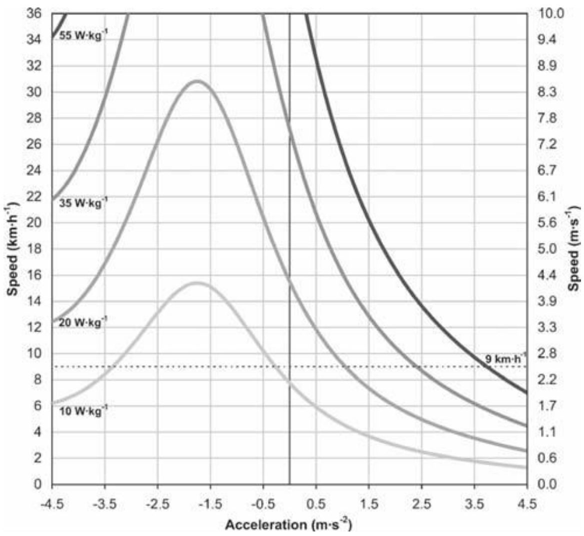


FIGURE 11—Isopower relationships calculated as function of speed (y-axis) and acceleration (x-axis). A speed of 9 kmlhj1 (horizontal sketched line) yields different power outputs depending on acceleration. For example, at a constant speed (9 kmlhj1), the metabolic power would amount to approximately 13 Wlkgj1, whereas at the same speed, but with an acceleration of 1 or 2.4 mlsj2, the metabolic power would increase to 20 or to 35 Wlkgj1. 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., 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 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. 11).

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 916 km h^{-1} amounts to approximately 18% of TD (Table 4). The metabolic power when running on a soccer field at 16 km h^{-1} amounts to:

$$P = EC_v KT = 3.6 \text{ X } 4.44 \text{ X } 1.29 \; \tilde{=} \; 20 \text{ W kg}^{-1}$$

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 6). 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 12, on average, ED is linearly related to TD, being approximately 20% higher. However, upon closer inspection of Figure 12, it becomes apparent that the EDI, that is, the ratio between ED and TD (isopleths of Fig. 12), for a given TD varies substantially among players, the ‘‘lazy players’’ being characterized by EDI ; 1.15, their more dynamic fellow mates reaching EDI values of approximately 1.30 (Fig. 13). 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 V_{O2} of approximately 57 mL kg^{-1} min^{-1} above resting). So defined, AI ranged from 0.15 to 0.25 (Fig. 14), 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 14 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, 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 5), we assumed that the same algorithm used for estimating EC was also applicable for ES 9 +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 represents the EC above resting metabolism. The evaluation of this last is not straightforward; however, it cannot be expected to play a substantial role.

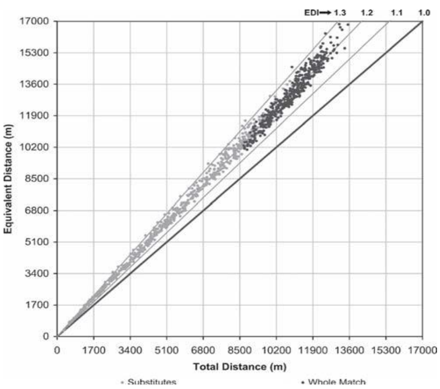


FIGURE 12—ED is plotted as a function of TD. Players who complete the whole match are symbolized in black circles, whereas substitutes are symbolized in gray circles. Every straight line represents a constant ratio between ED and TD defined as EDI.

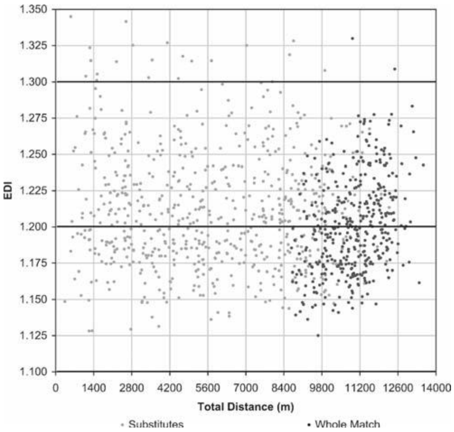


FIGURE 13—EDI is plotted as a function of TD. Players who complete the whole match are symbolized in black circles, whereas substitutes are symbolized in gray circles.

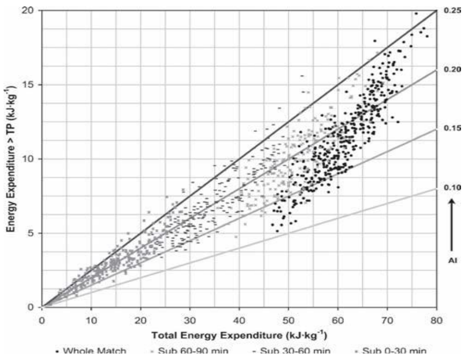


FIGURE 14—Energy expenditure above TP is plotted as a function of total energy expenditure. Players who completed the whole match are symbolized in black circles, substitutes who played from 60 to 90 min are symbolized in gray crosses, substitutes who played from 30 to 60 min are symbolized in gray dashes, 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.

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 T 498 kJ (1107 T 119 kcal), comparable to that found by other authors. 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 km h^{-1}), although they spent more than 42% of the total energy at high-power output (920 W 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 W 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. 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.

NEW PARAMETERS IN SOCCER PERFORMANCE ANALYSIS: IMPLEMENTATION OF GPS

It has been widely argued that in a game (or training) there are many accelerations and decelerations , followed or preceded by phases of walking or running at medium - low speed , but we have never been able to quantify the power generated by these variations. Unfortunately, traditional Match analysis does not yet take into account, accelerations and decelerations . To overcome this problem ,a new approach has been identified to estimate the energy cost of running in acceleration based on the equivalence of an accelerated frame of reference , with the Earth's gravitational field . In this case , running in acceleration on level ground is considered similar to running at a constant speed uphill , where the slope is set by the acceleration in an anteroposterior direction . Up until now , it continues to make reference to km performed , or to how much distance an athlete performs once he goes over 22 km / h . To reinforce this theory these indices were used to evaluate the overall performance of the player himself : therefore the more meters you do at that speed , the fitter you are. In fact for a player to reach this speed from a standing point it takes nearly two seconds and his maximum power get developed between 10 and 16 km / h . So if for some tactical reason he reached 21 km / h , for two seconds he would have developed the equivalent metabolic power of more than 50 watts / kg or about 3 times its V_{O2max} , but nobody would have noticed it because he did not exceed 22 km / h . As we can see from Figure 15 , data gathered on the individual player during a sprint show that he tends to have the same acceleration measured by Di Prampero (in the legend : DP) on sprinters , but after 10 meters he is quite unable to increase the sprint because he rarely reaches peaks as high throughout a match, as his acceleration is held on short spaces and its pace is dictated by the position of the ball , and therefore not by the stopwatch .

