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MONITORING TRAINING IN ELITE SOCCER: A NEW APPROACH BASED ON GPS DERIVED ESTIMATED METABOLIC POWER DATA

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PROLOGUE

Sport science is a discipline that studies the application of scientific principles and techniques with the aim of improving sporting performance. Through the study of science and sport, researchers have developed a greater understanding on how the human body reacts to exercise, training, different environments and many other stimuli. Sport scientists and performance consultants are growing in demand and employment numbers, with the ever-increasing focus within the sporting world on achieving the best results possible. This was the rationale behind my PhD in sport science: the application of scientific principles with the aim of improving sporting performance. For this reason, in agreement with my supervisors, I planned my studies and research in order to get practical results/applications that could benefit coaches, fitness coaches and sport scientists involved in team sports.

The main topic of my PhD project focused on the application of Global Positioning System (GPS) technology to elite soccer training monitoring process. In particular, we studied the energy cost and the metabolic power estimated from GPS instant speed and acceleration data. In our opinion, these “new” parameters allow coaches and fitness coaches to better understand the true physical demands related to different soccer training sessions or particular technical and tactical drills. This will contribute to the planning and development of soccer training programs which both enhance performance and reduce the risk of injury.

The present thesis is based on experimental work conducted at the Department of Pathophysiology and Transplantation, Faculty of Medicine, University of Milan, during 2011 and at the Research Institute for Sport and Exercise Sciences, Liverpool John Moores University, during the period 2011-2013 with the constant support and cooperation of the Department of Biomedical Sciences for Health, University of Milan.

PUBLICATIONS

The present thesis is primarily based on the following publications which will be referred to by their Roman numerals.

I. **Gaudino P**, Iaia FM, Alberti G, Strudwick AJ, Atkinson G, Gregson W. Monitoring training in elite soccer players: systematic bias between running speed and metabolic power data. *Int J Sports Med*. 2013; 134: 963-968.

II. **Gaudino P**, Iaia FM, Alberti G, Hawkins RD, Strudwick AJ, Gregson W. Systematic bias between running speed and metabolic power data in elite soccer players: influence of drill type. *Int J Sports Med*. 2013; In Press.

III. **Gaudino P**, Alberti G, Strudwick AJ, Iaia FM. Metabolic and musculo-skeletal demands during different small sided games in elite soccer players. Manuscript in preparation. 2014.

IV. **Gaudino P**, Gaudino C, Alberti G, Minetti AE. Biomechanics and predicted energetics of sprinting on sand: hints for soccer training. *J Sci Med Sport*. 2013; 16: 271-275.

V. Minetti AE, **Gaudino P**, Seminati E, Cazzola D. The cost of transport of human running is not affected, as in walking, by wide acceleration/deceleration cycles. *J Appl Physiol*. 2013; 114: 498-503.

ABSTRACT

Introduction: Several studies have previously analysed soccer training sessions and specific drills However, a new method was recently proposed to estimate energy cost and metabolic power from acceleration data together with the evolution of global positioning system (GPS), providing the opportunity to derive a more detailed and accurate description of the physical demands imposed to the player during training.

Purpose: The aims of the present investigation were to: i) compare measurements of high-intensity activity when calculated as high running speed or high predicted metabolic power derived from a combination of running speed and acceleration during field-based soccer training sessions; ii) evaluate the agreement between the two methods during soccer small-sided games (SSGs); iii) evaluate whether any bias between the two approaches is dependent upon playing position; iv) examine the extent to which changing the game format (possession play (SSG-P) vs game with regular goals and goalkeepers (SSG-G)) and the number of players (5vs5, 7vs7 and 10vs10) influenced the physiological and physical demands of SSGs.

Methods: Data were collected in training during the in-season period from 26 English Premier League and UEFA Champions League outfield players using global positioning system technology. Total distance covered, distance at different speed categories and maximal speed were calculated. In addition, the number of changes in velocity carried out and the absolute maximal values of acceleration and deceleration achieved were reported. By taking into account these parameters besides speed and distance values, estimated energy expenditure and metabolic power were calculated. Finally, high-intensity activity was estimated using the total distance covered at speeds >14.4 km·h^{-1} (TS) and the equivalent metabolic power threshold of >20 W·kg^{-1} (TP).

Results: Mean training session TS was 478 ± 300 m vs 727 ± 338 m for TP ($p<0.001$). This difference was greater for central defenders (~85%) vs wide defenders and attackers (~60%) ($p<0.05$). The difference between methods also decreased as the proportion of high-intensity distance within a training session increased ($R^2=0.43$; $p<0.001$). When different SSGs were analysed, high-intensity demands were systematically higher (~100%, $p<0.001$) when expressed as TP vs TS irrespective of playing position and SSG. The magnitude of this difference increased as the size of SSG reduced with a difference of ~200% observed in the 5vs5 SSG ($p<0.01$). A greater difference between TP and TS was also evident in central defenders compared to other positions particularly during the 5vs5 SSG (~350%; $p<0.05$). In addition, the total distance, distances run at high speed (>14.4 km·h^{-1}) as well as maximum velocity, acceleration and deceleration increased as pitch dimensions increased (10v10>7v7>5v5; $p<0.05$). Furthermore, the total distance, very high (19.8-25.2 km·h^{-1}) and maximal (>25.2 km·h^{-1}) speed distances, absolute velocity and maximum acceleration and deceleration were higher in SSG-G than in SSG-P ($p<0.001$). On the other hand, the number of moderate acceleration and decelerations as well as the total number of changes in velocity were greater as the pitch dimensions decreased (i.e. 5v5>7v7>10v10; $p<0.001$) in both SSG-G and SSG-P. Finally, predicted energy cost and metabolic power were higher in SSG-P compared to SSG-G and in larger compared to smaller pitch areas ($p<0.05$).

Conclusions: The high-intensity demands of soccer training are underestimated by traditional measurements of running speed alone, especially in central defenders, training sessions associated with less high-intensity activity and “small” SSGs. Estimations of metabolic power better inform the coach as to the true demands of a training session or a particular drill. A detailed analysis of different drills based on metabolic power is pivotal in contemporary soccer as it enables an in depth understanding of the workload imposed on each player which consequently has practical implications for the prescription of the adequate type and amount of stimulus required during training.

Keywords: Soccer, GPS, Acceleration, Energy cost, Metabolic power, High-intensity, Position

Chapter 1

INTRODUCTION

In this chapter, the background on which the present thesis is based will be given. In particular the first part provides a brief general overview of monitoring soccer training sessions and matches. The second part describes the Global Positioning System (GPS) technology, its advantages and disadvantages, and its application in monitoring physical performance. The third part discusses the theoretical model used to estimate energy cost and metabolic power from instant GPS speed and acceleration data.

1.1 Monitoring soccer training and match.

The optimal physical preparation of elite soccer players has become an indispensable part of the professional game, especially due to the increased physical demands of match-play. Elevated workload over extended periods of time may contribute to potentially long-term debilitating effects associated with overtraining and increased occurrence of injury events. Thus, player performance parameters, together with physiological and subjective ratings need to be carefully monitored and supplementary recovery sessions should be considered for players during heavy fixtures periods.

The physiological demands of contemporary professional soccer implicate an increased work rate, a higher frequency of competition, and as consequence, players are obliged to work harder than in previous decades. In top level soccer, first team players are required to play up to sixty matches in a season, and to compete in two or three occasions in a single week. Research has revealed that stress associated with multiple competitions and training causes fatigue and often temporarily impairs the performance of players. On the other hand, for squad players that do not play regularly, training load and intensity must be sufficient to ensure they are adequately prepared to cope with the physical demands of a match, and therefore if necessary, should perform additional field-based high-intensity training or engage in practice matches. Respect to official matches, recent technological developments have meant that sophisticated video camera systems, capable of quickly recording and processing the data of all players' physical contributions throughout an entire match, are now being used in elite club environments [Carling et al. 2008; Di Salvo et al. 2009; Vigne et al. 2010; Di Salvo et al. 2013]. The most up-to-date techniques of video match analysis allow close observation of the movements of players and ball on the soccer pitch throughout the 90 min of the game. The data obtained yield distances covered and relative speeds in addition to technical and tactical aspects. The results of these study show that the total distance covered in a match ranges from 10 to 13 km, with differences related to rank and role. The distance covered in the first half of the match is usually 5%-10% greater than that covered in the second half. Players spend ~70% of the total match duration performing low-intensity activities such as walking and jogging, whereas in the remaining ~30% they are involved in ~150-250 actions of ~15-20 m of high-intensity exercise. Distance covered at very high speed running (>20 or 25 km·h^{-1}) amounts to 5%-10% of the total distance covered during a match and average very high speed run duration is 2-4 s [Bangsbo 1994; Rampinini et al. 2007*b*; Di Salvo et al. 2009; Vigne et al. 2010].

Several instruments are generally used in order to try to estimate the energy expenditure during training sessions: chronometer, thermometer, heart rate, blood lactate concentration test, rating of perceived exertion (RPE), etc. [Foster et al. 2001; Impellizzeri et al. 2004; Coutts et al. 2009]. However, the multi-directional basis of sports such as soccer involve a number of acyclical changes in activity, each characterized by accelerations and decelerations of differing velocity, thus exacerbating the physical strain imposed on the players. This suggests that the above-listed instruments can only provide an approximation/general overview of the real training workload imposed to the players. Such instruments have several limitations including their inability to provide instantaneous physical parameters over the training sessions.

Over the last decade, GPS technology has entered the world of physical activities and sports. It offered an alternative method for the measurement of speed and position during locomotion studies in the field, with the potential to circumvent some of the limitations and minimize others. Firstly its use was restricted to monitoring long distance activities such as cycling, orienteering or cross-country skiing, but later, becoming more accurate and reliable even over short distances and changes of direction and speed, enabling this tool to be used to monitor training or particular exercises carried out in many outdoor sports [Aughey 2011; Cummins et al. 2013].

1.2 Global positioning system technology.

GPS is a satellite-based navigational technology originally devised by the United States (U.S.) Department of Defence for military purposes. In 1978, the first experimental GPS satellite was launched. The Gulf War from 1990 to 1991 was the first conflict where GPS was widely used. In 2005, the first modernized GPS satellite was launched. The system was maintained by the United States government and was freely accessible by anyone with a GPS receiver without charge or restriction even though when GPS was used by civilians the signal was intentionally degraded using an operational mode called “selective availability”. This was a deliberate degradation of the satellites’ signals by the U.S. Department of Defense, designed to deny any apparently hostile forces the tactical advantage of highly precise GPS data [Larsson & Henriksson-Larsén 2001; Townshend et al. 2008; Maddison & Ni Mhurchu 2009]. This “noise” was partially corrected using the principle of Differential Global Positioning System (DGPS): stationary receivers placed on known locations on the ground compare their fixed position with the position given by the satellites. The correction signals are sent via radio waves from these fixed receivers, via a differential receiver, to the GPS receiver [Shutz & Herren 2000; Larsson & Henriksson-Larsén 2001; Witte & Wilson 2005; Townshend et al. 2008]. In 2000, the President Bill Clinton announced that he had ordered the U.S. military to stop scrambling signals from its GPS satellite network. The “Selective Availability” was then discontinued in order to make the data available to civilian GPS owners [Maddison & Ni Mhurchu 2009].

Figure 1. *Representation of the GPS satellites network in orbit around the Earh.*

The GPS is currently the only fully functional global navigation satellite system (GNSS). It is a network of 24 operational satellites plus 3 additional back-up satellites in orbit around the Earth (**Figure 1**). This constellation of GPS satellites orbit at 11,000 nautical miles (about 20,000 km) around the Earth in six different orbital paths, each making one revolution in 12 hours [Shutz & Herren 2000; Terrier & Shutz 2005]. This mechanism leads the system to be able to provide continuous coverage in any part of the world (up to 8 satellites are accessible from any point an Earth) [Shutz & Herren 2000]. A GPS signal contains three different bits of information: a pseudorandom code, ephemeris data and almanac data. The pseudorandom code is simply an I.D. code that identifies which satellite is transmitting information. Ephemeris data contains important information about the status of the satellite (healthy or unhealthy), current date and time. This part is essential for determining a position. The almanac data tells the GPS receiver where each GPS satellite should be at any time throughout the day. Each satellite transmits almanac data showing the orbital information for the satellite and for every other satellite in the system [Terrier & Shutz 2005]. Each satellite is equipped with an atomic clock. The satellites first set the clock in the GPS receiver in synchronization with the atomic clock in the satellite. The satellites then constantly send information (at speed of light) about exact time to the GPS receiver. By comparing the time given by a satellite and the time within the GPS receiver, the signal travel is calculated. The distance to the satellite is then calculated by multiplying the signal travel time with the speed of light [Larsson & Henriksson-Larsén 2001; Larsson 2003]. By calculating the distance to at least three satellites, a single, two-dimensional position can be trigonometrically determined [Larsson 2003; Townshend et al. 2008] (**Figure 2**). By calculating the distance to at least four satellites, a three- dimensional position can be calculated. In Most commercially available GPS, speed is automatically determined by Doppler shift, i.e. measurements of the changes in satellite signal frequency due to the movement of the receiver [Shutz & Herren 2000].

The main advantages of GPS technology are that it is portable, waterproof, simple to use and auto-calibrate. It works anywhere in the world, with any weather conditions, 24 hours a day [Terrier & Shutz 2005]. GPS receivers are light, small size, and allow non-invasive and non-obtrusive free-living measurements including uphill or downhill locomotion on any surfaces (see **Appendix A**). In addition, through the use of appropriate software, this technology permits to get data in real time or to store them in the memory and subsequently download to a computer [Schutz & Chambaz 1997; Terrier & Shutz 2005; Maddison & Ni Mhurchu 2009].

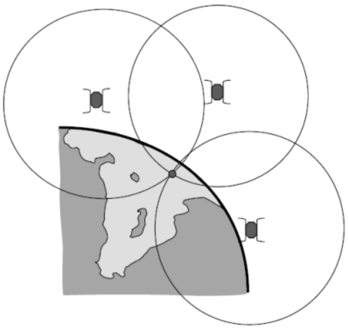

Figure 2. *Principal of determining the position by the use of a GPS. The distance to at least three satellites is required [Larsson 2003].*

The major disadvantage of GPS technology is that measurements can only be done in an environment in which access to the satellites is not obstructed. GPS regularly fail to record positions indoors. The signal travels by line of sight, meaning they will pass through clouds, glass and plastic, but will not go through most solid objects such as buildings, mountains and trees. This fact can cause degradation of the quality and accuracy of the signal or causing a drop in the signal during monitoring periods. Signal dropout occurs when a receiver temporarily loses satellite reception, creating a gap in the data. Finally, static activities cannot obviously be measured [Schutz & Chambaz 1997; Terrier & Shutz 2005; Duncan et al. 2009]. With specific regard to soccer, the use of GPS in stadia with high walls and curved roofs may provide unreliable data because fewer satellites are available to triangulate signals from devices [Cumminis et al. 2013]. In addition, the soccer federation does not permit the use of GPS within professional competition matches. Unfortunately, it has been demonstrated that data from GPS and semiautomatic video-based technology (i.e. video match analysis) are not interchangeable [Harley et al. 2001]. As a consequence, it is not possible to analyze GPS data from training and match data from video analysis together in order to quantify the cumulative players' loads during both training and match play. Finally, previous investigation suggested that caution must be applied if using real time data to monitor performance, especially if targets are set for athletes using post game/post training data [Aughey & Falloon 2010].

A number of informative, technical reviews on GPS [Aughey 2011; Cumminis et al. 2013] have been published outlining how this technology enables three-dimensional movement of an individual or group to be tracked over time in air-, aquatic-, or land-based environments. The recent development of portable GPS units has permitted wider application of this technology in a variety of settings, including sport, thus providing an additional means for describing and understanding the spatial context of physical activity. First utilized for athlete tracking in 1997 [Schutz & Chambaz 1997], GPS technology is now increasingly used in team sport settings to provide sports scientists, coaches, and trainers with comprehensive and real-time analysis of on-field player performance during competition or training. GPS technology has been used extensively in rugby league, rugby union, Australian football league (AFL), cricket, hockey, and soccer, with only limited research available in netball, hockey, and lacrosse. Current literature provides an array of information on the activity profile of field sport athletes. By measuring player movements, GPS can be used to objectively quantify levels of exertion and physical stress on individual athletes, examine competition performances, assess different positional workloads, establish training intensities, and monitor changes in player physiological demands. Player movement patterns and activity profiles (external loads) can be used in addition to tactical information and physiological responses (internal load) to characterize competitive match play. From its introduction, GPS was used to measure basic components of player movement patterns, speed, and distance travelled and the number of accelerations and decelerations [Cumminis et al. 2013].

There is an abundance of literature examining the validity and reliability of GPS for the measurement of movement in different sports (**Table 1**).

Table 1. Validation studies of GPS during human locomotion.

Study	**GPS receiver model (sample rate)**	**Task**	**Golden standard**	**Main findings**
Schutz & Chambaz 1997	Garmin GPS 45 (0.5Hz)	Walking, running, cycling	Chronometry	**Speed error**: SD of error=0.31m/s (walking); 0.19m/s (running); 0.22m/s (cycling)
Schutz & Herren 2000	Garmin 12XL (0.5Hz); Aztec SA RXMAR 1 (0.5Hz)	Walking, running	Chronometry	**Speed error**: SD of error=0.03m/s (walking); 0.03m/s (running)
Larsson 2001	Garmin 12CX (DGPS 0.5Hz)	Running	Chronometry	**Distance error**: Mean error for 115m straight section=0.8±2.78m **Speed error**: r=0.9995
Witte & Wilson 2004	RoyalTek REB 2100 (1Hz)	Cycling	Custom-built bicycle speedometer	**Speed error**: Overall 45%<0.2m/s; straights 57%<0.2m/s
Witte & Wilson 2005	Laipac Technology G30-L (1Hz); RoyalTek REB 2100 (1Hz)	Cycling	Custom-built bicycle speedometer	**Speed error**: Overall 59%<0.2m/s; straights 67%<0.2m/s
Edgecomb & Norton 2006	GPSports SPI 10 (1Hz)	Running	Computer based tracking system	**Distance error**: Mean error=4.8%; Absolute error=6.3% **Reliability**: TEM of 5.5%
Duncan & Mummery 2007	Garmin eTrex (1Hz)	Walking, cycling	Measured distance	**Distance error**: Absolute unit error from 5.03 to 8.53% (raw data); from 0.32 to 1.97% (clean data) **Reliability**: TEM from 3.74 to 15.51% (raw data); from 1.42 to 1.98% (clean data)
Townshend et al. 2008	Wonde Proud Technology GPS-BT55 (1Hz)	Walking, running	Chronometry	**Distance error**: Mean error=1.08±0.34m **Speed error**: r=0.9984 (straight); 0.9973 (curve)
MacLeod et al. 2009	GPSports SPI Elite (1Hz)	Running and sprinting with changes of direction	Timing gates	**Distance error**: Mean error=0.04% **Speed error**: r=0.99
Petersen et al. 2009	GPSports SPI 10 (1Hz); GPSports SPI Pro (5Hz); Catapult MinimaxX (5Hz)	Walking, running and sprinting with changes of direction	Timing gates	**Distance error**: Mean ± 90% CI = from 0.4±0.1% to 3.8±1.4% (Walking); from 2.6±1.0% to 23.8±8.8% (Sprinting) **Reliability**: Mean (90% CI) = from 0.3 (0.2 to 0.4) to 2.9% (2.3 to 4.0) (Walking); from 2.0 (1.6 to 2.8) to 30.0% (23.2 to 43.3) (Sprinting)
Coutts & Duffield 2010	GPSports SPI Elite (1Hz); GPSports SPI 10 (1Hz); GPSports WiSPI (1Hz)	Walking, running and sprinting with changes of direction	Timing gates	**Reliability**:[Distance] CV=3.6-7.1% (Total distance); 11.2-32.4% (High-intensity running); 11.5-30.4% (Sprinting). [Speed] CV=2.3-5.8% (Peak speed)

Gray et al. 2010	GPSports SPI Elite (1Hz)	Walking, running and sprinting with changes of direction	Theodolite	**Reliability**:[Intra-receiver] CV=1.85 (Linear walking); 4.80 (Non-linear sprinting). [Inter-receiver] CV=2.02 (Linear walking); 6.04 (Non-linear sprinting).
Barbero-Alvarez et al. 2010	GPSports SPI Elite (1Hz)	Sprinting (15 and 30m)	Timing gates	**Speed error**: [Peak speed] r=0.87(15m); 0.94(30m) **Reliability**: [Peak speed] CV=1.2% and ICC=0.97
Portas et al. 2010	Catapult MinimaxX (1-5Hz)	Running and sprinting with changes of direction	Measured distance	**Distance error**: Mean ± 90% CI = from 1.8±0.8% to 6.88±2.99% **Reliability**: CV from 2.2 to 4.5%
Duffield et al. 2010	GPSports SPI Elite (1Hz); Catapult MinimaxX (5Hz)	Running and sprinting with changes of direction	Vicon 3D digital optical motion analysis systems (100Hz)	**Distance error**: CV from 4 and 25% (both 1Hz and 5Hz). **Reliability**: ICC values from 0.10 to 0.70 (both 1Hz and 5Hz)
Randers et al. 2010	GPSports SPI Elite (1Hz); Catapult MinimaxX (5Hz)	Walking, running and sprinting with changes of direction	Video time-motion analysis (Amisco)	**Distance error**: Total: r=0.62(1Hz), r=0.90(5Hz). High-intensity running: r=0.54(1Hz), r=0.93(5Hz). Sprinting: r=0.42(1Hz), r=0.93(5Hz)
Jenninngs et al. 2010*a*	Catapult MinimaxX (1-5Hz)	Walking, running and sprinting with changes of direction	Timing gates	**Distance error**: Mean ± 90% CI = from 9.0% to 32.4% **Reliability**: CV = 3.6% (5Hz, circuit); 77.2% (1Hz, sprinitng over 10m)
Jenninngs et al. 2010*b*	Catapult MinimaxX (5Hz)	Walking, running and sprinting with changes of direction	-	**Reliability**: [Inter-receiver] Mean ± 90% CI = from 9.5±7.2% to 10.7±7.9%
Waldron et al. 2011	GPSports SPI Pro (5Hz)	Maximal sprint (30m)	Timing gates	**Distance error**: 95% ratio LOA showed systematic biases ranging from 1.05 to 1.29; **Speer error**: from 2.01 to 3.62 km/h; **Reliability**: CV=1.62 to 2.3% (Disance and speed); 0.78% (Peak speed)
Castellano et al. 2011	Catapult MinimaxX (10Hz)	Sprinting (15 and 30m)	Video camara (25Hz) and timing gates	**Distance error**: SEM=10.9% (15m); 5.1% (30m) **Reliability**: CV=1.30% (15m); 0.70% (30m).
Harley et al. 2011	Catapult MinimaxX (5Hz)	Walking, running and sprinting with changes of direction	Semi-automatic multiple-camera system (PzoZone)	**Distance error**: d=0.51 (Total); 0.45 (High-intensity running); 0.68 (Sprinting)
Johnston et al. 2012	Catapult MinimaxX (5Hz GPS)	Walking, running and sprinting with changes of direction	Tape measure (distance) & timing gates (speed)	**Distance error**: %TEM<5% **Speed error**: (peak speed) %TEM5-10% **Reliability**: (distance) %TEM=from 2.0 (Overall) to 112.0 (running at speed >25km/h)
Varley et al. 2012	Catapult MinimaxX (5-10Hz)	Acceleration, deceleration and running at constant speed	Tripod-mounted laser (50Hz)	**Speed error**: SEE: CV=3.1% (10Hz); 11.3% (5Hz) **Reliability**: CV=1.9% (10Hz); 6.0% (5Hz)

Akenhead et al. 2013	Catapult MinimaxX (10Hz)	Maximal sprint (10m)	Laser (2000Hz)	**Speed error**: Mean bias ± 95% LOA=0.12 and −0.40 m/s (during acc=0–0.99 and >4 m/s/s, respectevely). SEE=0.12 and 0.32m/s (during acc=0–0.99 and >4 m/s/s, respectevely). TE=0.05 and 0.12m/s (during acc=0–0.99 and >4 m/s/s, respectevely).
Vickery et al. 2013	Catapult MinimaxX (5-10Hz); GPSports SPI Pro X (15 Hz)	Different drills replicating movements typical of tennis, cricket and field-based (soccer) sports	Vicon 3D digital optical motion analysis systems (100Hz)	**Distance & Speed error**: The majority of distance and speed measures as measured using the 5, 10 and 15 Hz GPS devices, were not significantly different (p>0.05) to the VICON data. **Reliability**: CV=3-33%; ICC= r=-0.35-0.39 (Distance and speed measures; 5 and 15Hz GPS)

LOA=limits of agreement; SEE=standard error of the estimate ±95% CI; TE=typical error; MCS=semi-automatic multiple-camera system; SD=standard deviation; CI=confidence interval; CV= coefficient of variation; SEM=Standard error of measurement; TEM=technical error of measurement; ICC=intra-class correlation coefficient; r=Pearson's correlation coefficient; d=Cohen's effect sizes for between-group difference.
When no specified speed error is related to mean speed and reliability to distance covered.

The gold standard criterion method used to investigate GPS validity for distance is to measure a course with a trundle wheel or tape measure and, for speed, use of timing gates at the start and finish [Aughey 2011], a speed gun [Varley et al. 2012; Akenhead et al. 2013] or digital optical motion analysis systems [Duffield et al. 2010; Vickery et al. 2013]. GPS devices are currently manufactured with 1, 5, and 10 Hz sampling rates (the speed at which the unit gathers data). The literature suggests that GPS with a higher frequency rate provides greater validity for measurement of distance. When comparing the precision of distance acquisition between a 1 and a 5 Hz GPS, the standard error of a standing start 10m sprint was 32.4 and 30.9%, respectively [Jenning et al. 2010a]. By contrast, a 10 Hz GPS demonstrated a 10.9% standard error over a 15m sprint [Aughey 2011]. Recently, it has been reported that GPS devices at 1 Hz may be unable to record movements taking <1 s to complete [Johnston et al. 2012]. The newer 10 Hz units are capable of measuring the smallest worthwhile change in acceleration and deceleration [Varley et al. 2012]. The greater errors associated with measurement of distance with the 1 and 5 Hz versus the 10 Hz GPS devices indicate that the sampling rate may be limiting the accuracy of distance measurements and velocity.

The speed of a movement impacts the validity of the GPS-measured distance. The earliest validation of a GPS device (GPS 45, Garmin) showed various walk and run velocities (2–20 km·h^{-1}) were highly correlated (r = 0.99) with a chronometer [Schutz & Chambaz 1997]. A more recent study [Portas et al. 2010] shows GPS distance measurement error to be lowest during walking (~1.8 m·s^{-1}; standard error of estimate [SEE] 0.7%) and highest during running (~6 m·s^{-1}; SEE 5.6%). Similarly, another study [Johnston et al. 2012] reported that GPS is capable of measuring work rate patterns performed at velocities >20 km·h^{-1}; however, recommended caution when analysing work rate patterns at velocities >20 km·h^{-1}. These results indicate that movement velocity impacts upon accuracy, with GPS reported as a valid method for measurement of distance travelled at low to moderate but not high speeds. In addition, the validity and reliability of 10 Hz GPS for the measurement of instantaneous velocity has been shown to be inversely related to acceleration. Even using 10 Hz GPS, during accelerations of over 4 $m \cdot s^{-2}$, accuracy is compromised [Akenhead et al. 2013].

The validity of distance measures improves with longer duration activities [Jenning et al. 2010a]; for example, the coefficient of variation (CV) diminished from 32.4 to 9.0% for sprint distances of 10 and 40 m, respectively. The CV was further reduced to 3.8% for a range of velocities completed over a 140 m modified team-sport running circuit [Jenning et al. 2010a]. The factors of sampling frequency, distance, and speed, which affect GPS validity, similarly affect the reliability of GPS. The impact of sampling frequency still remains unclear; for example, the CV of a linear soccer task has been reported as 4.4-4.5% for a 1 Hz GPS and 4.6-5.3% for a 5 Hz [Portas et al. 2010]. However, another study [Jenning et al. 2010a] reported the CV of a 10 m sprint as 77% and 39% for 1 and 5 Hz, respectively. More recently, a higher sampling rate of 10 Hz has demonstrated improved reliability during the constant velocity and acceleration or deceleration phase (CV <5.3% and <6%, respectively) [Varley et al. 2012]. Whilst the data are currently ambiguous and may be explained through the use of different GPS manufacturers and models [Aughey 2011], it would seem that an increased sample rate appears to improve the reliability of GPS measures.

The reliability of GPS decreases with the increased velocity of movement. The CV of walking for a 5-Hz GPS was 1.4-2.6%, whilst the CV of sprinting over a 20 m distance was 19.7-30%. Similarly, CVs of 30.8% and 77.2%, respectively, for walking and sprinting over a 10 m distance were noted with a 1 Hz GPS [Jenning et al. 2010a]. The reliability of GPS devices is also negatively affected by movements requiring changes in direction. The CV for gradual and tight change of direction movements at walking pace has been reported as 11.5% and 15.2%, respectively [Jenning et al. 2010a]. The tight change of direction movements may demonstrate a decreased reliability due to the increased number of speed changes performed [Jenning et al. 2010a]. The re-test reliability between GPS devices is consistent. A recent study [Waldron et al. 2011] examined the re-test reliability between GPS units, finding random errors between two tests ranging from 0.56 to 1.64 $km \cdot h^{-1}$ and small mean biases (-0.01 to -0.14 $km \cdot h^{-1}$) for all sprint intervals.

Overall, studies conclude that GPS devices have an acceptable level of validity and reliability for assessing movement patterns at lower speeds and over increased distance efforts. The decreased reliability of GPS units to accurately measure movement patterns during short duration, high-speed, straight-line running, and efforts requiring changes in direction may limit both accuracy and reliability for assessing these aspects in team sports. However, GPS units with increased sampling frequency demonstrate improved reliability and validity and can be utilized in the monitoring of physical activity in situations such as team sports.

The evolution of the GPS technology led, as a consequence, to a wide use of it in order to monitor different individual and team sports during both training and competition. With regard to soccer, since players are not allowed to wear the GPS receiver during official matches, significant attention in the literature has centred upon estimating the external load associated with different training sessions and training drills (**Table 2**). To date, the application of GPS technology has frequently centred around evaluating the distance covered or time spent at specific running velocities with particular attention being focused on the volume of high-speed activity given its importance during match-play [Di Salvo et al. 2009;

Iaia et al. 2009; Vigne et al. 2010]. In particular, several studies have focused on the physical load evaluation of different small-sided games (SSGs) since they are a popular and effective method of training in soccer. During SSGs many prescriptive variables that can be controlled by the coaches may influence the exercise intensity during SSGs. These factors include pitch area, player number, coach encouragement, training regimen (continuous or interval, including work : rest manipulations), rule modifications, and the use of goals and/or goalkeepers [Hill-Haas et al. 2011].

Table 2. Summary of the studies that used GPS technology in soccer.

Study	**GPS receiver model (sample rate)**	**Subjects**	**Monitored activity**
Hill-Haas et al. 2008*a*	GPSports SPI 10 (1Hz)	16 young players	2v2 & 4v4 SSGs
Hill-Haas et al. 2008*b*	GPSports SPI 10 (1Hz)	16 young players	4v4 SSGs
Hill-Haas et al. 2009*a*	GPSports SPI 10 (1Hz)	16 young players	2v2, 4v4 & 6v6 SSGs
Hill-Haas et al. 2009*b*	GPSports SPI 10 (1Hz)	16 young players	2v2, 4v4 & 6v6 SSGs (interval and continuous regimes)
Castagna et al. 2009	GPSports SPI Elite (1Hz)	21 young players	Competitive matches
Castagna et al. 2010	GPSports SPI Elite (1Hz)	18 young players	Competitive matches
Casamichana et al. 2010	GPSports SPI Elite (1Hz)	10 young players	5v5 SSGs (small, medium and large pitch)
Buchheit et al. 2010*a*	GPSports SPI Elite (1Hz)	99 young players	Friendly matches
Buchheit et al. 2010*b*	GPSports SPI Elite (1Hz)	99 young players	Friendly matches
Hill-Haas et al. 2010	GPSports SPI 10 (1Hz)	16 young players	3v4 & 3v3 SSGs (+1 floater), 5v6 & 5v5 SSGs (+1 floater)
Barbero-Alvarez et al. 2010	GPSports SPI Elite (1Hz)	14 young players	15m & 30m distance sprint
Harley et al. 2010	Catapult MinimaxX v2.0 (5Hz)	112 young players	Competitive matches
Buchheit et al. 2011	GPSports SPI Elite (1Hz)	14 young players	Sprint during matches
Dellal et al. 2011*a*	GPSports SPI Elite (5Hz)	20 professional players	2v2, 3v3 & 4v4 SSGs
Dellal et al. 2011*b*	GPSports SPI Elite (5Hz)	20 professional players & 20 amateur players	2v2, 3v3 & 4v4 SSGs (1 touch, 2 touches and free play)
Dellal et al. 2011 *c*	GPSports SPI Elite (5Hz)	20 professional players	4v4 SSGs (1 touch, 2 touches and free play)
Harley et al. 2011	Catapult MinimaxX v2.0 (5Hz)	6 professional players	Competitive matches
Gomez-Piriz et al. 2011	GPSports SPI Elite (5Hz)	10 professional players	Training sessions composed predominantly of SSGs
Brandes et al. 2012	Forerunner 305, Garmin Inc. (1 Hz)	17 young players	2v2, 3v3 & 4v4 SSGs

Thorpe et al. 2012	GPSports SPI Elite (1Hz)	7 semi-professional players	Competitive matches
Mugglestone et al. 2012	GPSports SPI Elite (1Hz)	20 semi-professional players	Competitive matches
Dwyer et al. 2012	Catapult MinimaxX (1Hz) & GPSports SPI Elite (1Hz)	5 professional players	Sprint during matches
Dellal et al. 2012*a*	GPSports SPI Elite (5Hz)	20 professional players	2v2, 3v3 & 4v4 SSGs
Dellal et al. 2012*b*	GPSports SPI Elite (5Hz)	40 professional players	4v4 SSGs & friendly matches
Vescovi 2012	GPSports SPI Pro (5Hz)	21 professional female players	Sprint during matches
Casamichana et al. 2012	Catapult MinimaxX v4.0 (10Hz)	27 semi-professional players	3v3, 5v5 & 7v7 SSGs & friendly mathces
Del Coso et al. 2012	GPSports SPI Pro X (15 Hz)	19 semi-professional players	30m sprint test & soccer simulation
Souglis et al. 2013	Forerunner 305, Garmin Inc. (1 Hz)	22 professional players	Friendly matches
Buchheit et al. 2013	GPSports SPI Elite (1Hz)	33 young players	Competitive matches
Mendez-Villanueva et al. 2013	GPSports SPI Elite (1Hz)	103 young players	Competitive matches
Lovell et al. 2013	Catapult MinimaxX v2.0 (5Hz)	20 professional young players	Competitive matches
Aguiar et al. 2013	GPSports SPI Pro (5Hz)	10 professional players	2v2, 3v3, 4v4 & 5v5 SSGs
Akubat et al. 2013	Catapult MinimaxX v2.0 (5Hz)	10 amateur players	Soccer simulation
Varley et Aughey 2013	GPSports SPI Pro (5Hz)	29 professional players	Competitive matches
Scott et al. 2013	Catapult MinimaxX v2.0 (5Hz)	15 professional players	Training sessions
Vescovi 2013	GPSports SPI Pro (5Hz)	89 young female players	Competitive matches
Akenhead et al. 2013	Catapult MinimaxX v4.0 (10Hz)	36 semi-professional players	Competitive matches
Casamichana et al. 2013	Catapult MinimaxX v4.0 (10Hz)	28 semi-professional players	Training sessions
Castellano et al. 2013	Catapult MinimaxX v4.0 (10Hz)	14 semi-professional players	3v3, 5v5 & 7v7 SSGs

Where no specified the players who took part to the study were male.

1.3 Predicted metabolic power: 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 [Bangsbo 1994; Iaia et al. 2009; Osgnach et al. 2010]. Traditional approaches tried to estimate the physical demands of both official matches and training sessions by calculating the distance covered by the players in different speed categories with particular attention focused on the distance covered at high speed [Di Salvo et al. 2009; Vigne et al. 2010; Hill-Haas et al. 2011]. This representation of the external load however, does not take into account the additional distance covered or energy demands associated with accelerations and decelerations. As a matter of the fact, a massive metabolic load is imposed on players not only during the maximally intensive phases of the match or the training sessions (intended as high running speed) but every time acceleration or deceleration is elevated, even when speed is low [Osgnach et al. 2010]. In line with such observations, di Prampero et al. recently introduced a new approach to estimating the energy cost of accelerated and decelerated running [di Prampero et al. 2005].

Since the second half of the 19th century, the energetics and biomechanics of walking and running at constant speed have been the object of many studies, directed towards elucidating the basic mechanisms of these most natural forms of locomotion [Margaria 1938; Margaria et al. 1963; di Prampero 1986]. It has been demonstrated that the energy cost of walking increases with the speed, the function is given by a progressively steeper curve and it shows a minimum value at ~1.3 $m \cdot s^{-1}$ [Margaria et al. 1963; Minetti et al. 2002]. The energy cost of walking on the level at constant speed has been calculated to be equal to 1.85 ± 0.57 $J \cdot kg^{-1} \cdot m^{-1}$ (mean ± SD) at the speed of 0.69 $m \cdot s^{-1}$. The average minimum one was 1.64 ± 0.50 $J \cdot kg^{-1} \cdot m^{-1}$ at the speed of 1.0 ± 0.3 $m \cdot s^{-1}$ [Minetti et al. 2002]. On the other hand, the energy cost of running is a linear function of the speed, the extrapolated origin of the line being at about the basal level [Margaria et al. 1963]. The line of walking on the level cuts the line for running at 8.5 $km \cdot h^{-1}$, which means that below this speed value, walking is more economical than running; above it, running becomes more economical [Margaria et al. 1963]. The linear function for running means that the cost per kilometre is constant and independent of speed, which appears to be somewhat in conflict with the opinion that in increasing the speed of contraction, more energy is used in overcoming the viscosity of the muscle [Margaria et al. 1963]. The energy cost of running on level at constant speed has been demonstrated to be equal to 3.40 ± 0.24 $J \cdot kg^{-1} \cdot m^{-1}$ (mean ± SD), independent of speed [Minetti et al. 2002]. Furthermore, it has been demonstrated that both the energy cost of level walking and running at constant speed depend on the characteristics of the terrain, with cost being higher on soft than on hard ground [Zamparo et al. 1992; Lejeune et al. 1998]. The energy cost of running is also affected by the foot landing patterns, which allow a different efficiency of leg muscles and tendons [Ardigò et al. 1995] and increase when muscles are fatigued [Brueckner et al. 1991]. In addition, previous studies reported that when walking or running at constant speed on positive gradients both the energy cost of walking and running increase as a function of the incline (up to +0.15 for running and up to +0.40 for walking). When negative gradients are applied, both walking and running energy costs attain their lowest values at -0.10. Below this slope, and down to -0.20 for running and -0.40 for walking, the energy cost of both walking and running are negatively related to the incline, becoming higher the lower the slope (**Figure 3**) [Margaria 1938; Margaria et al. 1963; Minetti et al. 1994; Minetti et al. 2002].