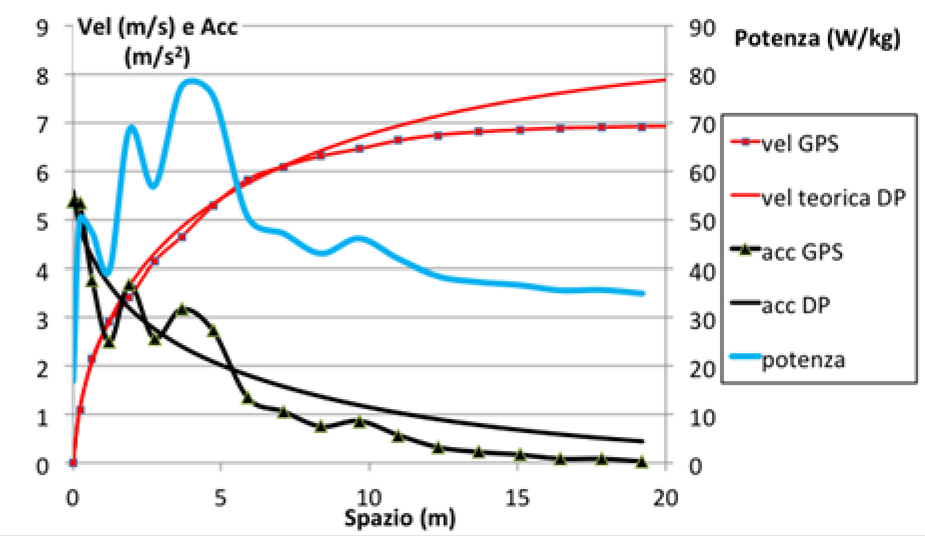


Figure 15

Another interesting fact visible in the graph regards the greater variability of the acceleration while sprinting with GPS ,opposed to Di Prampero's curve that results to be perfectly parabolic . The nature of his curve is the result of a regression that can be summarized as if the athlete ran on a track, however we know that during a running session we have a propulsive phase where weaccelerate (when we have the foot on the ground) and a phase where we decelerate due to the gravitational component present in the aerial phase . No wonder then if at a frequency of 5 Hz you notice fluctuations on the acceleration. We believe that it is very interesting to see the live performance of power that tends to increase within the first 5 meters , reaching a peak of about 70 watts / kg before falling back when the athlete accelerates less compared to the first meters. This confirms that running the first 10 meters is much more energy-costly (52 W / kg average) when speed is kept at medium-low standards , compared to the following 10 m where the athlete has already increased his speed (38 W / kg average) . If we analyze with GPS a 20 + 20 meters shuttle (Figure 16) we notice that : the breaking phase takes place in a very short space ± 2-3 meters, but it is preceded by a controlled-speed gait ; technically the individual keeps his pace constant for approximately ten meters as he knows he will have to slow down eventually, therefore he is already preparing for full speed descent. If we were to test this exercise on sprinters we would notice that they naturally tend to reach high speed, with disastrous results in the breaking and re-acceleration phase that occurs in a clumsy and slow fashion . In this case eccentric breaking is much faster (and economic) than positive acceleration . This is very important for various reasons , one of which , as indicated by the same authors, is that the system they used for calculating power only works up to negative accelerations of about -5 m / s^2 . Currently we have replaced the 5th degree equation offered by Minetti (relative to C_r of running up and down) with a more "comfortable " 3° degrees equation where even beyond the limits of inclination of ± 45 % , we continue to register positive energy cost data . As we will notice later on, breaking at such intensity (< -5m / s^2) is not so frequent in soccer (about 5% of all the braking); breaking at medium intensity is much more common, therefore the margin of error for this evaluation is bearable. At this point we realized that GPS can help us a lot during the evaluation, because this way we can also evaluate non-linear shifts, measure speed , accelerations and power on mixed routes with CoD (changes of direction).

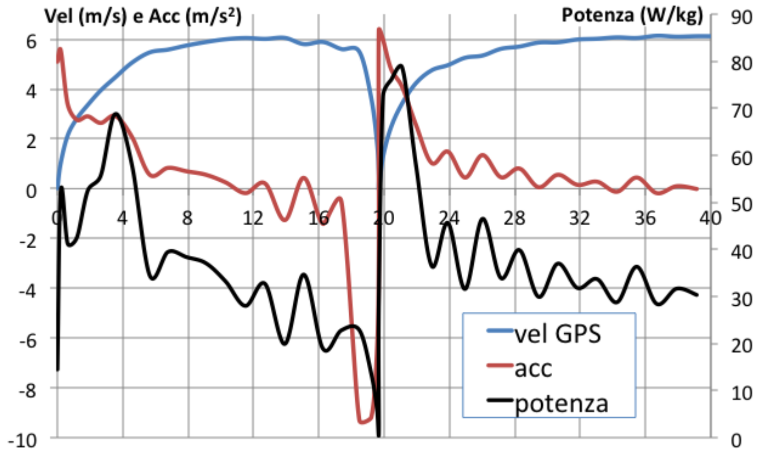


Figure 16

3.1 Match Analysis via GPS

The second step was to analyze some games with GPS systems to see if the data we were retrieving were similar to those obtained with video analysis . Table 7 below shows that data collected on some U17/18 matches (30 surveys) are very similar to those obtained by prof. Di Prampero.

CATEGORIA POTENZA	T (s) di Prampero Serie A	T (s) GPS Primavera
LP da 0 a 10 W·kg⁻¹	3818 ± 299	3135 ± 146
IP da 10 a 20 W·kg⁻¹	1173 ± 161	1416 ± 110
HP da 20 a 35 W·kg⁻¹	461 ± 91	531 ± 38
EP da 35 a 55 W·kg⁻¹	163 ± 38	157 ± 16
MP >55 W·kg⁻¹	91 ± 28	77 ± 46

Table 7

Data collected are totally reinforcing the studies conducted with video match analysis. As a result of this, we can confirm that stressing the importance of evaluating athletes according only to high speed parameters results to be detrimental in evaluating metabolic efforts performed by players. Following the proposals of DP , we simply recompiled his table with data gathered from GPS resulting in table 8:

Tipo fase	W/kg	Tempo di gara (s)	Lav tot (EE) in Joule	% tempo a potenza	% EE
Blanda	0-10	3241	18103	60,2%	27,8%
Media	10-20	1372	19351	25,5%	29,8%
Elevata	20-35	538	14009	10,0%	21,6%
Alta	35-55	157	8898	2,9%	13,7%
Max	>55	77	4642	1,4%	7,1%

Table 8

- If we mistakenly evaluate only speeds higher than the MAP (>16 km / h) these only refer to 4.3% of the total time in a game.
- A player performs 14.3 % of his time to a greater metabolic power than the MAP (maximum aerobic power set to 20 W/kg equaling to 57 mL kg^{-1} min^{-1} O_2);
- energy deployment (EE = Energy expenditure) depends on 42.4 % of actions above the MAP;
- the average metabolic power deployed during a game is 12 W / kg corresponding to 34.3 ml kg^{-1} min^{-1} net oxygen utilization ;
- average energy expenditure (EE) in a game equals to 65 kJ / kg, for a player weighting 70 kg amounts to 4550 kJ approximately 1100 kcal ;
- for over 50 minutes, a player tends to walk (up to 6 km / h), but for only 2-3 minutes he stands completely still .

Potenza (W/Kg)	Velocità (Km/h)	Watt %	V %
0÷8	0÷6	48,1%	58,2%
8÷15	6÷12	28,0%	29,9%
15÷20	12÷16	8,0%	7,8%
20÷25	16÷20	4,5%	2,9%
25÷30	20÷24	3,4%	1,0%
30÷35	24÷28	2,3%	0,2%
>35	???	5,7%	0,0%

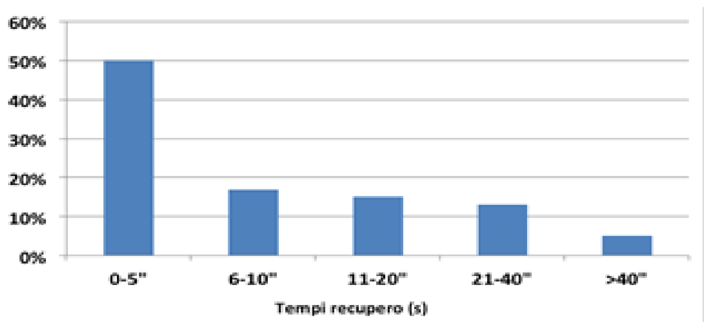
Table 9

In Table 9 we converted the various power zones of a player as if he ran at constant speed : if up to 16 km / h there is a certain similarity between the speed and power data (except to 0-6 km / h) , we notice that over 16 km / h the ratio tends to differ, so that when players deliver a metabolic power greater than 35 W / kg , there is no speed parameter that justifies it. So, it is arguable that what has been done to date using speed over a certain threshold, has limited value to indicate the efforts of a football player. If in the 70s we believed that the distance covered during a game corresponded to almost 10-12 km with about 1000 m performed at more than 20 km / h and this helped us to understand that football is played at variable speed, now this data are to be considered irrelevant. Nowadays, we believe that there is margin for radical changes to be adopdted in match analysis and as a result of this different approaches to structuring training sessions are being developed: ex, how often does an intense action occur? How much recovery do you need? And how is it distributed throughout a match?

Durata (s)	% num. tot azioni	Potenza media (W/kg)	Tempo di recupero W/kg<20
0-2”	62,2%	27,1	10” ± 16”
3-4”	21,8%	30,1	12” ± 15”
5-6”	9,4%	34,0	11” ± 14”
>6”	6,6%	35,2	14” ± 19”

Tabella 10

It is interesting to note (Table 10) that 62% of the actions performed over the MAP (> 20 W / kg) are exploited within 2 seconds ; after two seconds the player enters his most "aerobic" performance, recovering the effort in a very brief manner. Indeed it is noticeable that the switch from aerobic to anaerobic action occurs frequently followed by an average recovery of 10". Only 6.6% of the actions last for a period exceeding 6" and it is interesting to note that when the effort is prolonged beyond 2" the average power output rises and complementarily recovery time tends to increase. In simpler terms, only 0.8 % of all actions performed over the MAP took longer than 10" and the maximum we observed was 14 seconds.



Graphic 1

By analyzing recovery periods (Graphic 1) , we found out that the actions performed above MAP, one out of two were reiterated within 5" and this represents an extremely important figure to structure your training. Indeed, it is quite obvious that a player who is involved in an action, tends to make prolonged efforts separated by short interruptions; this is to prevent an excessive use of anaerobic glycolysis and exploit greater creatine-phosphate (CP) reserves, that can be restored in seconds. Therefore, when the ball is far off the player, he is passive in the action, so he has more time to recover. Out of all the data we gathered one of the most relevant was that RSA (repeated Sprint Ability) that resulted to be null in its fabrication with regards to Soccer, even though up until now we have always believed that this method was the closest to the real performance model of football.

Indeed:

• actions of up to 6" are quite rare and hardly ever consecutive ;

• in the first RSA repetition, the aerobic system is kept at basic levels, reaching the standard value an athlete obtains during the game around the 2°-3° rep. : leading to further high energy production through the anaerobic mechanism with a broad and unreasonable (for the model) premature lactate production;

• in this test the athlete starts from scratch while in a real life situation accelerations occur when a player is already working at 5-12 km/h;

• in the RSA recovery phase, pauses/breaks are static, while in real life scenarios you either walk or run at medium-low speed.

It is clear that in order to avoid a player to reach exhaustion we must come up with an alternative test that would be as close and efficient as possible to the Football Model for performance analysis from a

Biomechanical point of view, and that it would not push the athlete to produce an exaggerated amount of lactate.