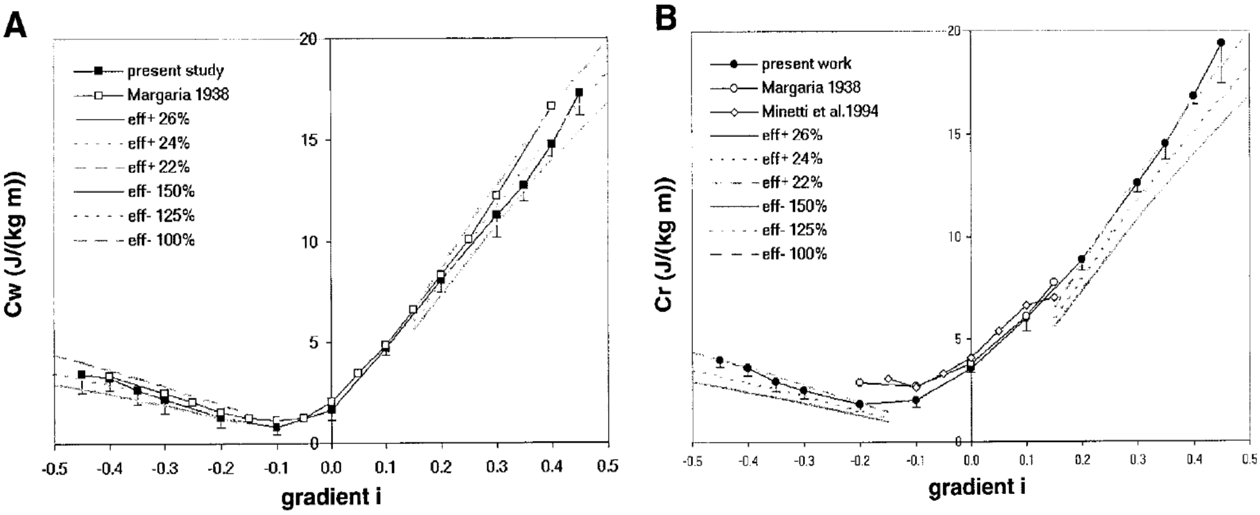

Figure 3. *Metabolic energy cost of walking (Cw; A) or running (Cr; B) as a function of the gradient from the works by Margaria 1983, Margaria et al. 1963, Minetti et al. 1994 and Minetti et al. 2002.*
Minimum energy cost of walking and average energy cost of running for each gradient have been reported. To accurately describe the relationship between Cw or Cr and the gradient "i" within the investigated range, 5th-order polynomial regression were performed, that yielded:

$$Cw_i = 280.5i^5 - 58.7i^4 - 76.8i^3 + 51.9i^2 + 19.6i + 2.5 \quad (R^2 = 0.999)$$
$$Cr_i = 155.4i^5 - 30.4i^4 - 43.3i^3 + 46.3i^2 + 19.5i + 3.6 \quad (R^2 = 0.999)$$

The curves represent the metabolic cost corresponding to a given positive and negative efficiency, according to:

$$C_{eff} = \frac{\dot{W}_{vert}}{v\,eff} = \frac{g\sin(arc\,tan|i|)}{eff}$$

Where C is the metabolic cost, $\dot{W}vert$ is vertical work rate, "v" is treadmill speed, "g" is gravity acceleration, and "eff" is efficiency. The "eff" values for uphill and downhill locomotion, respectively, were chosen as equal to 26% and 150% (solid curve), 24% and 125% (finely dashed curve), and 22% and 100% (grossly dashed curve) [Minetti et al. 2002].

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 [di Prampero et al. 2005]. Indeed, the only published works on this matter deal with either some mechanical aspects of sprint running [Cavagna et al. 1971] or with some indirect approaches to its energetics [di Prampero et al. 1993; Arsac & Locatelli 2002]. 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 [di Prampero et al. 2005]. It has been demonstrated that the muscles accelerating the body forward in sprint running must contract at a progressively increasing speed as the velocity of run rises: according to the force-velocity relation of muscle this may affect their mechanical power output. Almost all of the positive work done during the first second from the start is found as an increase of the kinetic energy of the body. However, as the run speed rises, air resistance and in particular the deceleration of the body forward, taking place at each step, rapidly increase, limiting the velocity of the run. The average mechanical power developed by the muscles during push at each step increases with the velocity of running. At low speed the contractile component of the muscles seems to be mainly responsible for the output, whereas at high speed (>25 $km \cdot h^{-1}$) an appreciable fraction of the power appears to be sustained by the mechanical energy stored in the "series elastic elements" during stretching to contracted muscles (negative work) and released immediately after in the positive work phase [Cavagna et al. 1971].

A recent study [di Prampero et al. 2005] determined the speed of the initial 30 m of an all-out run from a stationary start on a flat track. The peak speed of 9.46 ± 0.19 $m \cdot s^{-1}$ (mean ± SD) was reached after about 5 s, the highest forward acceleration (a_f), attained immediately after the start, amounting to 6.42 ± 0.61 $m \cdot s^{-2}$. In order to try to estimate the energy cost and metabolic power output during sprint running, di Prampero et al. proposed a new theoretical model. According to this model, accelerated running on a flat terrain is considered energetically equivalent to uphill running at constant speed that was previously studied [Minetti et al. 2002] and the uphill slope is dictated by the forward acceleration [di Prampero et al. 2005]. During acceleration, the runner's body (assumed to coincide with the segment joining the centre of mass and the point of contact foot terrain) must lean forward, as compared to constant speed running, by an angle $\alpha = \arctan g/a_f$ (g=Earth's acceleration of gravity). The complement (90-α) is the angle, with respect to the horizontal, by which the terrain should be titled upwards to bring the runner's body to a position identical to that of constant speed running (**Figure 4**). Therefore, accelerated running is considered similar do running at constant velocity up an "equivalent slope" (ES) where:

$$ES = \tan(90-\alpha) = 90 - \arctan g/a_f \qquad (1)$$

In addition, the average force exerted by active muscles during sprinting is greater than the subject's body weight by the ratio g'/g (**Figure 4**A). This ratio is called "equivalent normalized body mass" (EM) and represents the overload imposed on the athlete by the acceleration itself.

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

Both ES and EM are dictated by the forward acceleration; therefore they can be easily calculated once a_f is known. As already explained (**Figure 3**B) [Minetti et al. 2002], the energy cost (Cr_i, $J \cdot kg^{-1} \cdot m^{-1}$) of running uphill at constant velocity is described by:

$$Cr_i = 155.4i^5 - 30.4i^4 - 43.3i^3 + 46.3i^2 + 19.5i + 3.6 \qquad (3)$$

Where "*i*" is the incline of the terrain, and 3.6 ($J \cdot kg^{-1} \cdot m^{-1}$) is the energy cost of running at constant speed on flat compact terrain; therefore the energy cost of accelerated running (C_{sr}) can be easily obtained as:

$$C_{sr} = (155.4ES^5 - 30.4ES^4 - 43.3ES^3 + 46.3ES^2 + 19.5ES + 3.6) \cdot EM \qquad (4)$$

Where "*i*" has been replaced by ES, and the overall cost is multiplied by EM.

Metabolic power output (P_{met}) can be then calculated multiplying C_{sr} by running speed (v, in $m \cdot s^{-1}$):

$$P_{met} = C_{sr} \cdot v \qquad (5)$$

Therefore, once speed and acceleration are known, the metabolic power output by the athlete in any given moment can be easily estimated [di Prampero et al. 2005].

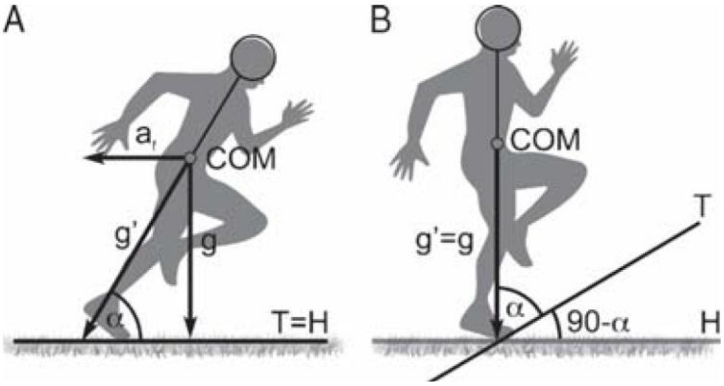

Figure 4. *Simplified view of the forces acting on a subject during accelerated running on flat terrain (A) or running uphill at constant speed (B).*
The runner's body is represented by a segment of straight line. COM = center of mass; T = terrain; H = horizontal; g = acceleration of gravity; a_f *= forward acceleration; g' = vectoral sum of af and g. Accelerated running on flat terrain (A) is considered to be equivalent to constant speed uphill running (B) wherein the angle of the terrain T with the horizontal H (90-α) is such that the angle of the subject's body with the terrain (α) is unchanged [Osgnach et al. 2010 modified from di Prampero et al. 2005].*

Based on this method, the energy cost of a 30 m sprint running was then calculated from speed and acceleration data provided by a 35 Hz radar Stalker ATS System™ (Radar Sales, Minneapolis, MN, US) [di Prampero et al. 2005]. The instantaneous energy cost attains a peak of ~50 J·kg^{-1}·m^{-1} immediately after the start; thereafter it declines progressively to attain, after about 30 m, the value for constant speed running on flat terrain (i.e. ~3.8 J·kg^{-1}·m^{-1}). The average energy cost over the 30 m sprint running was ~11.4 J·kg^{-1}·m^{-1} (i.e. about three times larger than that of constant speed running on flat terrain) (**Figure 5** A). Consequently, the metabolic power was calculated multiplying instantaneous energy cost by running speed (eq. 5). The peak power output was attained after about 0.5 s and it was estimated to be ~100 W·kg^{-1}. The average power over the first 4 s of the sprint running was in order of ~65 W·kg^{-1} (**Figure 5** B) [di Prampero et al. 2005].

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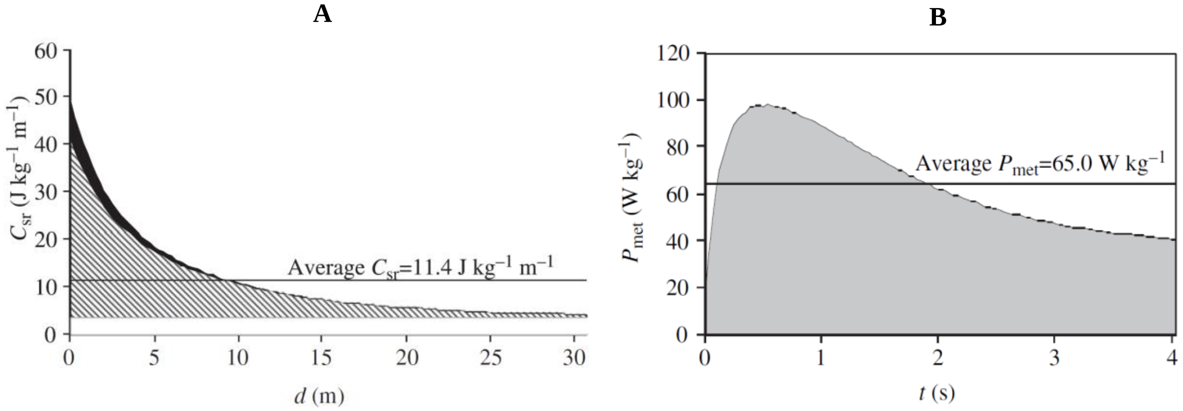

Figure 5. *Energy cost as a function of the distance (A) and metabolic power as a function of time (B) during sprint running.*
*(**A**) Energy cost (*C_{sr}*) of constant speed running is indicated by the lower horizontal thin line. Black and hatched distances between appropriate lines indicate effects of EM and ES, respectively. Upper horizontal thin line indicates average throughout the indicated distance. (**B**) Average power over 4 s is indicated by horizontal thin line [di Prampero et al. 2005].*

Using this approach, Osgnach et al. recently attempted to calculate the energy cost of official elite soccer matches [Osgnach et al. 2010]. In order to reduce possible errors due to the use of this method, equation 4 was slightly modified. This equation was based on data referred to running on a treadmill [Minetti et al. 2002]. Running on a soccer field has been demonstrated to be approximately 30% more costly than running on compact homogeneous terrain [Pinnington & Dawson 2001]. For this reason, the values of energy cost obtained by equation 4 were multiplied by a constant (KT = 1.29):

$$EC = (155.4ES^5 - 30.4ES^4 - 43.3ES^3 + 46.3ES^2 + 19.5ES + 3.6) \cdot EM \cdot KT \qquad (6)$$

Where *EC* is the energy cost of accelerated running on grass (in $J \cdot kg^{-1} \cdot m^{-1}$), *ES* is the equivalent slope: $ES = \tan(90 - \arctan g/a_f)$; g = Earth's acceleration of gravity; a_f = forward acceleration; *EM* is the equivalent body mass: $EM = [(a_f^2/g^2) + 1]^{0.5}$; and *KT* is a constant (KT = 1.29).

Equation 5 was applied to official elite soccer match data obtained from a 25 Hz multiple camera system (SICS®, Basssano del Grappa, Italy). The results of this study reported for the first time an estimation of the mean match energy expenditure equal to ~60 in $J \cdot kg^{-1} \cdot m^{-1}$. Distance covered at high metabolic power (>20 $W \cdot kg^{-1}$) amounted to 26% and corresponding energy expenditure to approximately 42% of the total. Researchers concluded that high intensity expressed as high power output during match-play are two to three times larger than those based solely on running speed [Osgnach et al. 2010].

1.4 Objectives

Despite the above-mentioned results and data, no study to date has compared the energy costs of field-based training in soccer using the two different approaches to determine the extent to which traditional approaches may underestimate the true physical demands. Such information is important since accurate determination of the training load placed upon athletes is critical in attempting to maximize performance enhancement and injury prevention strategies. Therefore, the aims of the current investigation were:

- to compare the energy cost of training when derived from the approach recently introduced based on estimated metabolic power [di Prampero et al. 2005; Osgnach et al. 2010] versus the traditional approach of distance covered at specific running speeds (*Study I*).
- to evaluate whether the degree to which the two approaches differ was dependent upon playing position and the type of training session undertaken (*Study I*).
- to evaluate the degree to which different Small-Sided Games (SSGs) influence the magnitude of the difference in high-intensity demands when derived by the two different approaches (*Study II*).
- to determine whether the degree to which the two approaches differ in the analyzed SSGs was dependent upon positional role (*Study II*).
- to provide a detailed analysis of different SSGs formats including new physical parameters such as changes in velocity as well as predicted energy expenditure and metabolic power in elite soccer players (*Study III*).

Chapter 2

MATERIALS & METHODS

The present thesis is based on three studies. *Study I* was designed in order to compare measurements of high-intensity activity during field-based training sessions in elite soccer players of different playing positions. Agreement was appraised between measurements of running speed alone and predicted metabolic power derived from a combination of running speed and acceleration. *Study II* evaluated the agreement between estimates of high-intensity activity during soccer small-sided games (SSGs) based on the two different methods and evaluated whether any bias between the two approaches was dependent upon playing position or drill characteristics. Finally, based on the acceleration and predicted metabolic power data in addition to speed data, *Study III* examined the extent to which changing the game format (possession play, SSG-P and game with regular goals and goalkeepers, SSG-G) and the number of players (5, 7 and 10 a-side) influenced the physiological and physical demands of SSGs.

2.1 Players and training observations.

Data were collected from 26 soccer players competing in the English Premier League (age = 26 ± 5 years; height = 182 ± 7 cm; body mass = 79 ± 5 kg) during the 2011-2012 in-season competition period.

<u>Study I</u>. A total of 628 individual training observations were undertaken on outfield players over a 10-week period with a median of 24 training sessions per players (range = 3-36). Players were assigned to one of five positional groups: central defender (training observations = 92), wide defender (training observations = 110), central midfielder (training observations = 103), wide midfielder (training observations = 145) and attacker (training observations = 178). Only data derived from the team field-based training sessions were analysed, no individual rehabilitation or individual fitness sessions were included for analysis. The warm up period prior to each training session was not included for analysis.

<u>Study II</u>. Three different SSGs were analyzed: 5vs5 (n = 10), 7vs7 (n = 11) and 10vs10 (n = 14) with each drill type incorporating two goalkeepers and regular sized goals (specific characteristics of each drill are reported in **Table 3**). Data were collected during the in-season competition period. A total of 420 individual drill observations were undertaken on outfield players with a median of 16 drill executions per player (range = 2-27). Players were assigned to one of five positional groups: central defender (drill observations = 13 in 5vs5; 26 in 7vs7; 28 in 10vs10), wide defender (drill observations = 19 in 5vs5; 17 in 7vs7; 34 in 10vs10), central midfielder (drill observations = 27 in 5vs5; 28 in 7vs7; 46 in 10vs10), wide midfielder (drill observations = 15 in 5vs5; 17 in 7vs7; 33 in 10vs10) and attacker (drill observations = 18 in 5vs5; 36 in 7vs7; 62 in 10vs10). Each drill was performed without interruption with constant supervision and motivation from coaches in order to maintain a high work-rate [Rampinini et al. 2007*a*]. A maximum of two touches of the ball per person were allowed during the drills, all being performed after a standardized warm up period.

Study III. A total of 873 individual drill observations were undertaken on outfield players with a median of 32 observations per players (range=7-52). Two different formats of SSGs were analyzed: small sided games played with goalkeeper and regular goals (SSG-G) and collective possession play only (SSG-P) where the objective was to keep the ball for longer than the opposing team. For both type of exercise three different modalities were performed and assessed: 5vs5 (player observations = 92 and 215 for SSG-G and SSG-P, respectively), 7vs7 (player observations = 124 and 85) and 10vs10 (player observations = 208 and 149). By considering the presence of the goalkeepers in SSG-G, the pitch dimensions in SSG-P slightly changed in order to keep the area per player almost unvaried (**Table 3**). As in *study II,* each drill was performed in a continuous regime, with the supervision, coaching and motivation of several coaches in order to keep up a high work-rate [Rampinini et al. 2007*a*]. During all the analyzed SSGs a maximum of two touches of the ball per person were allowed. Offside rule was not applied during the SSGs. In all formats the ball was always available by prompt replacement when hit out of the play [Dellal et al. 2011*a*; Dellal et al. 2012*b*; Castellano et al. 2013]. SSGs were completed after a standardized 20-minute warm up.

Table 3. Characteristics of the small-sided games included in *Study II* & *Study III*.

Drill	**Pitch dimension (m)**	**Pitch area (m^2)**	**Area per player (m^2)**		
5vs5 SSG-G	30x30	900	75	*Study II*	*Study III*
7vs7 SSG-G	45x35	1575	98		
10vs10 SSG-G	66x45	2970	135		
5vs5 SSG-P	27x27	729	73		
7vs7 SSG-P	37x37	1369	98		
10vs10 SSG-P	52x52	2704	135		

Goalkeepers were not included in any studies. The players were familiarized with both the SSGs formats and the material to be used during the weeks prior to the experimentation period. All participants were normally trained at the beginning of the testing protocol, none being affected by any pathology. Written informed consent was received from all players after a detailed explanation about the research design and its requirements, as well as the potential benefits and risks. The Ethics Committee of the University of Milan approved the study.

2.2 Data collection.

The players' physical activity during each training session or drill was monitored using portable global positioning system (GPS) technology (GPSports SPI Pro X, Canberra, Australia). The SPI Pro X (GPS and accelerometer integrated; size: 48 x 20 x 87 mm; 76 g) was placed into a harness that positioned the device between the player's shoulder blades. All devices were activated 15 min before the data collection to allow acquisition of satellite signals [Waldron et al. 2011]. In order to avoid inter-unit error players wore the same

GPS device for each training session [Jenninngs et al. 2010*b*]. During all training sessions 8-11 satellites were available for signal transmission, which is optimal for assessment of human movement [Jenninngs et al. 2010*b*]. This version of the SPI Pro provides raw position, distance and velocity data at 15 Hz (15 samples per second). For the purpose of this study, every three raw data points were averaged to provide a sampling frequency of 5 Hz. This type of system has previously been shown to provide valid and reliable estimates of the high-intensity distance covered in multi-directional sports such as soccer [Portas et al. 2010; Randers et al. 2010; Waldron et al. 2011; Varley et al. 2012].

2.3 Physical performance.

Total distance covered and duration was evaluated for each training session and SSGs analyzed in *Study I*, *II* and *III*. In addition, the physical demands of each training session for each player were evaluated through the assessment of speed and estimated energy cost (EC) and metabolic power (P_{met}) by adopting the equations proposed by di Prampero et al. and then modified by Osgnach et al. (equations 4, 5 and 6) in order to evaluate soccer player sprinting on grass [di Prampero et al. 2005; Osgnach et al. 2010]. The following three high-speed categories were used: high speed (HS; from 14.4 to 19.8 $km \cdot h^{-1}$), very high speed (VHS; from 19.8 to 25.2 $km \cdot h^{-1}$) and maximal speed (MS; >25.2 $km \cdot h^{-1}$) [Di Salvo et al. 2009; Gregson et al. 2010]. Metabolic power categories were defined as: high power (HP; from 20 to 35 $W \cdot kg^{-1}$), elevated power (EP; from 35 to 55 $W \cdot kg^{-1}$) and maximal power (MP; >55 $W \cdot kg^{-1}$) [Osganch et al. 2010]. To compare the high intensity energy costs of training when based on speed compared to P_{met}, the total distance covered at a speed >14.4 $km \cdot h^{-1}$ (TS) and the equivalent P_{met} (>20 $W \cdot kg^{-1}$; total high metabolic power; TP) were estimated. This threshold was set since 20 $W \cdot kg^{-1}$ is the P_{met} when running at a constant speed of approximately 14.4 $km \cdot h^{-1}$ on grass [Osganch et al. 2010].