First we must evaluate both a theoretical and practical aspect, highlighted in figure 18:

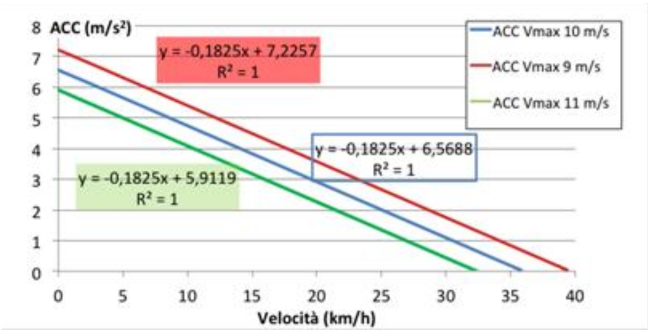


Figure 18

The acceleration is not absolute, because if the subject is running at very low speed (0-8 km / h) he is able to accelerate well up to 5-7 m/s^2, but if he is running at 18-22 km / his acceleration will only be 2-3 m/s^2, even though he is pushing to his fullest potential. It is vital for us to be able to register both values (speed and acceleration) in order to determine whether or not the athlete is performing his maximum acceleration at two different speeds. The graph tells us that even if the athlete reaches his maximum, the slope of the straight line between speed and acceleration does not vary (the equation of speed over acceleration is always that of Prof. Di Prampero). This is why in a game we used this index of maximum acceleration relative to speed and as a result we got the following:

Acc < 50% max → 80,1%
Acc > 50% max → 19,9%

In simpler terms, throughout a game athletes perform 20% of their accelerations over 50% of the maximum possible, while all the other actions are performed at moderate acceleration. With regard to breaking phases: for only 5 % of all decelerations a footballer breaks to his maximum (< -5 m/s^2) ; on the other hand many more (37% of them) are medium decelerations, that are still valuable but of medium speed.

-12 < Dec < -3 m/s^2 → 13%

Precisely for this purpose, we have introduced this parameter of intense deceleration from -3 m/s^2 .

We must note that the ratio between speed and acceleration (Fig. 18) is not visible from the breaks we have analyzed , meaning that when an individual tries to break in the least possible time, he is capable of performing considerable decelerations in the order of 10 / -12m s-2 even at high speed(≥20 km / h) (see Fig. 16) .

In fact, breaks occurring at the same speed of accelerations take less time to be executed, (breaking from 20 km / h can take place in 500 ms, while accelerating up to speed of 20 km / h occurs in ≈ 1”5 -2“).

Changes of Direction

Another interesting parameter concerns the changes of direction (CoD) , their size and their relationship with power and speed. The CoDs (shown in Table 11) are multiple (about 1000 with angles greater than 30°) and over 800 have angles > 30° but have also been performed at powers greater than 20 watts / kg . In practice we develop a CoD > 30° and at 20> W / kg every 30" .

Ampiezza (°)	Media e SD	% num. tot
0-30°	4161 ± 124	**80,5%**
30-60°	670 ± 69	**13%**
60-90°	229 ± 7	**4,4%**
90-135°	57 ± 13	**1,1%**
135-180°	52 ± 13	**1%**

Table 11

We believe it is of vital importance to relate the CoD with both power (since we can now calculate it) and speed . Table 12 shows that for all CoDs performed at angles wide (up to 30°) there is about 17% of all actions above the MAP that decrease below 10 % if the angle of the CoD is closed more than 90° and consequently more challenging .

Potenza met.	0-30°	30-60°	60-90°	90-135°	135-180°
<20 W/kg	83%	86%	92%	91%	90%
>20 W/kg	17%	14%	8%	9%	10%

Table 12

This entails that we must not undervalue those CoDs with small amplitude because very often they are carried out at both high speed and intensity. In this case Table 13 helps us analyze CoDs in relation to speed : when we execute a CoD over 90°, speed is almost always very low (55.6 % within 4 km / h) because we have to slow down in order to perform this action.

Velocità (km/h)	0°-30°	30-60°	60-90°	90-135°	135-180°
0-4	18,7%	32,3%	44,9%	55,6%	53,3%
4-8	49,4%	43,3%	37,4%	31,1%	32,6%
8-12	18,3%	15,7%	12,6%	9,7%	10,3%
>12	13,6%	8,7%	5,1%	3,6%	3,8%

Table 13

With angles opened up to about 60° we are able to perform some CoDs at higher speed , while the speed at which we often carry out CoDs with less amplitude is normally between 4 to 8 km / h .

3.2 Comparative evaluation of the standardized model through practical training examples

The final outcome of utilizing GPS is to monitor what happens during training and specify if training differs from the Football Model; for the sole purpose of identifying and classifying specifically for exercises with the ball, whether they have a greater correlation (not only metabolic but also coordinative and muscular) with this game.

Let’s start by analyzing one exercise (with no ball) that is widely used by fitness coaches: linear runs at medium intensity:

- linear runs at medium intensity performed "up and down" over distances ranging from 20- 40-60-80 m at speeds ranging from to 60 % to 100%;

- micro pauses of 15" - 20";

- macro pauses 1' - 1'30".

from Table 14 we notice that linear runs at medium intensity structured this way, not only they do not satisfy the required metabolic effort but also they lack Cods and intense breaks compared to a real life scenario (game).

Parametri	ALLUNGHI	GARA
VO_2 (ml/min/kg)	27 ± 2,7	34,3 ± 1,1
Tempo a vel > 16 km/h	14,4% ± 2,4	4,3% ± 1,1
Tempo a W/kg > 20	16,1% ± 2,5	14,3% ± 0,8
EE a W/kg > 20	60% ± 5	42,4% ± 0,6
Distanza effettiva (m/min)	94 ± 14	104 ± 3
Distanza equivalente (m/min)	113 ± 11	144 ± 4
(CdD > 30° e W/kg > 20)/min	0,9 ± 0,3	2.0 ± 0.5
Acc >50% max	11.2%	19,9%
Dec < -2 m/s^2	8.1%	42%

Table 14

From the table (15) we can say that in terms of effort distribution visible in power zones, time dedicated to actions with an intensity over 35 W/kg is much more than the game's (10,5 % vs 4,3 %) but these actions are not a result of accelerations, because an athlete tends to maintain a constant speed over 16 km/h for a prolonged period of time; in contrast, we notice that low intensity (where an athlete is walking or standing still), is considerably higher with respect to a game, so much so that in this kind of training the athlete remains still for 30% of the time, while in a game this phase lasts between 3-5 % of the total duration of the game.

Tipo fase	W/kg	% TEMPO GARA	% TEMPO ALLUNGHI	% EE GARA	% EE ALLUNGHI
Blanda	0-10	60,2%	71%	27,8%	28%
Media	10-20	25,5%	10%	29,8%	17,9%
Elevata	20-35	10,0%	8,1%	21,6%	27%
Alta	35-55	2,9%	5,3%	13,7%	16%
Max	>55	1,4%	5,2%	7,1%	12%

Table 15

In terms of energy expenditure (EE) the average power zone is merely influenced with this exercise. Practically, a great deal of anaerobic effort gets developed, where the athlete through the process of glycolysis will produce a lot of lactate as this physical activity gets prolonged for more than 2" -3". It is advisable not to reach high speed over long distances, but frequently vary both speed and direction, so that breaks and Cods would occur, including recovery phases where the athlete is not completely still (by walking for example). Therefore, in these exercises we should introduce a few variations in terms of accelerations and decelerations, with CoDs and medium intensity runs so that these exercises would come as close as possible to the metabolic, coordinative and neuro-muscular model of football.