In particular, in *Study II*, due to the different duration of the three SSGs analyzed, TS and TP distance covered in each of the three SSGs were also expressed as a percentage of the total distance to permit comparison between drills.

In addition, in *Study III*, the accelerations and decelerations lasting at least 1 s ($\Delta t=1$) were taken into account and analyzed as number of efforts. Based on a recent study by Minetti et. al. (See **Appendix B**) that demonstrated the substantial constancy of running metabolic cost at speed oscillating up to ~1 $m \cdot s^{-2}$, only changes in velocity >2 $m \cdot s^{-2}$ and <-2 $m \cdot s^{-2}$ were considered as mechanical and metabolic important demands. Consequently, the following four categories were used: high deceleration (HD; <-3 $m \cdot s^{-2}$), moderate deceleration (MD; from -2 to -3 $m \cdot s^{-2}$), moderate acceleration (MA; from 2 to 3 $m \cdot s^{-2}$), and high acceleration (HA; >3 $m \cdot s^{-2}$) [Osgnach et al. 2010]. Moreover, absolute maximal values of speed (in $km \cdot h^{-1}$), acceleration and deceleration (in $m \cdot s^{-2}$) reached during the exercises were calculated. Finally, since every drill had a different duration, the parameters taken into account for the statistical analysis were normalized by time (i.e. 4 minutes).

All the above-mentioned parameters were calculated using a custom Excel spreadsheet from instantaneous raw data of time, speed and distance available from the SPI Pro X software Team AMS

(GPSports SPI Pro X, Canberra, Australia). In the same program instantaneous acceleration values were calculated by dividing change in velocity by the change in time. Finally, equations 5 and 6 were also integrated in the custom spreadsheet in order to calculate total energy expenditure, average metabolic power, and distance covered in different metabolic power categories.

2.4 Statistical analysis.

Study I. Data were analysed with a generalized estimating equation model, which included the within-subjects factors of method type, player position and repeated training session.

Study II. Data were analysed using linear mixed modelling, which included the within-subjects factors of method type, player position and repeated drill.

Study III. A two-way ANOVA for repeated measures was performed in order to understand the main effect of the format type (SSG-G or SSG-P) and the number of the players involved (5, 7 or 10 a-side) on the physical parameters analysed.

Data are reported as mean ± standard deviation (SD). Significant main effects and interaction between factors were followed up with least significant difference (LSD) comparison [Perneger 1998]. Statistical significance was set at $p<0.05$. In addition, simple effect size (ES) estimated from the ratio of the mean difference to the pooled standard deviation was also calculated. Effect size values of 0.2, 0.5 and 0.8 were considered to represent small, moderate and large differences respectively [Vincent 1999]. The statistical analysis were performed using the software SPSS (version 19.0, IBM, Somers, USA).

Chapter 3

RESULTS & DISCUSSION

In this chapter the main results obtained from the three studies (*I*, *II* and *III*) are presented and discussed.

3.1 Running speed vs. metabolic power.

Table 4 shows the mean duration of training and distance covered in each speed category across the different playing positions. Overall session duration was 56.7 ± 18.0 min (mean ± SD) during which the players covered 3772 ± 1276 m. Mean HS, VHS and MS distance completed were 357 ± 218 m, 102 ± 94 m and 19 ± 34 m, respectively (mean ± SD). Training duration was similar between playing positions (**Table 4**). With the exception of attackers, the total distance covered by central midfielders was significantly greater compared with all other positions (central defenders ES=0.5, wide defenders ES=0.3, wide midfielders ES=0.4, $p<0.05$; **Table 4**) with a similar distance observed between remaining positions. The highest and lowest HS distance was covered by central midfielders and central defenders respectively ($p<0.001$; **Table 4**). The amount of VHS undertaken by wide defenders and attackers was greater than central defenders (ES=0.6, $p=0.026$ and ES=0.5, $p=0.002$, respectively; **Table 4**). No other differences were observed between positions including MS which was similar between all positions (**Table 4**).

Table 4. Training session duration and distance covered at different speed in relation to playing position (mean ± SD).

	Central defender (n=92)	**Wide defender (n=110)**	**Central midfielder (n=103)**	**Wide midfielder (n=145)**	**Attacker (n=178)**	**Follow-up tests (LSD)**
Duration (min)	53.4±18.4	55.9±18.1	58.1±19.7	55.2±16.6	59.5±17.4	CM=CD=WD=WM=A
TD (m)	3498±1204	3647±1302	4133±1538	3618±1138	3906±1183	(CM>CD=WD=WM)=A*
HS (m)	285±128	370±218	442±332	347±183	344±180	CM>WM=A=(WD>CD)*
VHS (m)	72±57	112±89	108±105	91±77	116±112	CM=WM=(WD=A>CD)*
MS (m)	16±31	20±33	21±37	17±28	21±38	CD=WD=CM=WM=A

*TD = Total distance; HS = High speed (14.4 - 19.8 km·h^{-1}); VHS = Very high speed (19.8 - 25.2 km·h^{-1}); MS = maximal speed (>25.2 km·h^{-1}). *Significant difference between playing positions ($p<0.05$).*

Table 5 outlines the predicted EC and P_{met} of training in relation to playing position. EC and P_{met} per training session was 24.7 ± 8.8 kJ·kg^{-1} and 7.7 ± 1.1 W·kg^{-1}, respectively (mean ± SD). Within each P_{met} category a mean distance of 425 ± 202 m, 147 ± 67 m and 155 ± 83 m were observed for HP, EP and MP respectively. With the exception of attackers, EC during training was greater in central midfielders compared to all other playing positions (central defenders ES=0.5, wide defenders ES=0.4, wide midfielders ES=0.5,

$p<0.05$; **Table 5**). Similarly, P_{met} was greater in central midfielders compared to all other positions (central defenders ES=0.5, wide defenders ES=0.8, wide midfielders ES=0.7, attackers ES=0.6, $p<0.01$; **Table 5**). With respect to the different P_{met} categories, central midfielders completed a greater HP distance compared to all other positions (central defenders ES=0.5, wide defenders ES=0.8, wide midfielders ES=0.7, attackers ES=0.6, $p<0.01$) and a greater EP distance compared to central defenders (ES=0.6, $p=0.001$; **Table 5**). Distance covered in the MP category was greater in central midfielders compared to central defenders (ES=0.5, $p=0.009$) and wide midfielders (ES=0.6, $p<0.001$). No other differences were observed between playing positions (**Table 5**).

Table 5. Energy cost and metabolic power in relation to playing position (mean ± SD).

	Central defender (n=92)	**Wide defender (n=110)**	**Central midfielder (n=103)**	**Wide midfielder (n=145)**	**Attacker (n=178)**	**Follow-up tests (LSD)**
EC ($kJ \cdot kg^{-1}$)	23.3±8.3	23.8±8.7	27.6±10.7	23.0±7.7	25.6±8.3	(CM>CD=WD=WM)=A*
P_{met} ($W \cdot kg^{-1}$)	7.8±1.1	7.5±1.0	8.4±1.2	7.6±1.0	7.7±1.2	CM>(CD=WD=WM=A)*
HP (m)	356±136	429±208	513±276	418±170	411±183	CM>(CD=WD=WM=A)*
EP (m)	130±53	143±69	168±79	145±60	146±68	(CM>CD)=WD=WM=A*
MP (m)	143±68	153±73	182±93	136±73	164±92	(CM>CD=WM)=WD=A*

*EC = Energy cost of accelerated running; P_{met} = Average metabolic power; HP = High P_{met} (20-35 $W \cdot kg^{-1}$); EP = Elevated P_{met} (35-55 $W \cdot kg^{-1}$); MP = Maximal P_{met} (>55 $W \cdot kg^{-1}$). *Significant difference between playing positions ($p<0.05$).*

Table 6 compares the high-intensity activity distance covered during training when expressed as total high-speed running (>14.4 $km \cdot h^{-1}$; TS) and total high-metabolic power (>20 $W \cdot kg^{-1}$; TP). The TP (727 ± 338 m; mean ± SD) was significantly greater than TS (478 ± 300 m) (ES=0.8, $p<0.001$). The magnitude of this difference (% change) was also dependent upon playing position (**Table 6**) with central defenders displaying a greater % difference relative to both wide defenders (ES=0.4, $p=0.01$) and attackers (ES=0.4, $p=0.02$). No other differences were observed between the remaining playing positions. Further analysis of the difference in high-intensity activity when derived by the two methods indicated that the magnitude of the difference increased as the percentage of high intensity distance covered per session (average between TS and TP) decreased ($r=0.90$, $p<0.001$; **Figure 6**).

Table 6. Total high-intensity training distance covered estimated from high-velocity running (>14.4 km·h^{-1}; TS) and high-metabolic power (>20 W·kg^{-1}; TP) relative to playing position (mean ± SD).

Distance (m)	**Central defender (n=92)**	**Wide defender (n=110)**	**Central midfielder (n=103)**	**Wide midfielder (n=145)**	**Attacker (n=178)**	**Follow-up tests (LSD)**
TS	373±179	502±306	570±403	455±259	482±291	(CM>WM)=WD=A>CD*
TP	628±250^{+}	725±342^{+}	863±436^{+}	699±291^{+}	722±324^{+}	CM>(CD=WD=WM=A)*
% Difference	84±59	62±49	70±48	72±53	63±38	CM=WM=(CD>WD=A)*

TS = Total high-speed (>14.4 km·h^{-1}); TP = Total high metabolic power (>20W·kg^{-1}). $^{+}$*Significant difference from TS (p<0.05). *Significant difference between playing positions (p<0.05).*

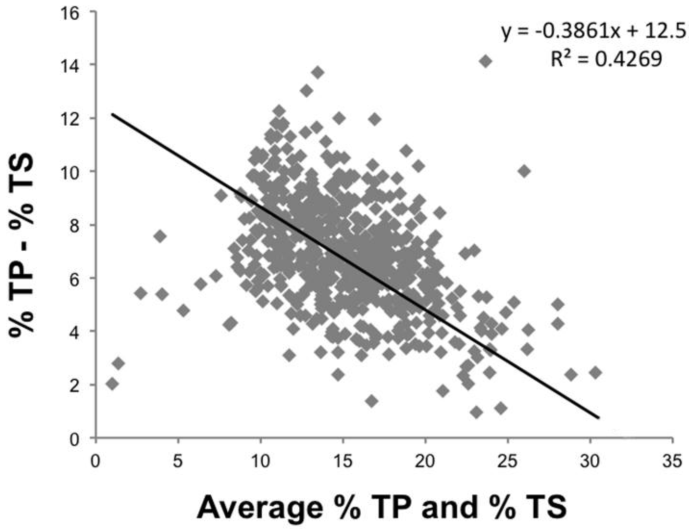

Figure 6. *Bland-Altman plot comparing the difference in high-intensity training distance covered (% of total training session distance) estimated from high-speed running (>14.4 km·h^{-1}; % TS) and high-metabolic power (>20 W·kg^{-1}; % TP) relative to the mean (p<0.001). TS = Total high-speed (>14.4 km·h^{-1}); TP = Total high metabolic power (>20 W·kg^{-1}).*

Attempts to evaluate the physical demands of soccer-specific activity have routinely centred upon the distance covered or time spent at different speeds. Recent observation from match-play however, suggest that such approaches underestimate the total energy cost since they fail to take into account the energy demands associated with accelerations and decelerations [Osgnach et al. 2010]. The present findings (*Study I*) demonstrate that previous approaches also underestimate the high-intensity demands of soccer training in elite players to a similar extent to those observed in match-play. Furthermore, the magnitude of this difference is dependent to some extent on both playing position and the type of training session undertaken.

To the authors knowledge the present investigation represents the first attempt to quantify the overall external load typically associated with daily field-based training activity in elite soccer players. The mean total distance covered (3772 m; range=831-9502 m) and the mean TS distance covered (478 m; range=0-2272 m) per session equated to ~40% and ~20% of the distance typically covered during match-play, respectively. In line with match-play observations [Di Salvo et al. 2007; Osgnach et al. 2010; Vigne et al. 2010], also in training there were significant differences between playing positions reflecting position-specific training methodologies that are routinely adopted in order to prepare the players for the physical and technical demands of match-play. For example, the total distance was generally highest in central midfield players with the lowest values in central defenders. Similarly, the highest and lowest TS distance was observed in central midfielders and central defenders, respectively, with attackers covering the greatest VHS distance. Interestingly, the distance covered at MS did not show any differences between playing positions. This may partly reflect the fact that players may not frequently reach maximal speeds during soccer-specific training activities [Mendez-Villanueva et al. 2011]. Indeed, the average distance covered at MS during training sessions represented only the 0.5% of total distance covered.

To date, assessment of the external training load in soccer using GPS technology has typically centred around the distance covered or time spent undertaking movements at determined speed categories [Aughey 2011; Hill-Haas et al. 2011]. This approach, however, underestimates the total energy cost since it fails to incorporate the energy cost associated with accelerations and decelerations which frequently arise during soccer-specific activities [Osgnach et al. 2010]. The latter represent more energetically demanding movements than constant-velocity movements to such an extent that high metabolic demands also arise at low running speeds in the presence of high accelerations or decelerations [Cavagna et al. 1971; di Prampero et al. 2005; Osgnach et al. 2010]. In the present investigation the mean energy cost associated with training was ~25 kJ·kg^{-1} (range=5-67 kJ·kg^{-1}) compared to ~60 kJ·kg^{-1} observed during match-play [Osgnach et al. 2010]. When expressed as average metabolic power this equated to ~7.5 W·kg^{-1} (range=4.6-12.8 W·kg^{-1}). Interestingly, when comparing the total energy cost of training sessions between playing positions mean energy cost was similar in central midfielders and attackers. In contrast, when expressed as metabolic power, higher values were observed in central midfielders (~8.5 W·kg^{-1} vs ~7.7 W·kg^{-1}). This likely reflects the higher volume of high intensity activity undertaken by central midfielders compared to attackers and suggests that assessments of the physical demands of training using metabolic power data is more precise since it takes into account both speed and acceleration values.

Further support for the application of metabolic power is provided when examining the high-intensity component of training which typically represents the most physically demanding elements. Since the metabolic power when running at constant speed on grass at 14.4 km·h^{-1} is approximately 20 W·kg^{-1} [Osgnach et al. 2010], the extent to which the use of speed per se underestimates the true energy cost of activity can be further explored by comparing the distance covered at a speed >14.4 km·h^{-1} (TS) with the distance at a metabolic power >20 W·kg^{-1} (TP). In S*tudy I* 13% of the total distance was covered at TS compared to 19% at TP indicating that traditional approaches may underestimate the high-intensity demands of training by ~6%. These estimations compare favourably with underestimation of ~8% (18% vs 26%) reported during match-play [Osgnach et al. 2010].

The degree to which the high-intensity demands of training are underestimated when based upon speed categories only may also be influenced by playing position. For example, central defenders displayed a greater difference (represented as % change) between TS and TP compared with both wide defenders and attackers. It would seem likely that these differences are directly related to the nature of their involvement in match-play and training [Di Salvo et al. 2009]. The reactive nature of the work undertaken by central defenders as they attempt to counter the movements of the opposition may require a high number of brief explosive accelerations and decelerations. In contrast, wide defenders, particularly more attacking orientated defenders and attackers may produce less explosive accelerations as a function of the freedom they have to dictate their own activity profile as a consequence of the need to initiate movement patterns to create attacking opportunities [Di Salvo et al. 2009]. Alternatively, the high TS values reported in wide defenders may indicate simply that a large proportion of their high-intensity activity occurs at “constant” speeds.

Alongside examining the influence of playing position, it was determined whether the type of training session, specifically the amount of high-intensity activity undertaken within a training session influenced the degree to which the two methods of estimating training load differed. A trend was observed for the magnitude of the difference between methods to decline as the amount of high-intensity activity within a training session increases (**Figure 6**). This suggests that during training sessions which incorporate a large percentage of high-intensity activity, underestimation of the true external load using traditional monitoring approach will be minimised. Conversely, training sessions with limited high-intensity activity in the presence of accelerations and decelerations will magnify the difference between the two methods. Given that different approaches to training are employed by different coaches (e.g. different types of small-sided games), the present data may suggest that certain training strategies may have greater implications for deriving true estimates of the external load placed upon players using traditional approaches. It should be noted, however, that no differentiation between types of training session was undertaken within the present investigation; consequently, further work is needed to provide a more detailed comparison of the two estimates across different types of training or different drills used during training.

3.2 Influence of drill type.

High-intensity activity was systematically higher (99%; ES=0.8, p<0.001) when expressed as distance covered at high P_{met} (>20 $W{\cdot}kg^{-1}$; TP) versus high speed (>14.4 $km{\cdot}h^{-1}$; TS) irrespective of playing position and SSG (i.e. 5vs5, 7vs7 and 10vs10).

A main effect of drill type was observed in *Study II* for the percentage of total distance covered at TS (p<0.001) and TP (p<0.01) with values increasing from 5vs5 through to 10vs10 (**Figure 7**). The % TP was greater than % TS across all SSGs (p<0.001; ES=2.8, 2.2 and 1.9 in 5vs5, 7vs7 and 10vs10, respectively; **Figure 7**). The magnitude of this difference was also dependant on drill type (p<0.01; **Figure 7**) with values decreasing from 5vs5 through to 10vs10 (5vs5 vs. 7vs7, ES=0.6; 5vs5 vs. 10vs10, ES=1.0; 7vs7 vs. 10vs10, ES=0.7).

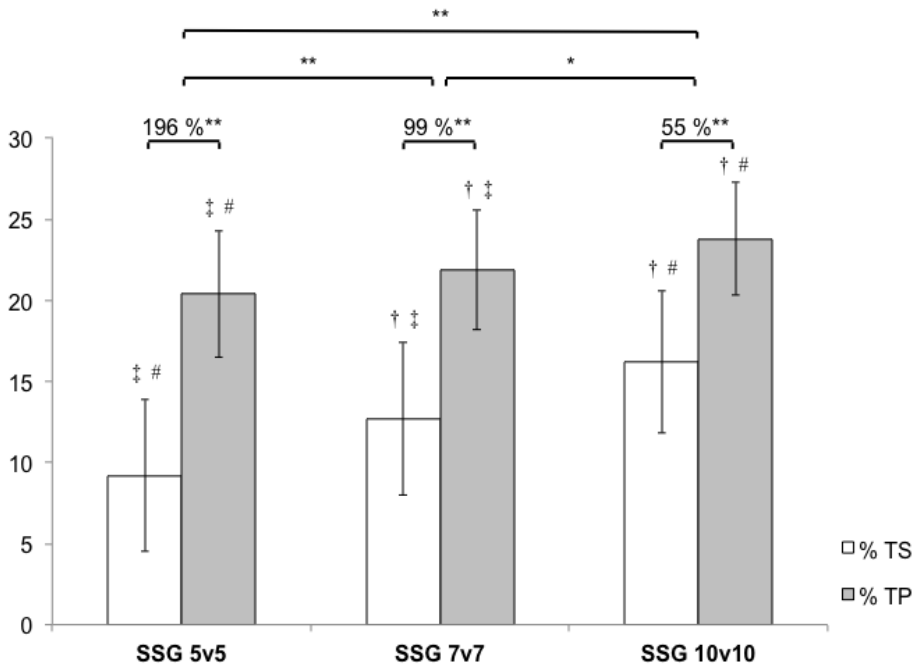

Figure 7. *Distance covered at high speed (TS) and high metabolic power (TP) expressed as percentage of total distance covered during the three different SSGs (mean ± SD and percentage change).*
*† Significant difference from the same parameter in 5vs5 SSG (p<0.01); # Significant difference from the same parameter in 7vs7 SSG (p<0.01); ‡ Significant difference from the same parameter in 10vs10 SSG (p<0.001); *Significant differences between the indicated parameters or drills (p<0.01). **Significant differences between the indicated parameters or drills (p<0.001).*

Overall Effect of Playing Position. Except for wide defenders, the total distance covered by central midfielders was greater compared to all other playing positions (ES>0.04, p<0.05). The TS and TP distance covered was similar between all positions. Furthermore, TS was lower relative to TP across all positions (ES=0.8, p<0.001). However, the magnitude of this difference (i.e. % change from TS to TP) was greater in central defenders compared to wide defenders (ES=0.4, p<0.001), central midfielders (ES=0.2, p=0.004), wide midfielders, (ES=0.3, p=0.01) and attackers (ES=0.3, p=0.01). No other differences were observed between playing positions.

5vs5. Total distance, TS and TP were similar between playing positions (**Table 7A**). TP was greater than TS in all playing positions (ES>1.5, p<0.001). The percentage change from TS to TP was greater in central defenders compared to the other playing positions (ES>0.3, p<0.05) and, with the exception of central midfielders, lower in wide defenders relative to all over positions (ES>0.8, p<0.05). No other differences were observed between playing positions (**Table 7A**).

7vs7. Total distance covered was greater in central midfielders compared to central and wide defenders (ES>1.0, p<0.05), however, no other differences were observed between playing positions (**Table 7B**). TS and TP were similar between playing positions with TS lower relative to TP across all positions (ES>1.1, p<0.001). In addition, the magnitude of the difference between TS and TP was not significantly different between positions (p>0.05; **Table 7B**).

10vs10. Total distance covered by central and wide midfielders was greater compared to the other positions (ES>0.7, p<0.05; **Table 7C**). Central defenders performed less TS compared to central and wide midfielders (ES>0.6, p<0.05). In addition, central and wide midfielders covered a greater TP compared to all the other positions (ES>0.6, p<0.05). TP was greater than TS in all playing positions (ES>1.2, p<0.001). No significant differences were observed in the percentage difference between TS and TP among playing positions (p>0.05). However, large (=0.9) and moderate (=0.7) effect sizes were found when comparing central defenders and central midfielders with wide defenders, wide midfielders and attackers, respectively (**Table 7C**).

Table 7. Total distance, and high-intensity distance covered in 5vs5 (A), 7vs7 (B) and 10vs10 (C) SSGs calculated using the two different methods (TS and TP). Data are represented as mean ± SD.

A)

SSG 5vs5 (5 min)	**Central defender (n=13)**	**Wide defender (n=19)**	**Central midfielder (n=27)**	**Wide midfielder (n=15)**	**Attacker (n=18)**	**Follow-up tests (LSD)**
TD (m)	466 ± 51	488 ± 35	528 ± 74	485 ± 65	483 ± 73	CD=WD=CM=WM=A
TS (m)	39 ± 25	54 ± 20	53 ± 30	38 ± 21	46 ± 35	CD=WD=CM=WM=A
TP (m)	97 ± 24$^{\#}$	105 ± 21$^{\#}$	113 ± 37$^{\#}$	94 ± 31$^{\#}$	98 ± 35$^{\#}$	CD=WD=CM=WM=A
% Change	349 ± 532	108 ± 52	154 ± 105	222 ± 193	220 ± 251	(WD<WM=A)=CM<CD*

B)

SSG 7vs7 (8 min)	**Central defender (n=26)**	**Wide defender (n=17)**	**Central midfielder (n=28)**	**Wide midfielder (n=17)**	**Attacker (n=36)**	**Follow-up tests (LSD)**
TD (m)	803 ± 67	777 ± 96	890 ± 99	816 ± 66	813 ± 86	(CD=WD<CM)=WM=A*
TS (m)	95 ± 42	109 ± 63	107 ± 44	110 ± 30	111 ± 42	CD=WD=CM=WM=A
TP (m)	173 ±39$^{\#}$	172 ± 50$^{\#}$	204 ± 54$^{\#}$	184 ± 22$^{\#}$	179 ± 46$^{\#}$	CD=WD=CM=WM=A
% Change	115 ± 102	92 ± 79	111 ± 68	75 ± 33	93 ± 146	CD=WD=CM=WM=A

C)

SSG 10vs10 (14 min)	**Central defender (n=28)**	**Wide defender (n=34)**	**Central midfielder (n=46)**	**Wide midfielder (n=33)**	**Attacker (n=62)**	**Follow-up tests (LSD)**
TD (m)	1474 ± 132	1485 ± 99	1652 ± 131	1587 ± 146	1484 ± 158	CD=WD=A<CM=WM*
TS (m)	209 ± 80	250 ± 74	258 ± 83	288 ± 85	249 ± 80	(CD<CM=WM)=WD=A*
TP (m)	337 ± 78$^{\#}$	350 ± 65$^{\#}$	406 ± 77$^{\#}$	403 ± 76$^{\#}$	351 ± 88$^{\#}$	CD=WD=A<CM=WM*
% Change	72 ± 37	45 ± 21	69 ± 46	46 ± 24	46 ± 21	CD=WD=CM=WM=A

*TD=Total distance; TS=Total high speed (>14.4 $km\cdot h^{-1}$); TP=Total high power (>20 $W\cdot kg^{-1}$). $^{\#}$Significant difference from TS (p<0.001). *Significant difference among playing positions (p<0.05).*

In *Study I* the physical demands associated with the overall training session undertaken by elite soccer players were assessed. However, individual training sessions incorporate a variety of training drills often in the form of SSGs which impose specific physical loads on the players [Hill-Haas et al. 2011]. As a consequence, the magnitude of the relationship between two methods of assessing high-intensity demands is likely to differ to a greater degree when specific modes of training are considered. In order to test this hypothesis, in the present investigation the two methods were compared using a range of SSGs (5vs5, 7vs7 and 10vs10) typically undertaken by a group of elite soccer players competing in the English Premier League. The traditional approach underestimated (~100%) the high-intensity demands independent of the type of SSG. Furthermore, the magnitude of this underestimation is greater compared to values (~45% and ~70%) previously observed during match-play [Osgnach et al. 2010] and those representing entire soccer training sessions (*Study I*). This largely reflects the magnitude of the differences observed in the smaller SSGs since the difference between methods increased as the pitch dimensions/area per player decreased (55%-196 % in 10vs10-5vs5; **Figure 7**). Both % TS and % TP of the total distance covered decreased with a reduction in pitch dimensions and area per player. However, the magnitude of the decrease in % TS was greater relative to % TP leading to a greater difference between the two methods in the “smaller” SSGs (**Figure 7**). Such changes likely reflect the increased difficulty in attaining high speeds within smaller confined playing areas whilst the requirement to accelerate and decelerate is maintained. This is supported by the fact that the average percentage difference between TS and TP in the 10vs10 SSG was similar to that reported during match-play (~45%) [Osgnach et al. 2010] where the large playing area enhances the ability to attain high speeds. These results suggest that the use of P_{met} provides a more valid indication of the high-intensity demands of soccer training particularly when training sessions or drills are performed in small areas.

Alongside the effect of pitch dimension, *Study I* demonstrated that the magnitude of the difference between the two methods of assessing high-intensity demands during overall training sessions was also influenced by playing position with the greatest differences observed in central defenders. This likely reflects the reactive nature of the work undertaken by central defenders where a relatively high number of brief explosive accelerations and decelerations are needed in order to counter the movements of opposing attackers [Di Salvo et al. 2009]. In line with these observations, in the present investigation, TS remained lower relative to TP across all playing positions independent of SSG type (**Table 7**). Furthermore, the magnitude of this reduction in TS relative to TP was generally greater in central defenders compared to other playing positions. These positional differences were particularly evident during the smallest (5vs5) SSG where the ability to perform high-speed activity was reduced across all positions (**Table 7**), however, the corresponding TP remained high in central defenders reflecting the relatively high number of brief accelerations and decelerations in this position. In contrast, in wide positions, players may often accelerate/decelerate to a lesser extent [Di Salvo et al. 2009], consequently this would have reduced the difference between TS and TP relative to central defenders.

In contrast to the 5vs5 SSGs, no significant differences were found between positions during 7vs7 and 10vs10 SSGs with regard to the percentage difference between TS and TP. Nevertheless, the difference was generally greater in central defenders (moderate to large effect sizes) compared to wide defenders, wide midfielders and attackers. During the larger SSGs, the increased pitch dimensions and area per player enabled all playing positions to perform greater amounts of high-speed activity particularly central and wide midfield positions where TS was greater relative to central defenders (**Table 7**). Consequently, this reduced both the differences between TS and TP and subsequently between playing positions relative to the smaller 5vs5 SSGs.

3.3 Metabolic and musculo-skeletal demands during different SSGs.

Total distance, distance covered at different speed categories and maximal speed reached in each drill (i.e. 5vs5, 7vs7 and 10vs10 played in both game formats: possession play, SSG-P and game with regular goals and goalkeepers, SSG-G) are reported in **Table 8** (mean ± SD). The players covered a greater total distance when the area per player increased irrispective of drill type (10vs10>7vs7>5vs5; $p<0.003$). A significant Game x Group interaction was observed for all the drills with total distance covered being systematically higher in the SSG-P ($ES>0.5$, $p<0.001$).

A similar trend (i.e. 10vs10>7vs7>5vs5) was noted for the TS ($ES>1.0$, $p<0.001$), HS ($ES>0.6$, $p<0.001$) and VHS ($ES>1.0$, $p<0.001$) distances. The MS distance was more elevated in the 10vs10 as compared to 7vs7 and 5vs5 ($ES>0.7$, $p<0.001$; **Table 8**). No significant differences were found between SSG-G and SSG-P for the TS and HS distances, while VHS and MS distances were greater in SSG-G ($ES>0.7$, $p<0.001$ and $ES>1.0$, $p<0.001$, respectively; **Table 8**).

Absolute maximal speed values were higher when the pitch dimensions were greater (i.e. 10vs10>7vs7>5vs5) in both SSG-G and SSG-P ($ES>1.0$, $p<0.001$). Different to the other speed parameters, the absolute maximal velocity reached was systematically higher in SSG-G compare to SSG-P ($ES>1.0$, $p<0.001$).

Table 8. Distance and speed parameters obtained during the SSGs. Results have been normalized by time (for a 4 min period) and then expressed as mean ± SD.

	5vs5 SSG-G	**5vs5 SSG-P**	**7vs7 SSG-G**	**7vs7 SSG-P**	**10vs10 SSG-G**	**10vs10 SSG-P**	**Follow-up tests (LSD)**
TD (m)	402 ± 47	419 ± 28	412 ± 38	443 ± 37	441 ± 31	466 ± 45	10v10>7v7>5v5* SSG-P>SSG-G*
TS (m)	42 ± 17	31 ± 10	57 ± 14	50 ± 18	76 ± 14	85 ± 24	10v10>7v7>5v5* SSG-G=SSG-P
HS (m)	39 ± 15	30 ± 10	47 ± 10	47 ± 16	57 ± 10	73 ± 20	10v10>7v7>5v5* SSG-G=SSG-P
VHS (m)	3 ± 3	1 ± 1	10 ± 5	3 ± 3	16 ± 5	12 ± 7	10v10>7v7>5v5* SSG-G>SSG-P*
MS (m)	0 ± 0	0 ± 0	1 ± 1	0 ± 0	2 ± 2	0 ± 1	10v10>7v7=5v5* SSG-G>SSG-P*
Max Speed ($km \cdot h^{-1}$)	20 ± 1	19 ± 1	23 ± 2	20 ± 1	26 ± 1	23 ± 1	10v10>7v7>5v5* SSG-G>SSG-P*

TD=Total distance; TS=Total high speed running (>14.4 $km \cdot h^{-1}$*); HS=High speed (14.4 - 19.8* $km \cdot h^{-1}$*); VHS=Very high speed (19.8 - 25.2* $km \cdot h^{-1}$*); MS=Maximal speed (>25.2* $km \cdot h^{-1}$*); Max Speed=Absolute maximal value of speed reached. *Significant difference (p<0.001).*

The key parameters related to changes in velocity are presented (mean ± SD) in **Table 9.** The total number of changes in velocity increased as the size of SSG decreased (5vs5>7vs7>10vs10; ES>0.5, p<0.001). The same trend was detected when the number of moderate accelerations and decelerations were analysed (5vs5>7vs7>10vs10; ES>0.5, p<0.001 and ES>0.7, p<0.001, respectevely) with the only exception in the comparison between the number of moderate deceleration in 5vs5 vs. 7vs7 SSG-G where no difference was found (p>0.05). No difference was detected in the number of high acceleration or high deceleration when the area per player was modified (p>0.05). An opposite trend was detected with regard to the absolute maximal acceleration and deceleration values reached during the SSGs that were greater in “larger” SSGs (10vs10>7vs7>5vs5; ES>0.3, p<0.05 and ES>0.6, p<0.001, respectively) with the only exception when comparing absolute maximal acceleration in the 10vs10 and 7vs7 where no significant difference was found (p>0.05; **Table 9**).

In addition, despite a trend showing higher values in SSG-P compared to SSG-G, no significant differences were found in the number of moderate and high accelerations and decelerations between SSG-G and SSG-P (p>0.05). The total number of changes in velocity showed the same trend (i.e. SSG-P>SSG-G) although no significant differences were detected (p>0.05) with the only exception in 5v5 SSG where the total number of changes in velocity was significantly higher in SSG-P compared to SSG-G (ES=0.4, p=0.03). On the other hand, values of absolute maximal acceleration and deceleration were found to be significantly greater in SSG-G than in SSG-P (ES>1.0, p<0.001 and ES>0.9, p<0.001, respectively; **Table 9**).

Table 9. Drill characteristics based on changes in velocity. Results have been normalized by time (for a 4 min period) and then expressed as mean ± SD.

	5vs5 SSG-G	**5vs5 SSG-P**	**7vs7 SSG-G**	**7vs7 SSG-P**	**10vs10 SSG-G**	**10vs10 SSG-P**	**Follow-up tests (LSD)**
TCV (No.)	20 ± 5	22 ± 5	18 ± 3	18 ± 5	14 ± 3	16 ± 3	5v5>7v7>10v10* SSG-G=SSG-P
MA (No.)	8 ± 2	9 ± 2	7 ± 2	8 ± 2	6 ± 1	6 ± 2	5v5>7v7>10v10* SSG-G=SSG-P
HA (No.)	2 ± 1	1 ± 0	2 ± 1	1 ± 1	1 ± 0	1 ± 1	5v5=7v7=10v10 SSG-G=SSG-P
Max Acc ($m \cdot s^{-2}$)	3.4 ± 0.3	3.2 ± 0.4	3.7 ± 0.3	3.3 ± 0.4	3.8 ± 0.2	3.4 ± 0.3	10v10>7v7>5v5[#] SSG-G>SSG-P*
MD (No.)	8 ± 2	9 ± 2	7 ± 2	8 ± 3	6 ± 1	6 ± 1	5v5>7v7>10v10* SSG-G=SSG-P
HD (No.)	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	2 ± 1	5v5=7v7=10v10 SSG-G=SSG-P
Max Dec ($m \cdot s^{-2}$)	3.8 ± 0.3	3.5 ± 0.4	4.1 ± 0.3	3.7 ± 0.3	4.5 ± 0.3	3.9 ± 0.4	10v10>7v7>5v5* SSG-G>SSG-P*

TCV=Total number of changes in velocity (i.e. sum of accelerations and decelerations>2 $m \cdot s^{-2}$*); MA=Number of moderate accelerations (2-3* $m \cdot s^{-2}$*); HA=Number of high accelerations (>3* $m \cdot s^{-2}$*); Max Acc=Absolute maximal value of acceleration reached; MD=Number of moderate decelerations (2-3* $m \cdot s^{-2}$*); HD=Number of high decelerations (>3* $m \cdot s^{-2}$*); Max Dec=Absolute maximal value of deceleration reached. *Significant difference (p<0.001); [#]Significant difference (p<0.05).*

Predicted metabolic parameters of SSGs are reported as mean ± standard deviation in **Table 10**. Total energy cost (EC) and the average metabolic power (P_{met}) showed the same trend being higher in 10vs10 compared to 7vs7 and 5vs5 while no differences were found between the latter two drills (10vs10>(7vs7=5vs5); ES>0.3, p<0.01 and ES>0.1, p<0.05 for EC and P_{met}, respectively). Distance covered at TP, HP, EP and MP increased when the number of players increased (10vs10>7vs7>5vs5; ES>0.4, p<0.01 in TP; ES>0.5, p<0.01 in HP; ES>0.3, p<0.05 in EP and ES>0.4, p<0.001 in MP).

In addition, all the predicted metabolic parameters (i.e. EC, P_{met}, TP, HP, EP and MP) were systematically higher in SSG-P as compared with SSG-G (ES>0.3, p<0.001 in EC; ES>0.5, p<0.001 in P_{met}; ES>0.2, p<0.001 in TP; ES>0.2, p=0.007 in HP; ES>0.3, p=0.02; in EP and ES>0.2, p=0.04; in MP; **Table 10**).

Table 10. Predicted metabolic parameters related to the six different SSGs. Results have been normalized by time (for a 4 min period) and then expressed as mean ± SD.

	5vs5 SSG-G	**5vs5 SSG-P**	**7vs7 SSG-G**	**7vs7 SSG-P**	**10vs10 SSG-G**	**10vs10 SSG-P**	**Post Hoc Test (LSD)**
EC ($kJ\cdot kg^{-1}$)	2.8 ± 0.4	2.9 ± 0.3	2.8 ± 0.3	3.0 ± 0.3	2.9 ± 0.2	3.1 ± 0.4	10v10>7v7=5v5^ SSG-P>SSG-G*
P_{met} ($W\cdot kg^{-1}$)	12.2 ± 1.7	12.9 ± 1.1	12.4 ± 1.3	13.3 ± 1.2	12.8 ± 1.0	13.5 ± 1.6	10v10>7v7=5v5$^{\#}$ SSG-P>SSG-G*
TP (m)	84 ± 21	88 ± 13	92 ± 17	100 ± 18	106 ± 15	118 ± 24	10v10>7v7>5v5^ SSG-P>SSG-G$^{\#}$
HP (m)	48 ± 12	50 ± 8	53 ± 10	58 ± 11	62 ± 10	70 ± 14	10v10>7v7>5v5^ SSG-P>SSG-G^
EP (m)	17 ± 5	18 ± 5	18 ± 5	20 ± 5	22 ± 5	23 ± 6	10v10>7v7>5v5$^{\#}$ SSG-P>SSG-G$^{\#}$
MP (m)	19 ± 6	20 ± 4	21 ± 5	22 ± 5	23 ± 4	25 ± 6	10v10>7v7>5v5* SSG-P>SSG-G$^{\#}$

*EC=Energy cost; P_{met}=Average metabolic power; TP=Total high power (>20$W\cdot kg^{-1}$); HP=High power (20 - 35 $W\cdot kg^{-1}$); EP=Elevated power (35 - 55 $W\cdot kg^{-1}$); MP=Maximal power (>55 $W\cdot kg^{-1}$). *Significant difference ($p<0.001$); ^Significant difference ($p<0.01$); $^{\#}$Significant difference ($p<0.05$).*

The major findings from *Study III* were that the total distance, distances covered above 14.4 $km\cdot h^{-1}$ as well as maximum speed, acceleration and deceleration were bigger when the area per player increased (10vs10>7vs7>5vs5) with the total, very high and maximal speed distances, absolute velocity and maximum acceleration and deceleration achieved being greater in the small sided games as compared with possessions. Conversely, the number of moderate accelerations and decelerations as well as the total number of changes in velocity were higher as the pitch dimensions decreased (i.e. 5vs5>7vs7>10vs10) in both SSG-G and SSG-P. In addition, all the predicted metabolic parameters (EC, P_{met}, TP, HP, EP and MP) were systematically higher in SSG-P as compared with SSG-G and in big versus small pitch areas.

To the best of our knowledge this is the first study which analyses comprehensively the estimated metabolic and mechanical demands of different small-sided games and possessions in top-class soccer players. A detailed analysis of these drills is pivotal in contemporary soccer as it enables an in depth understanding of the workload imposed on each player which consequently has practical implications for the prescription of the adequate type and amount of stimulus during exercise training.