Possession ball

Various types of ball possessions with different technical-tactical purpose have been proposed :

- 10 vs 10 in a space of 60 x 65 m;
- the work was composed of 2-3 series of 2'- 4';
- the break between sets was 60 ".

We notice that in the ball possession exercises the metabolic effort is quite modest, accounting to almost 70% of the game's power (metabolic) (Table 16). Moreover, the number of CoDs > 30° > 20 W / kg account for only 30% of what happens in a game . Likewise in terms of muscular and coordinative effort, intense accelerations are approximately 40% of the game's and intense decelerations are about 25% of the game's.

Parametri	POSSESSO	GARA
VO_2 (ml/min/kg)	27,4 ± 3,2	34,3 ± 1,1
Tempo a vel > 16 km/h	3,5% ± 2,2	4,3% ± 1,1
Tempo a W/kg > 20	10,2% ± 2,6	14,3% ± 0,8
EE a W/kg > 20	38% ± 6	42,4% ± 0,6
Distanza effettiva (m/min)	93 ± 16	104 ± 3
Distanza equivalente (m/min)	109 ± 17	144 ± 4
(CdD > 30° e W/kg > 20)/min	2.1 ± 0,5	2.0 ± 0.5
Acc >50% max	7,4%	19,9%
Dec < -2 m/s²	10.8%	42%

Table 16

The average distance traveled by a player per minute does not reach 100 meters, and this fact, combined with limited intensive actions, allows us to say that this exercise does not have the minimum requirements of the model and therefore must be restructured. This exercise makes an individual develop an EE equal to 38 % over the MAP against 42.4 % (game) , but on the other hand the time spent working at low intensity greatly increases compared a game: this is due to the little integration of the athlete with the ball, and consequent decrease of metabolic effort. (Table 17) .

Tipo fase	W/kg	% TEMPO GARA	% TEMPO POSSESSO	% EE GARA	% EE POSSESSO
Blanda	0-10	60,2%	73%	27.8%	35%
Media	10-20	25,5%	17%	29.8%	27%
Elevata	20-35	10,0%	6,8%	21.6%	20%
Alta	35-55	2.9%	2,2%	13.7%	11%
Max	>55	1.4%	1,4%	7.1%	9%

Table 17

It is more than likely that an increase in surface of the field or conversely a decrease in the number of players, could positively change this exercise. Moreover, the duration of the same series (even if more intense) should be prolonged; even though we believe that in order to come as close as possible to the model we need to be a few points above the V_{O2} of the match.

- Exercise: 10 vs 10 game on a field 60 X 65 (doors placed just outside the box)

Almost all workouts end with a short game that lasts for 15-30 minutes. The game gets interrupted once or twice for short pauses (60”) and tactical indications. It’s often believed that making players finish their training with an exercise like this, would make them respond in a much better way in terms of mental, coordinative and metabolic effort. This happens only if the game’s parameters are met. (Table 18).

Parametri	PARTITA ALLENAMENTO	GARA
VO_2 (ml/min/kg)	28,2 ± 1,3	34,3 ± 1,1
Tempo a vel > 16 km/h	4% ± 1,5	4,3% ± 1,1
Tempo a W/kg > 20	11,4% ± 1,4	14,3% ± 0,8
EE a W/kg > 20	39% ± 3	42,4% ± 0,6
Distanza effettiva (m/min)	103 ± 8	104 ± 3
Distanza equivalente (m/min)	118 ± 6	144 ± 4
(CdD > 30° e W/kg > 20)/min	1,1 ± 0,3	2.0 ± 0,5
Acc >50% max	11,2%	19,9%
Dec < -2 m/s^2	11.0%	42%

Table 18

The trend however is that the match played at the end of training is often performed on small surfaces, where every single player, who normally covers about 300 m^2 of field in a real game, during training only has to cover 100-150 m2 . As we see from these data (Table 19), the metabolic effort is much lower (similar to ball possessions); also accelerations, decelerations and CoDs are half of those that actually happen during a game. To confirm this , we see that in these games at the end of practice, players tend to take longer breaks even compared to the game's.

Tipo fase	W/kg	% TEMPO GARA	% TEMPO PARTITA ALLENAMENTO	% EE GARA	% EE PARTITA ALLENAMENTO
Blanda	0-10	60,2%	74,5%	27,8%	37%
Media	10-20	25,5%	15,8%	29,8%	26%
Elevata	20-35	10,0%	6,3%	21,6%	18%
Alta	35-55	2,9%	2,3%	13,7%	10%
Max	>55	1,4%	1,1%	7,1%	9%

Table 19

AGE GROUPS COMPARATIONS WITHIN A SOCCER CLUB

4.1 Introduction

The purpose of this study is to compare the external load retrieved in training among the various age groups of a professional football club, starting with the U15s up to the first team. 12 weeks of practice have been monitored , U15 (three days of practice per week, 20 players h 1,76 ± 0,2m, BM 65 ± 1 Kg) U16 (four days practice per week, 21 players h 1,80 ± 0,1m, BM 71 ± 1,5 Kg), U17-18 (5 days of practice per week, 19 players h 1,82 ± 0,25 m, BM 74 ± 2,3 Kg) and first team (5 days of practice, 25 players h 1,83 ± 0,27 m BM 75 ± 1,8 Kg), goalkeepers have not been included in this study. For every team, physical tests have been registered at the beginning, in the course and at the end of the season (table 20).

For all age groups up until the U17-18s we have proceeded with the same set of tests (Anthropometric evaluation, CMJ, Speed Test 10-20mt, Yo-Yo int. Rec. Test lev.1) while for the first team we have proceeded with Isokinetic tests to evaluate the lower limbs, CMJ, anthropometric measurements and Mognoni's test to evaluate metabolic effort. The final scope of this study was to highlight differences in volume/intensity between the "formative training for academy players" and the training aimed at improving game performance as it should be in a first team.