The total distance, distances covered at high speed (>14.4 $km\cdot h^{-1}$) and high power (>20 $W\cdot kg^{-1}$) as well as the average metabolic power were greater when the pitch area increased which is in line with previous studies reporting more elevated exercise intensities with a larger pitch area and a reduced number of players or ball contacts allowed per individual possession [Kelly & Drust 2009; Casamichana et al. 2010; Hill-Haas et al. 2011; Castellano et al. 2013].

On the contrary, the moderate as well as the total number of changes in velocity became higher as the pitch dimensions decreased (**Figure 8**), suggesting that, compared to big, small areas of play tax different physiological components of performance which are not detectable by measuring the distances covered and speed attained. Furthermore, accelerations and decelerations tended to be greater in the SSG-P compared with SSG-G, possibly due to the tighter nature of the former. The importance of changing velocity is supported by recent findings showing that in professional players 18% of the total distance during a soccer match is generally obtained by accelerating or decelerating at >1 $m \cdot s^{-2}$ while 7.5%, 4.3% and 3.3% is covered at 1-2 $m \cdot s^{-2}$, 2-3 $m \cdot s^{-2}$ and >3 $m \cdot s^{-2}$, respectively [Akenhead et al. 2013(*b*)]. Therefore it appears clear that in addition to kinematic (i.e. running speeds) and cardiovascular variables (i.e. heart rate), there is also a mechanical load component given by accelerating and decelerating that plays a role and requires to be taken into account in the quantification of the total workload placed upon the players. Thus, where mechanical load is the focus, specific physiology may not be targeted with drills in open spaces involving many components, whereas ball possessions in small areas such as 4vs4 and 5vs5 may aid to achieve this purpose. In these situations it is just as important to expose players to the necessary overload to ensure they can withstand the mechanical stresses competitive matches impose on them.

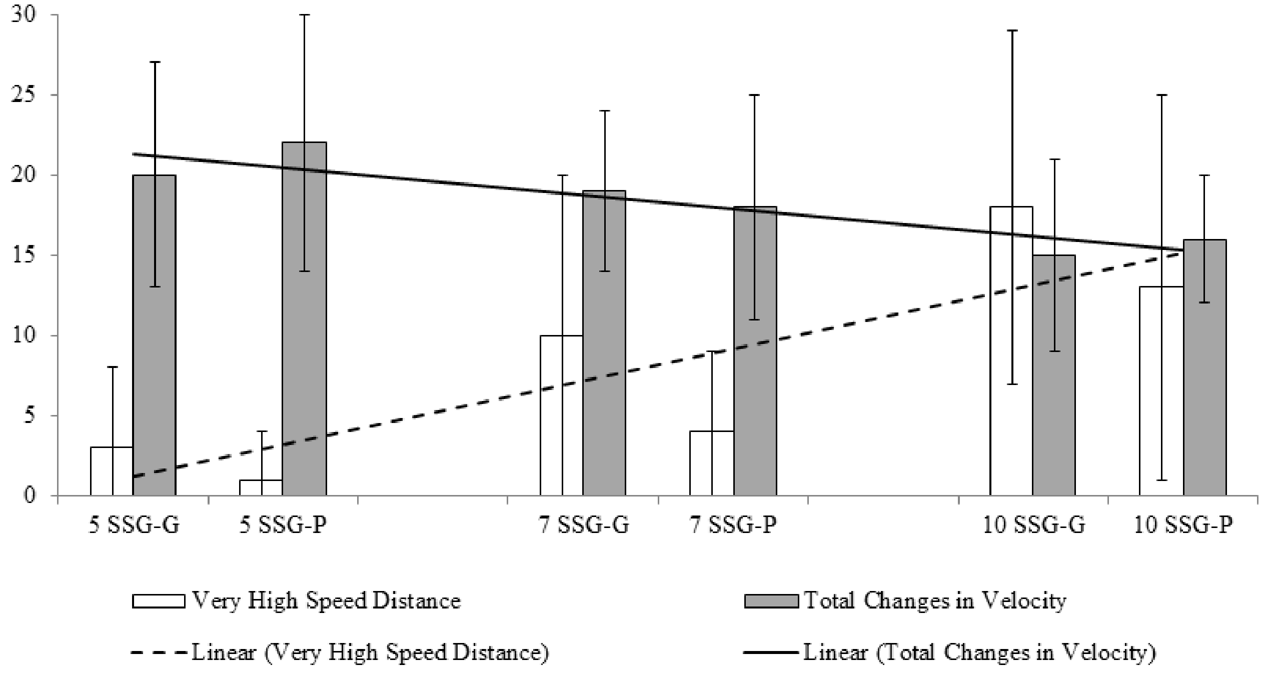

Figure 8. *Very high speed distance covered (>19.8 $km \cdot h^{-1}$, in meters) and the total number of changes in velocity (i.e. sum of accelerations and decelerations >2 $m \cdot s^{-2}$) performed during the 6 different SSGs (mean±SD).*

A different trend is observed when the aim is taxing absolute values of maximal acceleration, maximal deceleration and maximal speed, all being more pronounced in bigger pitches and during small sided games with goalkeepers than in possessions (**Figure 9**). This indicates that big spaces and "open nature" games are required in order to hit these targets. However, the number of times players reach the peak intensity during changes in velocity is quite reduced as only 34% of the sprint efforts during soccer games are preceded by a maximal acceleration while 85% of maximal accelerations had a final velocity <4.17 m·s^{-1} [Varley & Aughey 2013].

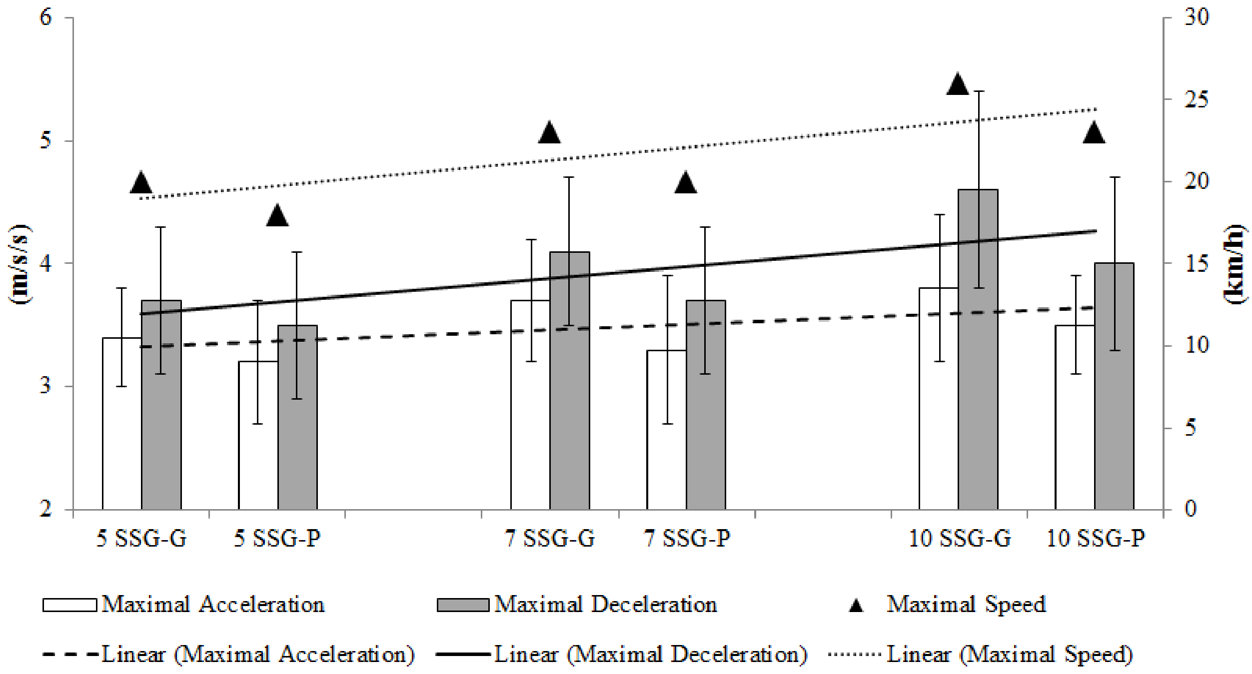

Figure 9. *Absolute maximal acceleration (m·s^{-2}), maximal deceleration (m·s^{-2}) and maximal speed (km·h^{-1}) reached during the six SSGs analysed (mean±SD).*

A novelty from this investigation was the use of a mathematical model for calculating the estimated energy expenditure and metabolic parameters during different types of small sided games. This approach was previously utilized for analysing official games [Osgnach et al. 2010]. In accordance with this investigation, in the present study a greater distance run at high power (>20 W·kg^{-1}) was observed compared to high speed (>14.4 km·h^{-1}), not only during SSG-G but also in SSG-P, with the difference getting more pronounced as the pitch dimensions decreased (5vs5>7vs7>10vs10; **Figure 10**). This indicates that the use of power zones become a more accurate tool than speed thresholds especially when assessing the demands of games played in small areas. On the other hand, both the energy expenditure and the distances run at high power increase when the pitch area gets bigger; since the estimated metabolic parameters are influenced by both accelerations and speed and even though the number of changes in velocity is higher in "small" SSGs, the distance covered at high speed in big areas contribute to higher metabolic values (**Figure 10**). The average metabolic power and high power distances were systematically higher in the SSG-P than in SSG-G played with the same number of players which is in accordance with observations showing that the inclusion of goalkeepers reduced the tempo of the game as players performed less high-intensity running and increased low-intensity activities [Hill-Haas et al. 2011]. Similarly, a recent study by Castellano et al., investigating the differences on physiological and physical demands between two different game formats, possession play (SSG-P) and regulation goals and goalkeepers (SSG-G), reported greater values of heart rate, total distance covered and distance covered at high speed in SSG-P [Castellano et al. 2013]. In addition, a previous study by Dellal et al. showed RPE values to be lower during the free play SSGs [Dellal et al. 2012*b*]. Thus, all together these seem to suggest that possessions rather than games with goalkeepers are preferred when the aim is the maintenance of a higher average intensity. In contrast, 5vs5 and 7vs7, the distance run at high speed is more stimulated during games than possessions, but it become greater in SSG-P when playing 10vs10. Overall, with exception for the maximal speed, acceleration and deceleration, 10vs10 possessions in medium-big areas may represent an effective stimulus for training the vast majority of the metabolic and musculo-skeletal parameters involved in soccer performance. However, regardless of the physiological components taxed, all small sided games included in the present study produced an average intensity close to or above the values registered during competitive games and therefore represent a valid tool to develop match specific fitness.

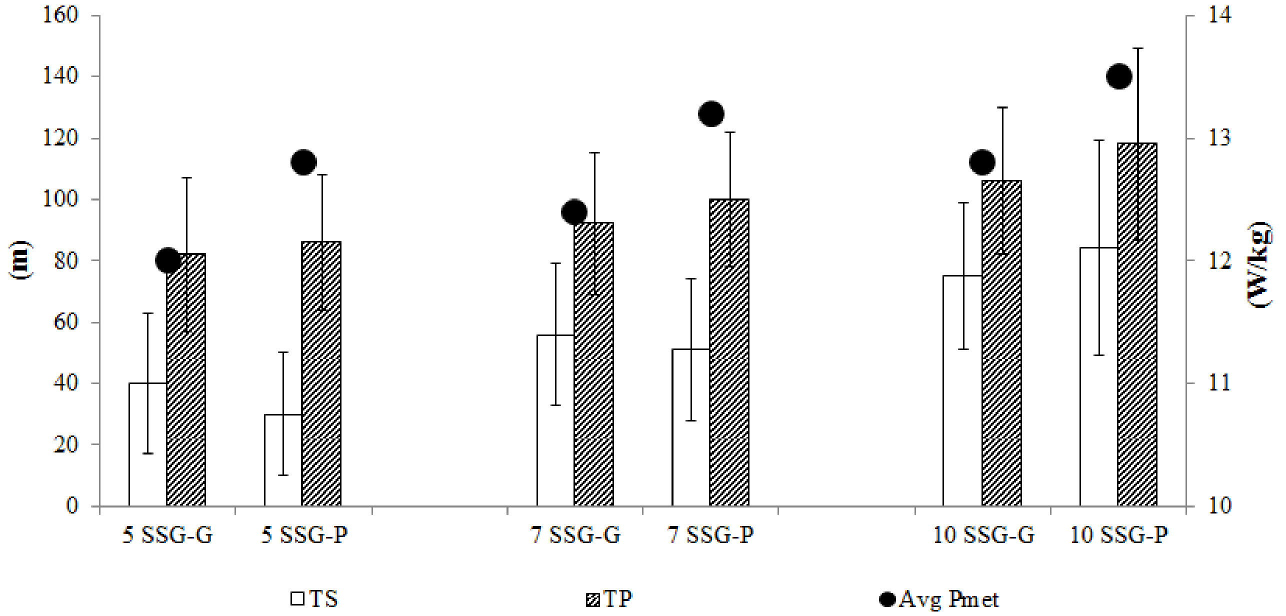

Figure 10. *TS (total high speed running; i.e. >14.4 km·h^{-1}), TP (total high power; i.e. >20 W·kg^{-1}) distance covered (m) and Avg Pmet (average metabolic power; in W·kg^{-1}) reached during the six SSGs (mean±SD).*

The present investigation has important practical implications as it provides novel guidelines on how to utilize scientific information to maximize the training and delivery of field based sessions to elite soccer players. It has been shown that different game formats generate different metrics and therefore target different physical components of performance. The approach therefore, is to overload specific areas of physiology in isolation rather than stimulating to lesser degrees every component within the same drill. As a consequence, during field based conditioning, it is paramount that training load is fully understood and appropriate for the intended physiological and performance adaptations.

Chapter 4

CONCLUSIONS, PRACTICAL IMPLICATIONS & PERSPECTIVES

In relation to the main aspects investigated in this thesis (*Study I*, *II* and *III*), the conclusions and practical implications are:

- Since accelerations and decelerations are physical demanding tasks [Cavagna et al. 1971; di Prampero et al. 2005; Osgnach et al. 2010], underestimation of the stress imposed by these activities on soccer players during training could influence the degree to which the planning and implementation of training influences adaptation and thus performance as well as the incidence of injury.

- *Study I* reported the average energy expenditure and metabolic power associated with elite soccer training sessions (~1 hour) to be equal to ~25 $\mathrm{kJ \cdot kg^{-1}}$ and ~7.5 $\mathrm{W \cdot kg^{-1}}$, respectevely. In addition, it has been demonstreted how the high-intensity demands of soccer training in elite players are underestimated by traditional measurements of running speed alone (~6%), especially in training sessions or playing positions associated with less high-intensity activity. Estimations of metabolic power better inform the coach as to the true demands of a training session. Consequently, the use of this monitoring approach may contribute to the development of training programmes which serve to further enhance performance and reduce the incidence of injury.

- *Study II* showed that the high-intensity demands of elite soccer small-sided games (SSGs) are underestimated by traditional measurements of running speed alone. High-intensity demands were systematically higher (~100%) when expressed as distance covered at metabolic power >20 $\mathrm{W \cdot kg^{-1}}$ (TP) versus distance covered at speeds >14.4$\mathrm{km \cdot h^{-1}}$ (TS) irrespective of playing position and SSG. The magnitude of this difference increased as the size of SSG reduced with a difference of ~200% observed in the 5vs5 SSG. A greater difference between TP and TS was also evident in central defenders compared to other positions particularly during the 5vs5 SSG (~350%). The application of this new monitoring approach will better inform the coach and practitioner to develop specific training programmes that involve different SSGs which both enhance performance and reduce the risk of injury.

- The main findings from *Study III* were that the total distance, distances run at high speed as well as maximum velocity, acceleration and deceleration increased along with pitch dimensions (10vs10>7vs7>5vs5). Furthermore, the total distance, very high and maximal speed distances, absolute velocity and maximum acceleration and deceleration were higher in games with regular goals and goalkeeprs (SSG-G) than in possession play (SSG-P). On the other hand, the number of moderate accelerations and decelerations as well as the total number of changes in velocity were greater as the pitch dimensions decreased (i.e. 5vs5>7vs7>10vs10) in both SSG-G and SSG-P. In addition, energy cost, average metabolic power and distance covered at different metabolic power categories were more elevated in SSG-P compared to SSG-G and in big compared to small pitch areas. Thus, in conclusion, small-sided games represent an appropriate and efficient training mode to stimulate all the specific physical aspects of playing soccer. However, since it has been demonstrated that different SSGs formats generate different metrics and therefore target different physical components of perormance, the detailed description of their demands given in *Study III* can be useful to coaches, assisting in the planning of appropriate soccer specific training sessions.

Future perspectives:

- Present investigation analysed training sessions and different SSGs performed by elite men players. However, based on the detailed parameters presented in this research, it would be interesting to compare professional versus amateur players, as well as young or female players.

- Future studies should be designed to estimate the metabolic and mechanical variables of soccer SSGs specific to different playing positions.

- Recent studies have provided evidence for the safe use of session rate of perceived exertion (sRPE) as a valid indicator of an internal training response in soccer training [Impellizzeri et al. 2004]. It would be interesting to correlete the sRPE values (perceived load) with the parameters presented in *Study III* (i.e. metabolic and mechanical variables; external load) with regard to elite soccer training sessions.

APPENDICES

Appendix A:

BIOMECHANICS AND PREDICTED ENERGETICS OF SPRINTING ON SAND: HINTS FOR SOCCER TRAINING

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Original research

Biomechanics and predicted energetics of sprinting on sand: Hints for soccer training

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ABSTRACT

Objectives: The purpose of this study was to analyse energetic and biomechanical parameters of sprinting on sand surface, aimed at the evaluation of inherent aspects of soccer training programs, injury prevention and recovery processes.

Design: Twenty-nine professional soccer players took part in this study: they performed maximal sprints and maximal shuttle sprints on a 12 m distance on natural grass, artificial turf and soft, dry sand.

Methods: Speed, acceleration, deceleration, stride length, stride frequency, flight and contact time, estimated energy cost, metabolic and mechanical power, efficiency and stiffness values, have been calculated through the instrument SPI-Pro (GPSports, Canberra, Australia) supported by two fixed cameras.

Results: The comparison between values recorded on sand with those recorded on natural or artificial grass has highlighted significant decreases ($p < 0.001$) of speed, acceleration, stride length, flight time and mechanical power, efficiency and stiffness. Contact time, energy cost, metabolic power ($p < 0.001$) and deceleration ($p < 0.05$) were higher on sand whereas no significant differences were found regarding stride frequency ($p > 0.05$).

Conclusions: These results show that on sand it is possible to perform maximal intensity sprints with higher energy expenditure and metabolic power values, without reaching maximum speed and with smaller impact shocks. Furthermore, exercises with change of direction carried out on this surface allow to reach higher deceleration values. In addition, sprinting on sand potentially entails a limited stretch of the involved muscles. It can therefore offer a valid alternative to traditional training, injury prevention and rehabilitation programs.

1. Introduction

Sand surfaces differ from the compact ones due to the presence of air gaps: this involves the compression and the displacement of the surface under pressure of the foot during the running stride. Consequently, the foot slips and sinks, forcing the lower limb muscles to carry out additional work to stabilize the point of reaction force on the surface.[1,2]

Previous studies have measured physiological differences in walking and running at constant speed when comparing sand with conventional surfaces.[3,4,5] Other authors studied the energy cost (EC) of walking and running at various speeds, comparing sand and hard surfaces. They found EC coefficients (ratio of sand to firm ground EC values) between 1.8 and 2.7 for walking[1,2,3] and between 1.2 and 1.6 for running.[1,2,6] According to Zamparo et al.[2] their findings could be attributed to a reduced recovery of potential and kinetic energy at each stride when walking on sand and to a reduced recovery of elastic energy when running on sand. In addition, no significant differences were found between the sand bare foot and sand in shoes running trial EC measures.[6] Finally, it was also demonstrated that when running on sand EC increases slightly with speed, whereas on firm ground it is independent of speed.[1,2]

The purpose of the present study was to investigate energetic and biomechanical variations in short sprint tests with or without change of direction performed by professional soccer players on sand surface, compared to natural grass and artificial turf. Since the present literature does not offer studies on this subject, a detailed analysis of sprint exercises carried out on sand could reveal useful information to plan a training session that involves this particular surface, in order to better design the workload protocol.

2. Methods

Informed consent to participate in the study was obtained from 29 male professional soccer players (age 19 ± 1 years, height 178.2 ± 5.3 cm, mass 71.8 ± 6.1 kg, VO_{2max}

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58.85 ± 4.15 ml kg^{-1} min^{-1}; mean ± SD). The Ethics Committee of the University of Milano approved the study. Players with different position on the field were tested: 7 defenders, 15 midfielders and 7 forwards. Goalkeepers were not included in the study. All participants were normally trained at the beginning of the testing protocol and none of them was affected by muscular or neuromuscular pathologies.

After a standardized warm up (12 min), each athlete was requested to perform two different exercises: a maximum speed sprint on 12 metres (12 m) and a maximum speed shuttle sprint (with 180° change of direction) on an equal distance of 12 m, for a total of 24 m (12 m + R). These two exercises were carried out on natural grass, on 3rd-generation artificial turf (Mondoturf NSF, MONDO, Alba, Italy) and on a soft, dry sand surface 30 cm deep. The average grain size was 0.5 mm. The sprint distance of 12 m (run in about 2 s) was chosen as representative of the typical high-intensity effort made by soccer players during a match.[7] Each test was carried out during the same day and repeated twice. Only the best test was considered in the statistical analysis. Between each trial a complete recovery time of 5 min was allowed. During the tests, every player wore the soccer boots normally utilized during the training.

A non-differential Global Positioning System (GPS) 5 Hz receiver (SPI-Pro, GPSports, Canberra, Australia) was used for data collection. The SPI-Pro units contain also a triaxial accelerometer (100 Hz). The technological evolution of the GPS models and especially the increase in sampling frequency has led to confirm that this is a valuable instrument for calculating distance and speed during different outdoor activities.[8,9] A standard error of the estimate (SEE) of 1.5–2.2% and a coefficient of variation (CV) of 2.2–4.5% were found for the measurement of distance covered during soccer-specific activity[10] and a CV of 1.2% was calculated for the measurement of peak speed in sprinting.[11]

In the present study, players carried out all the tests with the device (mass = 76 g; size = 48 mm × 20 mm × 87 mm) worn in a purpose designed vest (GPSports, Canberra, Australia) to ensure that the range of movement was not restricted. According to the suggestions found in literature,[12,13] in order to avoid inter-unit error players wore the same GPS device for each trial. Through the GPS data and the software that makes possible to download and analyse data on a computer (Team AMS, GPSports, Canberra, Australia), the following parameters were calculated for each trial: duration, average and maximum speed, average and maximum acceleration and maximum deceleration. The 12 m + R tests were exclusively performed in order to obtain the deceleration data, all the other parameters regard the 12 m sprint tests.

In order to estimate the EC of each sprint performed by the soccer players, the theoretical model proposed by di Prampero et al.[14] was adopted. According to this model, accelerated running on a flat terrain is considered energetically equivalent to uphill running at constant speed that was previously studied by Minetti et al.[15] and the uphill slope is dictated by the forward acceleration. The average EC (in J kg^{-1} m^{-1}) of every sprint performed on natural grass or artificial turf was calculated through the equation proposed by di Prampero et al.[14] and then modified by Osgnach et al.[16] to evaluate soccer players sprinting on grass (Eq. (1)):

$$EC_{ag} = (155.4ES^5 - 30.4ES^4 - 43.3ES^3 + 46.3ES^2 + 19.5ES + 3.6) \cdot EM \cdot KT \qquad (1)$$

where EC_{ag} is the energy cost of accelerated running on grass (in J kg^{-1} m^{-1}), ES is the equivalent slope: ES = tan(90 − arctan g/a_f); g = Earth's acceleration of gravity; a_f = forward acceleration; EM is the equivalent body mass: $EM = (a_f^2/g^2 + 1)^{0.5}$; and KT is a constant (KT = 1.29).

To calculate the average EC of sprinting on sand (EC_{as} in J kg^{-1} m^{-1}, Eq. (2)), Eq. (1) was further amended multiplying EC_{ag} by a constant (KS = 1.45) to take into account that running on sand is approximately 45% more costly than running on natural grass.[6]

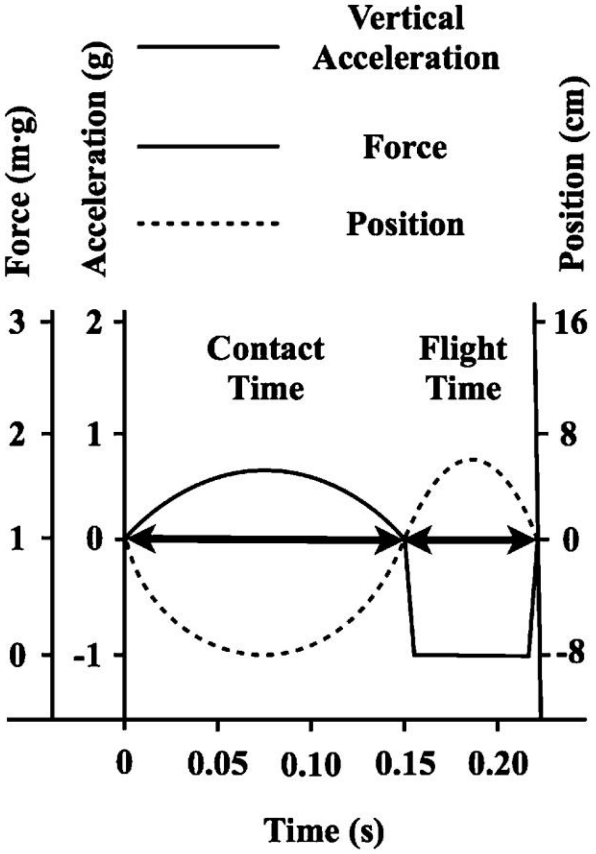

Fig. 1. Trend of acceleration (in $g = 9.81$ m s^2), force (in $m{\cdot}g$ = body mass in kg multiplied by 9.81) and centre of mass (COM) position on the vertical axis (in cm) during contact and flight phases in sprinting (12 m).

$$EC_{as} = (155.4ES^5 - 30.4ES^4 - 43.3ES^3 + 46.3ES^2 + 19.5ES + 3.6) \cdot EM \cdot KT \cdot KS \qquad (2)$$

In addition, average metabolic power (P_{met} in W kg^{-1}, Eq. (3)) was calculated in both cases multiplying EC by running speed (v):

$$P_{met} = EC \cdot v \qquad (3)$$

On the other hand, by multiplying data of acceleration (a_f) by running speed (v), the values of average mechanical power (P_{mec} in W kg^{-1}) were calculated (Eq. (4)):

$$P_{mec} = a_f \cdot v \qquad (4)$$

Consequently, the overall efficiency of sprinting (ratio between P_{mec} and P_{met}) was calculated with regard to the three different surfaces.

In addition, through the accelerometer data contact time (t_c) to the ground for left and right foot and flight time (t_f) were calculated during the entire sprint for all strides. These parameters (t_c and t_f) were measured using the time course of the acceleration on the vertical axis. As illustrated in Fig. 1, which describes the time course on the vertical axis of ground reaction force, vertical acceleration and position of the centre of mass (COM) in sprint running, the force (thus the body acceleration) expressed by the extensor muscle, continues to show positively until the foot is in contact with the ground. Therefore, it is possible to deduce that as long as the acce-

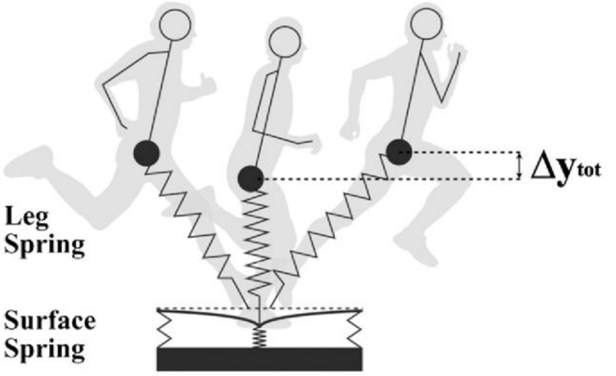

Fig. 2. Spring-mass model representing a runner's leg in contact with a compliant surface. Δy_{tot} is the maximum vertical displacement of the centre of mass (COM) during the contact phase.

leration is greater than zero the body is accelerating upward, and to do that the foot should still be in contact with the ground. Hence, the take-off (beginning of the t_f) occurs when the acceleration value (on the vertical axis) decreases below the initial one.[17]

Furthermore, the values of stiffness k_{tot} (in kN m^{-1}) were calculated through the method proposed by Morin et al.[18] for measuring stiffness during running only from body mass, t_c and t_f values. Stiffness is the ability that the system has to withstand a strain which obviously varies according to the surface with which the person is in contact and speed.[19] Therefore, what is understood as stiffness (k_{tot} in Eq. (5)) should be regarded as a combination of k_{surf} (surface stiffness) and k_{leg} (leg stiffness) according to the spring-mass model.[17,20,21] From a more practical point of view, k_{tot} could represent an index of the impact hardness during the sprint running. In addition, since the k_{leg} of the player is supposed not to change consistently performing maximal sprint running on the three different conditions, k_{tot} will be mainly influenced by k_{surf}.

A better understanding of the spring-mass model can be supported by the representation, in Fig. 2, of a athlete running on a soft surface (low k_{surf}) at the beginning, in the middle and in the end of the contact phase. In this case, the surface compression (surface spring) is in series with the compression of the spring that represents the leg (leg spring). The lowering of the COM (Δy_{tot}) is equal to the sum of compression of both leg spring and surface spring. The k_{tot} is equal to the series combination of k_{leg} and k_{surf}. Thus, k_{tot} (Eq. (5)) is the ratio of the maximal ground reaction force (F_{peak}, in N) and the vertical displacement of the COM (Δy_{tot}, in m) at the time of maximum compression both changing as function of t_c and t_f[18,20] so was calculated as:

$$k_{tot} = \frac{F_{peak}}{\Delta y_{tot}} \tag{5}$$

with

$$F_{peak} = m \cdot g \cdot \frac{\pi}{2} \cdot \left(\frac{t_f}{t_c} + 1\right) \tag{6}$$

F_{peak} being the maximal ground reaction force during contact (in N), m is the athlete's body mass (in kg), g is the gravitational acceleration and t_c and t_f, respectively, the flight and contact times (in s).

$$\Delta y_{tot} = \frac{F_{peak} \cdot t_c^2}{m \cdot \pi^2} + g \cdot \frac{t_c^2}{8} \tag{7}$$

In addition, each test was also video recorded with two fixed cameras (25 Hz) in order to obtain the time taken and the number of strides performed by the athletes. Consequently average stride length and stride frequency values were calculated.

After the data collection, statistical analysis was made through an analysis of variance (One-way ANOVA) for paired data, followed by a Bonferroni test (post hoc test), in order to identify if there were significant differences between the three surfaces considered with respect to the parameters analyzed. With regard to average acceleration and maximum deceleration values, the test of homogeneity of variance resulted in significance ($p < 0.05$) hence a Brown–Forsythe test (One-way ANOVA) followed by a Games–Howell test (post hoc test) were made. SPSS Statistics 19 (IBM, Somers, New York, USA) was employed for the statistical analysis. The level of statistical significance was set at $p < 0.05$ for all tests.

3. Results

The comparison between the values recorded on sand with those recorded on natural or artificial grass has highlighted significant decreases ($p < 0.001$) in terms of average speed, maximum speed, average acceleration, maximum acceleration, average stride length, flight time, average P_{mec}, and stiffness that were lower on sand. Differently, average EC, average P_{met} and contact time were highest ($p < 0.001$) during sprinting on sand surface. Efficiency values (ratio between P_{mec} and P_{met}) of sprinting were calculated to be equal to 0.17 with regard to both natural and artificial grass and 0.12 for sand.

Concerning maximum deceleration values in 12 m + R a significant difference ($p < 0.05$) was found only comparing sand with natural grass. A particular interesting finding was represented by the lack of significant differences ($p > 0.05$) between the different surfaces as regards stride frequency. In addition, no significant differences ($p > 0.05$) were found between tests performed on natural grass compared to artificial turf with respect to all parameters analyzed in this study. All data (mean ± SD and level of statistical significance) are shown in Table 1.

4. Discussion

In the literature there are no previous studies concerning sprints on sand compared with similar exercises carried out on hard surfaces. The use, innovative in this field, of GPS with integrated accelerometers, supported by video cameras, led to confirm some existing theories, and to hypothesize other ones based on new parameters such as acceleration, deceleration and maximum speed on these three different surfaces. It is very important to underline that there was not a significant difference ($p > 0.05$) regarding all the parameters analyzed in this study comparing natural and artificial turf. According to these results, it is reasonable to hypothesize that there are no differences in training effects or injury risk carrying out exercises on natural grass or on 3rd-generation artificial pitches.

On the other hand, a decrease of maximum acceleration and maximum and average speed ($p < 0.001$) were measured by GPS (5 Hz) in tests performed on sand compared to natural or synthetic grass and that may be due to the consistency and the instability of the sand. As proposed by Zamparo et al.,[2] an additional mechanism that may have led to a decreased acceleration on sand could be identified with the tendency of the foot to slip backwards during the push phase of the stride. Moreover, a significant difference ($p < 0.05$) was detected with regard to the values of maximum deceleration registered during the change of direction in 12 m + R tests that was higher on the sand surface compared to natural grass. This suggests that exercises with change of direction might be better suited to this surface (sand), on which it is possible to reach more important maximum deceleration values. This result could be very valuable for the planning of training sessions focused on eccentric force during prevention or recovery processes.

Table 1
Results (mean ± SD) of all the parameters analyzed on natural grass, artificial turf and sand surface during the (a) 12 m and (b) 12 m + R tests.

	Natural grass	Artificial turf	Sand
Duration (s)[a]	1.98 ± 0.06	1.99 ± 0.09	2.28 ± 0.09***
Average speed (m s^{-1})[a]	6.05 ± 0.2	6.01 ± 0.29	5.27 ± 0.23***
Maximum speed (m s^{-1})[a]	7.04 ± 0.47	7.12 ± 0.35	6.22 ± 0.41***
Average acceleration (m s^{-2})[a]	2.97 ± 0.29	2.98 ± 0.20	2.62 ± 0.15***
Maximum acceleration (m s^{-2})[a]	7.05 ± 1.95	7.00 ± 1.70	5.94 ± 1.18***
Maximum deceleration (m s^{-2})[b]	8.00 ± 1.26	7.97 ± 2.09	9.13 ± 1.57*
EC: average energy cost (J kg^{-1} m^{-1})[a]	17.13 ± 1.68	17.17 ± 1.14	21.97 ± 1.19***
P_{met}: average metabolic power (W kg^{-1})[a]	103.92 ± 12.17	103.91 ± 9.59	116.26 ± 9.14***
P_{mec}: average mechanical power (W kg^{-1})[a]	17.99 ± 2.10	18.01 ± 1.66	13.86 ± 1.13***
Number of contacts[a]	8.92 ± 0.35	8.90 ± 0.30	10.05 ± 0.46***
Average stride length (m)[a]	1.34 ± 0.06	1.34 ± 0.05	1.19 ± 0.05***
Stride frequency (Hz)[a]	4.46 ± 0.31	4.46 ± 0.24	4.41 ± 0.26
t_f: average flight time (s)[a]	0.068 ± 0.008	0.068 ± 0.009	0.049 ± 0.006***
t_c: average contact time (s)[a]	0.151 ± 0.010	0.153 ± 0.013	0.180 ± 0.012***
F_{peak}: maximal ground reaction force (kN)[a]	1.62 ± 0.17	1.61 ± 0.17	1.42 ± 0.15***
Δy_{tot}: vertical displacement of the COM (m)[a]	0.079 ± 0.009	0.081 ± 0.011	0.104 ± 0.013***
k_{tot}: stiffness (kN m^{-1})[a]	20.77 ± 3.82	20.30 ± 3.93	13.85 ± 2.40***

* $p < 0.05$, significant difference from natural grass values.
*** $p < 0.001$, significant difference from natural grass values.

Data of acceleration have led to obtain average EC values of sprinting on sand 30% greater ($p < 0.001$) than those found sprinting on grass, which has not previously been investigated. Higher values of EC measured sprinting on sand can be seen as a positive characteristic with respect to the use of this surface during training sessions. This also confirms the theories of various authors who identified the instability of the surface as the main cause of the increased EC on sand and then the necessity to provide for additional energy expenditure associated with muscle contraction to generate forces that control joint excursion or stability, besides the reduced elastic response.[1,2,6] The possibility to perform maximal intensity exercises (with an high EC) without reaching maximum speed can certainly be considered as a positive feature with regard to the use of sand in a rehabilitation phase of an injured athlete, since it will allow players to train at high metabolic intensity reducing the risk to get injured again.

As the calculation of P_{met} values in this instance are based on maximal exercise values they should be equal on the different surfaces. The higher estimated EC of sprinting on sand led to achieve a 10% higher P_{met} ($p < 0.001$). It can be interpreted as an indicator of the possibility to express maximal power when running at lower speed on sand and perhaps more easily than it can be done when sprinting on grass. This is another positive aspect to consider as regards to training on this surface. For example, it could be particularly useful to perform physical training sessions on sand surface during the pre-season, when a higher metabolic workload is required to prepare the players to start the in-season period in their best physical condition.

The resulting difference (−29%) of the overall efficiency could have been mainly determined by a corresponding decrease of transmission efficiency when sprinting on sand, by assuming a constant muscular efficiency in the three surface conditions (the product of the two efficiencies makes the overall efficiency). As a matter of fact, the contraction speed of propulsive muscles, potentially affecting muscular efficiency, is supposed not to vary much on grass and on sand. This rationale supports the view that transmission efficiency could be one of the main determinants of the increase in EC sprinting on sand. This is also in agreement with Pinnington et al.[5] who demonstrated a higher degree of co-contraction in muscles crossing the knee and the ankle when running on sand. This could be the cause of lower "transmission" efficiency since muscles need to work "one against the other" for a stabilization strategy.

In addition, the values of t_f and t_c recorded by the accelerometer (100 Hz) during the sprints showed a significant difference ($p < 0.001$) between the sand surface (with higher t_c values) and the other two conditions. Consequently, this factor also led to a significant difference ($p < 0.001$) for the values of k_{tot}, higher in tests performed on natural or artificial grass. With regard to these data (k_{tot}), it was calculated a difference between those recorded on sand and on natural grass (not significantly different from those measured on synthetic turf) of 33%. This result demonstrated that a lower stress of joint and muscle-tendon structures occurred during exercises conducted on sand: a very important aspect concerning injury prevention and recovery process. Regarding this, training on sand could be used in elite soccer as an alternative to the normal training sessions during the competitive period to try to relax the joints that are usually overused. For the same reasons, the values of k_{tot} found in this study led to suggest that training on sand could be feasible and probably beneficial during the recovery process when the player feels pain running on grass (e.g. after anterior cruciate ligament surgery). Obviously when injured players carry out some exercises on this surface during their rehabilitation process, they need to have already recovered a good level of strength. It will not be the first thing that the injured player should do, but it could be an important step after physiotherapy, before returning to training on grass.

From k_{tot} values found in this study during sprints on sand and on grass, a stiffness value of the soft, dry sand surface (k_{sand}) was estimated to be equal to 41.57 kN m^{-1} (see Appendix A). The k_{sand} value is commeasurable with those reported in the literature, experimentally obtained by using a completely different procedure.[22] This supports the validity and reliability of the adopted theoretical method.

With regard to the results obtained through the images recorded by video cameras (25 Hz), it is important to point out that significant differences ($p < 0.001$) were found by comparing exercises carried out on sand with those performed on the other two surfaces about number of contacts, greater on sand, and average stride length, greater on natural and artificial grass. These results are also in agreement with those previously found by Pinnington et al.[5] that reported greater hip and knee flexion when running on sand. On the other hand, no significant differences ($p > 0.05$) were recorded with regard to stride frequency, which was almost unchanged in the tests carried out on the three different surfaces. This indicates that changes of speed in sprints on the different surfaces were due to a different stride length, and not to a different stride frequency. This means that sprinting on sand probably entails a limited stretch of the involved muscles if compared to a similar exercise carried out on natural or synthetic grass and, therefore, a lower risk of injury.