Average team Test									
	CMJ	Isocinetic		Mognoni	B.M.	H	Speed 10	Speed 20	Yo-Yo Int.
		torque ext	torque flex						
First team	44 ± 6	200 N-M ± 25	155 N-M ± 32	162 ± 5- 4,0 ±1,5	1,83 ±0,27	75 ± 1,8			
U 17-18	40 ± 4				1,82 ± 0,25	74 ± 2,3	1,73 ± 0,10	3 ± 0,10	17 ± 0,5 Km/h
U 16	35 ± 3				1,80 ± 0,1	75 ± 1,5	1,76 ± 0,11	3,01 ± 0,09	17 ± 1 Km/h
U 15	35 ± 4				1,76 ± 0,2	65 ± 1	1,88 ± 0,08	3,24 ± 0,13	16 ± 1 Km/h

Table 20. Average teams' Tests

4.2 Methods

In every practice we monitored, 6 GPS Qstarz (10hz) per team were used. All of them have been placed in the upper-central part of the athletes' back. The study has not been influential in any way on the structure of the training sessions, every micro-cycle has been prepared by the respective technical staff, composed of: 1st Coach, 2nd Coach, Fitness Coach, Goalkeepers coach, Technical coach. Data analysis has been conducted through a dedicated software called LeGalaColli v.9079b, that generates a large volume of figures and parameters; the most relevant ones concern the concept of metabolic power derived from Prof. Di Prampero's studies that are consequently elaborated by professor Colli. An initial synoptic table collects data gathered during training, correlating them with the parameters of the new "Match Analysis". As we can see from figure 19, the synoptic table shows the following data:

- *Average Watts (Metabolic power)*
- *Average VO2*
- *Distance/minute (m)*
- *% Intense accelerations*
- *% Intense decelerations*
- *CoD/min*
- *CoD/min >30°*
- *% Equivalent distance*
- *% Speed > 16Km/h*
- *% Anaerobic*
- *% Watt > 20 t ≥ 3''*
- *Kcal*
- *Total distance (m)*
- *% W>35/W>20 (very high intensity).*

	A	B	C	F	G	H	I	J	L	M	N	O	P
1	dev.st		1,3	11	3,0%	3,0%	1	2	4,0%	2,0%	5,0%	7%	
2	nedia		11,7	121	11%	13%	1,5	18,0	26%	6,2%	45,0%	25%	1100
3			w med	dist/ min	a int	dec int	Cd D/m in	CdD/ min >30°	% Dist Equiv	%vel> 16	%an aer	% w>20 t>=3"	kcal
4	0	4542	8,2	85	8%	11%	0,8	14,6	26%	2,4%	39%	20%	620
5	236	1481	7,9	85	8%	9%	0,9	15,9	22%	1,4%	33%	12%	165
6	1635	2015	13,0	129	14%	21%	1,4	22,9	32%	6,4%	46%	31%	82
7	2099	2455	12,5	125	13%	18%	1,5	18,7	31%	2,9%	46%	14%	74
8	2542	2919	10,9	110	10%	18%	0,8	17,0	29%	3,8%	42%	19%	68
9	1635	2919	10,9	110	11%	16%	1,1	17,9	30%	3,8%	44%	20%	233
10	3209	3615	13,1	131	15%	19%	1,9	22,2	31%	6,1%	49%	28%	88
11	3874	4272	12,8	126	13%	20%	1	21,4	32%	4,1%	45%	16%	84

	Q	R	S	T	U	V	W	X	Y	Z	AA	AB	AC	AD
1		peso	6%			7%	2,4	1,9	3,0%	1,00	5	2	3	
2		70	37%			41%	19,6	10,3	15,0%	4,50	13	5	9	
3	min reg	dist tot	%W> 35 /w>20	T vel> 16	T w> 20	%T vel/w HI	y (lun gh)	x (lar gh)	% t w>20 /Ttot	n az int/m in	Tr 0-5w /min	rec > 60"/ Hr	rec 40-60"/ Hr	eserci zio
4	75,7	6414	26%	110	466	24%			10,3%	3,0	29,8	8	9	tutto
5	20,8	1759	27%	18	105	17%	0,0	0,0	8,5%	2,4	29,7	14	23	ris
6	6,3	817	26%	24	70	35%	0,0	0,0	18,5%	4,6	11,9	0	0	1° poss
7	5,9	739	27%	10	65	16%	0,0	0,0	18,4%	6,1	14,8	0	0	2° poss
8	6,3	691	23%	14	57	25%	0,0	0,0	15,1%	4,3	18,9	0	10	3° poss
9	21,4	2355	25%	49	197	25%	0,0	0,0	15,3%	4,4	19,8	6	3	ti possess
10	6,8	884	28%	25	82	30%	0,0	0,0	20,1%	5,8	14,3	0	0	partite spond
11	6,6	833	29%	16	70	24%	0,0	0,0	17,5%	5,7	14,3	0	9	partite spond

Fig 19

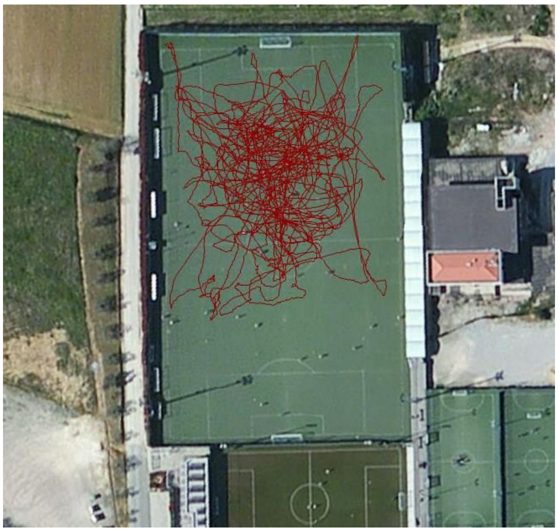


Fig 20

The above mentioned data are given by the software for training evaluation/analysis. Other info (not mentioned) refers not only to physiological situations, but also to tactical situations that dictate key points to the remaining technical staff (not only fitness coaches), (fig. 20)

The principle insight to the evaluation of the training session is given by the synoptic table (fig.19) , as it portrays in a very detailed fashion the quality of exercises being performed; however for the purpose of this study, other parameters have been identified in order to measure "quality" of the entire session and compare it with other training sessions (composed of different exercises) , other weeks of work, and different age groups.

Therefore, this software allows us to monitor the athlete (with a 360° view) and the team not only referring to specific exercises but also to the total amount of work being delivered. The parameters identified for quantifying the "total external load" (re-elaborated) are(fig 21):

- *Total Juole (Energy Expenditure,)*
- *Joule > 20 W (identifies work delivered at high intensity: > 20W o > MAP)*
- *Cod > 30° > 20 W (value estimating reactive during Cods strength)*
- *Total Distance (meters)*
- *Distance > 20 W (meters covered at high intensity)*

	SPESA ENERGETICA			FORZA REATTIVA	ALTISSIMA INTENSITA'	TEMPO	DISTANZE		
	JOULE Tot.	% j > 20 w	Joule > 20 w	CDD>30° >20W	% W>35/W>20	Minuti	Distanza Tot.	% Dist >20W	Distanza > 20w
01-ago		%			33%			%	
Players	39450	35	13808	74	25%	106	7156	21	1503
	39276	33	12961	87	29%	110	7081	20	1416
	40286	33	13294	98	30%	106	7194	19	1367
	36773	32	11767	74	28%	110	6620	18	1192
	38541	36	13875	121	30%	105	6897	21	1448
	39158	33	12922	88	26%	105	7103	19	1350
MEDIA	38914	34	13105	90	28%	107	7009	20	1379

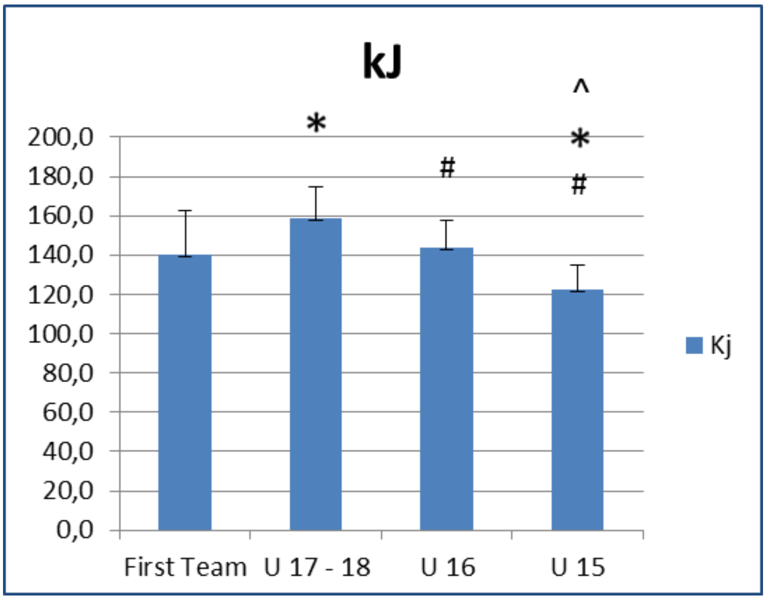
Fig. 21

4.3 Results

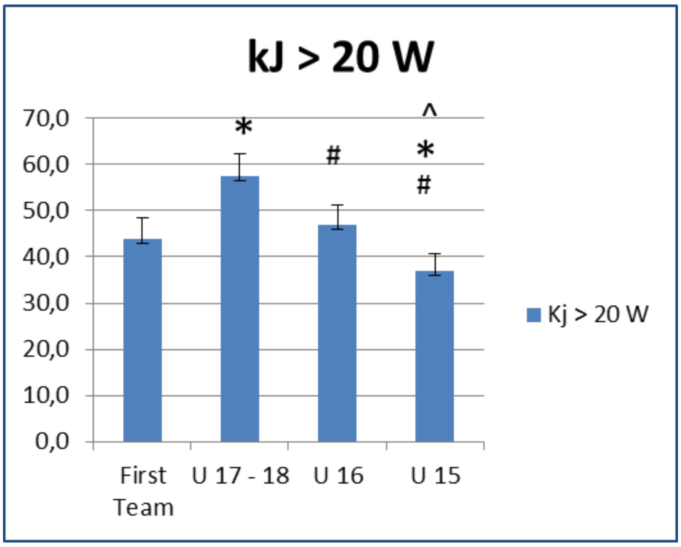
Index:

- *kJ (total Joule/1000)*
- *% kJ > 20 W (% J > 20 W/1000)*
- *kJ > 20 W (high intensity Joule/1000)*
- *Cod (>30° >20 W)*
- *Km (Total Distance)*
- *% Km > 20 W (Distance covered at High Intensity)*

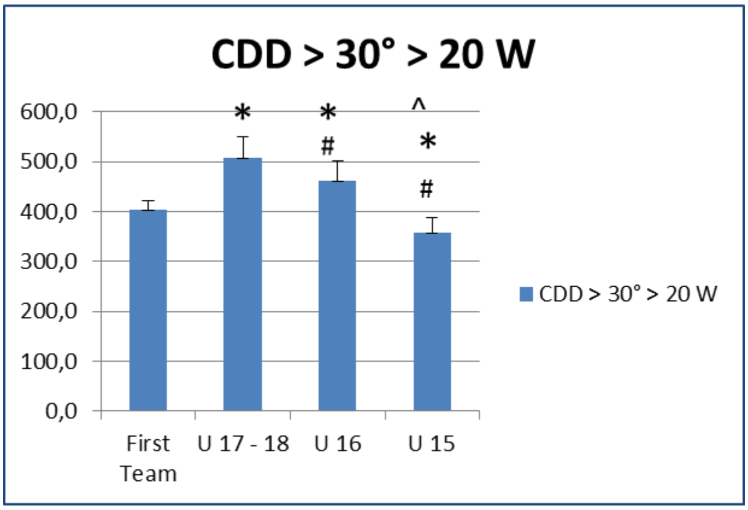
The weekly average data gathered in the period of studies (12 weeks) for the all the various age groups are shown as follows: U15: kJ 122,5 ± 12,2; % kJ > 20 W 30,4 ± 2,2; kJ > 20 W 37 ± 3,7; Cdd 356,4 ± 32; Km 21 ± 3; Km > 20 W 3,6 ± 0,4. For the U16 : kJ 143,6 ± 14,2; % kJ > 20 W 31 ± 2,4; kJ > 20 W 46,9 ± 4,3; Cdd 461,5 ± 39,2; Km 25 ± 3,1; Km > 20 W 4,9 ± 0,6. U17-18: kJ 158,6 ± 16,3; % kJ > 20 W 37,4 ± 2; kJ > 20 W 57,4 ± 5; Cdd 507 ± 41,6; Km 29,4 ± 2,2; Km > 20 W 5,5 ± 0,3. First Team: kJ 140,4 ± 22,2; % kJ > 20 W 31 ± 2,3; kJ > 20 W 44 ± 4,5; Cdd 403,7 ± 18,8; Km 26,1 ± 5,1; Km > 20 W 4,8 ± 0,5 (Graphs 2,3,4,5,6).



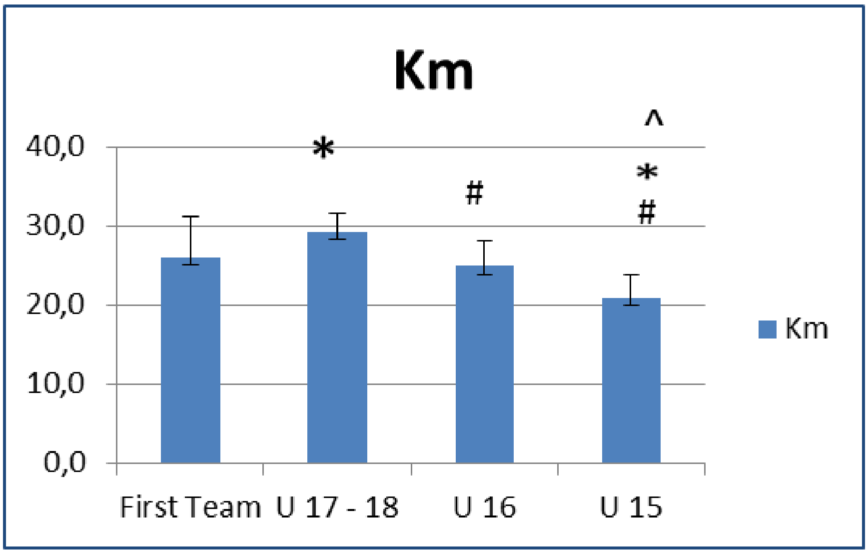
*Graph 2. Total Energy Expenditure: *Significant difference (p < 0,05) between first team and U 17-18; between first team and U 15; there are no significant differences between first team and U16. # Significant difference (p< 0,05) between U 17-18 and U 16 and U 15. ^ Significant difference (p< 0,05) between U 16 and U 15.*



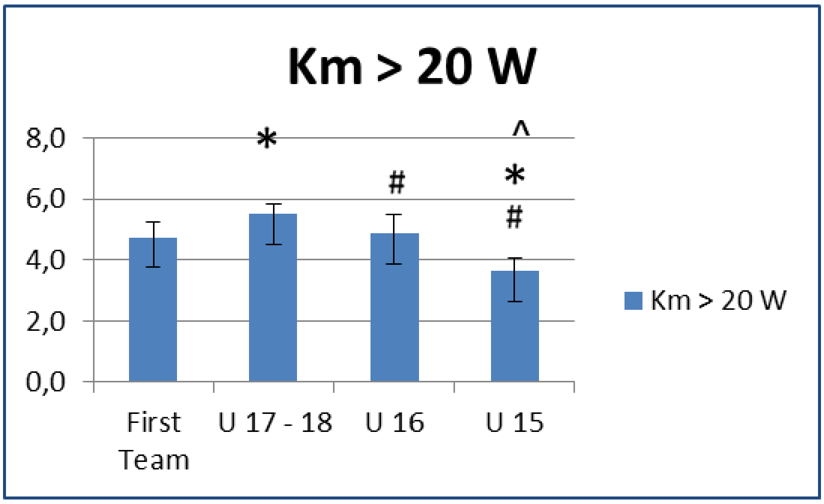
*Graph 3. Energy Expenditure at high Intensity: *Significant difference (p < 0,05) between first team and U 17-18; between first team and U 15; there are no significant differences between frist team and U 16. # Significant difference (p< 0,05) between U 17-18 and U 16 and U 15. ^ Significant difference (p< 0,05) between U 16 and U 15.*



*Graph 4. Change of direction at high intensity: *Significant difference (p < 0,05) between first team and U17-18; between first team and U 16; b tween first team ande U 15; # Significant difference (p< 0,05) between U 17-18, U 16 and U 15. ^ Significant difference (p< 0,05) between U 16 and U 15.*



*Graph 5. Total distance: *Significant difference (p < 0,05) between first team and U 17-18; between first team and U 15;there are no significant differences between first team and U16. # Significant difference (p< 0,05) between U 17-18, U 16 and U 15. ^ Significant difference (p< 0,05) between U 16 and U 15.*



*Graph 6. Distance covered at high intensity: *Significant difference (p < 0,05) between first team and U 17-18; between first team and U 15; there are no significant differences between first team and U 16. # Significant difference (p< 0,05) between U 17-18, U 16 and U 15. ^ Significant difference (p< 0,05) between U 16 and U 15.*

4.4 Recommendation

By looking at these graphs we can say that the team with the highest parameters is the U17-18. Surprisingly their values/data are higher than the first team's (on all the tests taken into account) in terms of volume and intensity (> 20 w/ > maximal aerobic power) over the exact number of days of practice. Even the U16, (with one day less of practice) registered the same volume of work as the first team, with higher results in high intensity CoDs. The U15 are the group that developed less volume of work and intensity over the week(considering they practice one day less a week compared to the U16 and two days less a week compared to the U17-18 and the first team). It must be said that the new parameters used for training evaluation need to be revised with care and attention, especially when it comes to interpreting the two key words we previously used, “volume” and “intensity”. Screening training sessions with these advanced measuring systems (GPS, Software LaGalaColli) demands in depth analysis by the technical staff who need to take into account remaining data portrayed by the software (see specific exercises (fig. 19), and the methodology according to which these exercises have been executed: as it greatly influence the effect of work-loads on athletes, either quantitatively or qualitatively. We believe the reason why parameters emerged from the analysis of U17-18 are considerably higher than the other age groups’, is due to the fact that the “formation” of a player depends on various types of training (technical/tactical and physical); by mixing up these various types of training we are capable of limiting an athlete’s deficits, in order to educate and prepare him for professional football. Data retrieved from the other age groups confirm that considering less days of practice, the work load is proportionally not very distant from the values collected on top players. (Data not been yet elaborated)

4.5 Conclusion

The purpose of this study was to compare the external load of the different age-groups within a professional football club through innovative measuring systems based on the studies conducted by Prof. Di Prampero on Metabolic Power. We can confirm that both quantity and intensity of physical work are discriminative traits of the age groups we have analyzed. The approach to practice, quality of players, and technical-tactical-physical-psychological objectives are all variables that carry fundamental importance on the variation of work load amongst different teams; 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 season. It is also believed that sharing this data could be the starting point for strengthening the knowledge of our area of work and begin a confrontation with other academies, as they are currently raising general awareness in the World of Football.

"One's destination is never a place, but a new way of seeing things."

Henry Miller

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