5. Conclusions

In conclusion, the present study showed that sand surface could be a useful alternative tool for training, injury prevention and recovery process. The obtained stiffness values, lower on sand, have to be considered positively as a reduction of risk, and then in favour of the preventive use of sand surface and its application in the training program. Furthermore, on the basis of the obtained results regarding maximum speed, maximum deceleration, stride frequency, stride length, estimated EC and P_{met} it is possible to conclude that on sand surface it is possible to carry out maximal intensity sprints, also with change of direction including greater deceleration values, without reaching maximum speed, maintaining the same stride frequency, and with smaller stride length. That could be obviously interpreted as a factor that increases the safety of the exercise, maintaining the final training goal.

Finally, using GPS, triaxial accelerometer and video cameras, this protocol is reproducible on any surface, even on those where force platforms or optical measurement systems are not possible to be used to calculate speed, acceleration, deceleration or t_c and t_f.

A future study could be designed to estimate, through higher spatial/temporal resolution video cameras, the amount of sand laterally moved during the stride, which does not contribute to the forward propulsion of the athlete but increases the mechanical work done.

Practical implications

- On sand surface it is possible perform maximal intensity sprints, with higher EC and P_{met} values, without reaching maximum speed and with smaller impact shocks.
- Sprinting on sand entails a limited stretch of the involved muscles.
- Exercises with change of direction carried out on sand allow to reach higher deceleration values.

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Appendix A. Sand stiffness

From the stiffness values (k_{tot}) found in the present study sprinting on sand and on natural or artificial grass, a value of stiffness of the soft, dry sand surface was estimated.

According to the spring-mass model (Fig. 2) and by considering leg spring and leg surface as two springs in series,[20] it is possible to calculate k_{tot} through the following equation:

$$k_{\text{tot}} = \frac{1}{(1/k_{\text{leg}}) + (1/k_{\text{surf}})} \tag{8}$$

From which:

$$k_{\text{surf}} = \frac{k_{\text{tot}} \cdot k_{\text{leg}}}{k_{\text{leg}} - k_{\text{tot}}} \tag{9}$$

Natural grass is certainly more rigid than sand, thus on that surface the vertical displacement of the COM is expected to be closer to the one of the leg spring only.[20] Hence k_{tot} on grass is approximately equal to k_{leg}. By assuming a substantially constant value of k_{leg} at different speeds and surfaces, in order to calculate k_{sand} (k_{surf} in Eq. (9)), it is possible to replace k_{tot} with k_{tot} on sand (13.85 kN m^{-1}) and k_{leg} with k_{tot} on natural grass (20.77 kN m^{-1}) previously calculated in this study. Then k_{sand} was found to be equal to 41.57 kN m^{-1}.

The obtained k_{sand} appears in good agreement with that reported by Barrett et al.[22] They measured a surface stiffness of 59.1 ± 29.4 kN m^{-1} for dry, uncompacted sand compared with a value of 379.5 ± 118.3 kN m^{-1} for a wet compacted sand surface, a value more than six times stiffer. In collecting their data Barrett et al. used a PBC piezoelectric accelerometer and a Schulumberger displacement transducer using four masses (3.86, 7.24, 10.62 and 14.0 kg) dropped from four different heights (100, 200, 300 and 400 mm) to represent the kinetic energies typically experienced during heel strike in running. Five trials at each test condition were conducted at four different sand surface depths (100, 150, 200 and 150 mm) which resulted in 640 trials.[22]Probably the lower values of k_{sand} calculated in the present study are due to a greater sand depth (300 mm) with respect to Barrett's experiments in addition to the difference between the human foot impact and the drop mass impact.

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Appendix B:

THE COST OF TRANSPORT OF HUMAN RUNNING IS NOT AFFECTED, AS IN WALKING, BY WIDE ACCELERATION/DECELERATION CYCLES

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The cost of transport of human running is not affected, as in walking, by wide acceleration/deceleration cycles

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Minetti AE, Gaudino P, Seminati E, Cazzola D. The cost of transport of human running is not affected, as in walking, by wide acceleration/deceleration cycles. *J Appl Physiol* 114: 498–503, 2013. First published December 6, 2012; doi:10.1152/japplphysiol.00959.2012.—Although most of the literature on locomotion energetics and biomechanics is about constant-speed experiments, humans and animals tend to move at variable speeds in their daily life. This study addresses the following questions: *1*) how much extra metabolic energy is associated with traveling a unit distance by adopting acceleration/deceleration cycles in walking and running, with respect to constant speed, and *2*) how can biomechanics explain those metabolic findings. Ten males and ten females walked and ran at fluctuating speeds (5 ± 0, ± 1, ± 1.5, ± 2, ± 2.5 km/h for treadmill walking, 11 ± 0, ± 1, ± 2, ± 3, ± 4 km/h for treadmill and field running) in cycles lasting 6 s. Field experiments, consisting of subjects following a laser spot projected from a computer-controlled astronomic telescope, were necessary to check the noninertial bias of the oscillating-speed treadmill. Metabolic cost of transport was found to be almost constant at all speed oscillations for running and up to ±2 km/h for walking, with no remarkable differences between laboratory and field results. The substantial constancy of the metabolic cost is not explained by the predicted cost of pure acceleration/deceleration. As for walking, results from speed-oscillation running suggest that the inherent within-stride, elastic energy-free accelerations/decelerations when moving at constant speed work as a mechanical buffer for among-stride speed fluctuations, with no extra metabolic cost. Also, a recent theory about the analogy between sprint (level) running and constant-speed running on gradients, together with the mechanical determinants of gradient locomotion, helps to interpret the present findings.

running economy; speed oscillation

IT IS WELL KNOWN THAT THE metabolic cost of transport of human walking ($J \cdot kg^{-1} \cdot m^{-1}$) is a U-shaped function of the progression speed, whereas running cost is speed independent (6). These and many other findings in the literature on human locomotion are based on constant-speed experiments on treadmills (14) although, in real life, human and animal gaits very often occur at variable speeds (11). When considering this feature of daily locomotion, one could be tempted to estimate the overall cost of transport by combining, in a sort of a discrete integral, the data obtained at fixed progression speeds, weighed for their duration in the accelerative/decelerative pattern. Particularly, that approach would underestimate the real metabolic cost of transport of running at oscillating speeds because, as mentioned above, the cost is speed independent. Whereas the cost of deceleration could be considered nil because the body kinetic energy could be dissipated as heat (which we know is not the case, Ref. 14), acceleration is expected to involve some extra mechanical/metabolic energy (as occurring in road vehicles).

A few years ago, Minetti and collaborators (9) showed that walking at a speed cyclically oscillating within a wide range (±2 km/h) resulted in the same cost of moving at the average constant speed. Mechanical measurements suggested that the human body behaves similarly to a hybrid car: the inherent mechanical energy increase and decrease occurring within a single stride in a constant speed sequence can be combined to be equivalent to a number of accelerating strides followed by the same number of decelerating strides, resulting in a similar energy balance at the end of the speed-oscillating cycle. In synthesis, as hybrid cars minimize the extra fuel consumption due to the oscillating speed in the urban environment by converting deceleration energy into acceleration (via electric energy), humans limit the extra cost of oscillating walking by exploiting the inherent within-stride energy fluctuation in multiple accelerating/decelerating strides. In the absence of a relevant anatomical structure capable of cumulatively storing deceleration energy of several steps for later use, during long-term oscillating speed cycles, the negative work is not done within the steps of the accelerative phase for it to be postponed to the overall decelerative phase, where conversely steps do not show any residual positive work, which is normally typical of constant-speed locomotion (9). In this way, the peculiar energy time course serves as a virtual storage/release system, allowing performance of long-term acceleration cycles at no extra metabolic cost.

Apart from describing a fundamental aspect of legged locomotion, the interest about oscillating-speed gaits is today boosted by the need to infer the metabolic consumption of sport activities such as soccer (12), rugby (5), and other field games, where subjects run at a variable speed. In particular, match analysis and other video techniques are devoted to sample players' movements, even in real time, from which the associated oxygen consumption could be indirectly estimated and the relevant training programmed.

In this study, we extend previous metabolic measurements on oscillating-speed walking (9) to running, with the aim to eventually establish the maximum acceleration/deceleration range at which the cost of transport does not deviate from that of the fixed average speed. The experiments have been conducted both on a variable-speed treadmill and overground to check the reliability of the laboratory-based methodology (noninertial reference system), previously confirmed for walking (9) and also in oscillating-speed running.

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Table 1. *Anthropometric characteristics of the subjects*

	N	Age, yr	Height, cm	Mass, kg	BMI	Sex
Walking	20	24 ± 4	171 ± 7	64 ± 10	21.8 ± 2.3	10 males/10 females
Running	10	28 ± 4	178 ± 5	72 ± 8	22.9 ± 2.5	males

Applicable values are means ± SD. BMI, body mass index.

MATERIALS AND METHODS

Ten female and ten male subjects (see Table 1 for anthropometric data) participated in the study, after having signed their informed consent. The investigation has been approved by the Ethical Committee of the University of Milan.

As in the previous study on walking, experimental sessions were organized both in the laboratory and in the field. Due to the complexity of the outdoor experimental protocol needed to test subjects in a truly inertial system, laboratory measurements were the first to be done. Running experiments were performed only by male subjects.

Laboratory session. A motorized treadmill (Ergo LG; Woodway) was programmed to move at constant and oscillating speed, as described by linear ascending and descending speed ramps, each lasting 3 s. The average speed was 11 km/h, and the five oscillations were ±0, ±1, ±2, ±3, and ±4 km/h. After familiarization with the treadmill and the experimental protocols, the subjects ran for 5 min in each condition, chosen from a random sequence and separated by 10-min rest. Heart rate (HR), oxygen uptake ($\dot{V}O_2$), and CO_2 production were measured by a portable metabograph (k4b2; Cosmed) both at rest while standing and during exercise. The metabolic cost of transport (C) was calculated by dividing the net oxygen uptake, collected in the last minute of each condition, by the average progression speed. The final units, i.e., $J \cdot kg^{-1} \cdot m^{-1}$, were obtained by dividing by the subject mass and by converting ml O_2 into J according to the measured Respiratory Quotient (RQ = CO_2 production/O_2 consumption).

In addition, 18 reflective markers were located on the most relevant joints of one subject to estimate the 3D path of the body center of mass (7), by means of motion-capture system (100 Hz; Vicon). The time course of that trajectory was used to infer the changes in mechanical energies (potential and horizontal/vertical kinetic and total) involved in running at the widest oscillating speed (see Fig. 4).

To obtain a complete set of speed-oscillation gaits on the same subjects and to slightly extend the oscillations originally investigated, we also replicated the above protocol for walking by following the procedure illustrated previously (9). The average speed chosen for walking was 5 km/h with 5 oscillations (±0.0, ±1.0, ±1.5, ±2.0, ±2.5 km/h).

Field measurements. Subjects ran by following a green spot projected by a 532-nm, 300 mW laser (WickedLasers) on the soccer pitch of the San Siro "Meazza" Stadium in Milan (Fig. 1). The mechanical frame of a digitally motorized telescope (NextStar 4SE, Celestron) was programmed by custom software (LabView 8.6, National Instruments) as to move the attached laser from a height of about 40 m and describe a circular path with 68-m diameter (the width of the soccer pitch). At the average speed chosen, moving along that path was expected to generate a centrifugal acceleration of 0.27 $m \cdot s^{-2}$, which was considered as uninfluential to the current dynamics with respect to straight-line running. The software controlled, via a RS-232 serial port, both azimuth and altitude of the two-step motors of the telescope as to project the laser dot at constant angular speed (11 ± 0 km/h) and at the other four oscillating speeds (Fig. 2). This was achieved by dividing the circular trajectory into 180 steps (2° each) and by setting the speed and duration of the linear translation between them. The 10 subjects, wearing protective laser goggles and equipped with the same portable metabograph used in the laboratory, completed four full circles for each condition. The assessment of the metabolic cost followed the same procedure as described above.

In both research environments, blood lactate (La) was sampled (Lactate Plus, Nova Biomedical) 4 min after each investigated condition to check the aerobic regime of running experiments.

Statistics. All recorded data are presented as means ± SD in Table 2. For statistical analysis of $\dot{V}O_2$, HR, La, RQ, and C, a one-way ANOVA for reapeated measures was performed (with a post hoc Bonferroni test) to check the effects of the five oscillation levels, both in walking and in pooled data. A two-way ANOVA for repeated measures was performed on running data (cost: variable of interest; within factors: acceleration level and environment, i.e., laboratory vs. field, with a post hoc Bonferroni test). The null hypothesis was rejected when $P < 0.05$.

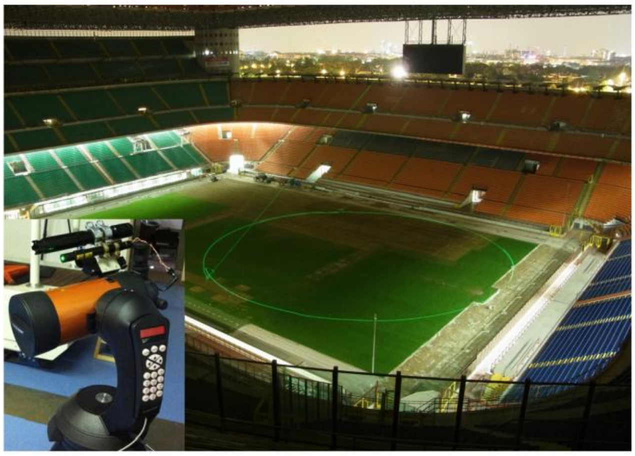

Fig. 1. A photograph in "bulb" setting of the circle traveled, in the San Siro Stadium (Milan), by the spot projected by a laser beam fitted to a motorized astronomical telescope (*inset*).

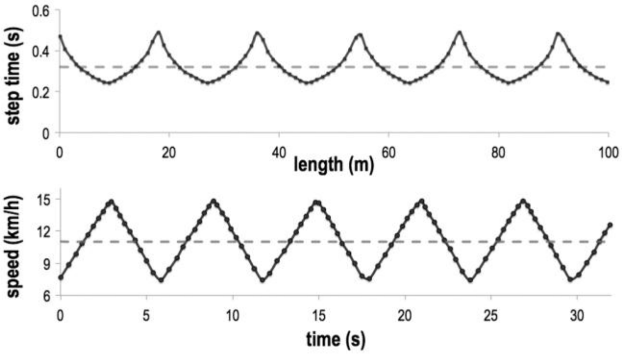

Fig. 2. The graph shows an example of the time interval between equally spaced locations along the circle (*top*) during which the 2-step motors of the telescope were set to move at a constant speed, resulting in the widest oscillating speed protocol adopted (11 ± 4 km/h, *bottom*).

Table 2. *Metabolic parameters measured during walking (laboratory session) and running (laboratory, field, and pooled data) at constant and oscillating speeds*

Exercise and Location	Speed				
Walking, km/h	**5 ± 0.0**	**5 ± 1.0**	**5 ± 1.5**	**5 ± 2.0**	**5 ± 2.5**
Laboratory					
$\dot{V}O_2$, $mlO_2 \cdot kg^{-1} \cdot min^{-1}$	15.24 ± 2.24	**16.46 ± 2.45‡**	**16.60 ± 2.51‡**	**17.37 ± 2.13‡**	**17.91 ± 2.70‡**
HR, bpm	104 ± 18	112 ± 25	**109 ± 19‡**	**111 ± 19‡**	**114 ± 20‡**
RQ	0.82 ± 0.05	0.81 ± 0.05	0.82 ± 0.05	0.82 ± 0.05	0.83 ± 0.04
C, $J \cdot kg^{-1} \cdot m^{-1}$	2.79 ± 0.46	**3.05 ± 0.49‡**	**3.09 ± 0.55‡**	**3.28 ± 0.47‡**	**3.42 ± 0.57‡**
Running, km/h	**11 ± 0**	**11 ± 1**	**11 ± 2**	**11 ± 3**	**11 ± 4**
Laboratory					
$\dot{V}O_2$, $mlO_2 \cdot kg^{-1} \cdot min^{-1}$	42.04 ± 3.52	43.62 ± 4.31	42.94 ± 4.30	**42.59 ± 3.89‡**	**42.81 ± 4.07‡**
HR, bpm	160 ± 13	163 ± 14	**164 ± 13***	161 ± 11	164 ± 13
La, mmol/l	2.6 ± 1.3	2.3 ± 1.2	2.2 ± 1.4	2.2 ± 1.3	2.3 ± 1.2
RQ	0.95 ± 0.08	0.93 ± 0.05	0.92 ± 0.06	0.94 ± 0.07	0.91 ± 0.06
C, $J \cdot kg^{-1} \cdot m^{-1}$	4.32 ± 0.42	4.49 ± 0.48	4.40 ± 0.49	**4.37 ± 0.44‡**	**4.37 ± 0.48‡**
Field					
$\dot{V}O_2$, $mlO_2 \cdot kg^{-1} \cdot min^{-1}$	40.88 ± 3.44	39.10 ± 4.00	42.33 ± 4.27	**43.9 ± 4.77‡**	**44.83 ± 5.40‡**
HR, bpm	170 ± 10†	170 ± 11†	**174 ± 7*†**	171 ± 7†	174 ± 11†
La, mmol/l	2.3 ± 0.9	2.0 ± 1.1	2.3 ± 1.3	2.8 ± 1.5	2.9 ± 1.2
RQ	0.94 ± 0.08	0.93 ± 0.05	0.94 ± 0.05	0.98 ± 0.08	0.97 ± 0.06
C, $J \cdot kg^{-1} \cdot m^{-1}$	4.18 ± 0.34	4.03 ± 0.41	4.32 ± 0.42	**4.56 ± 0.49‡**	**4.66 ± 0.55‡**
Pooled Laboratory & Field					
$\dot{V}O_2$, $mlO_2 \cdot kg^{-1} \cdot min^{-1}$	41.46 ± 3.43	41.36 ± 4.66	42.64 ± 4.17	43.22 ± 4.27	43.82 ± 4.75
HR, bpm	165.9 ± 12.9	167.5 ± 13.1	169.7 ± 11.4	166.3 ± 10.8	169.1 ± 13.0
La, mmol/l	2.5 ± 1.1	2.2 ± 1.2	2.2 ± 1.3	2.5 ± 1.4	2.6 ± 1.2
RQ	0.94 ± 0.07	0.93 ± 0.05	0.93 ± 0.06	0.95 ± 0.07	0.94 ± 0.07
C, $J \cdot kg^{-1} \cdot m^{-1}$	4.25 ± 0.38	4.26 ± 0.49	4.36 ± 0.44	4.47 ± 0.46	4.52 ± 0.52

Values are means ± SD. Values in boldface indicate significant differences with the constant speed trial. *$P < 0.05$; ‡$P < 0.01$; †indicates field values significantly different from laboratory values (†:$P < 0.05$). HR, heart rate; RQ, respiratory quotient; La, lactate.

RESULTS

Walking. $\dot{V}O_2$ and C increased as a function of the oscillation speed (see Table 2) by showing significant differences with respect to the constant-speed condition at all oscillation levels, and HR was significantly higher at the upper three levels; RQ values were found to be independent from the acceleration protocol.

Running. Data are presented for nine male subjects because one of them reported blood lactate measurament higher than 4 mmol/l. Although moderately (but significantly) higher C values at the highest two oscillation levels (with respect to that at constant speed running) are shown, the data trend is very similar in both laboratory and field experiments. For this reason, we also present pooled data from the two environments in Table 2. It can be noted that the small increase of metabolic cost at high oscillation speeds is greater in the field condition, signaling that the noninertial bias of laboratory experiments, if any, could affect results only at high-acceleration running.

ANOVA revealed significantly higher HR values in the field condition, with no effects of the acceleration levels. The +10 bpm difference can be explained by the higher ambient temperature (31°C) during the field experiments with respect to the laboratory (25°C). It has been reported that a hot environment causes a decrease of central blood volume, with a parallel decrease of stroke volume, resulting in a higher HR with no change in $\dot{V}O_2$ (13).

DISCUSSION

As discussed previously (9), acceleration/deceleration cycles should be theoretically associated with some extra metabolic expenditure. By considering the increases in kinetic energy of the body center of mass due to acceleration, the extra positive mechanical external work ($\Delta W^+{}_{EXT}$, $J \cdot kg^{-1} \cdot m^{-1}$) was estimated (9) to exceed the one already associated with constant-speed running according to

$$\Delta W^{+}_{EXT} = 2\frac{\Delta v}{\delta t} \qquad (1)$$

where Δv is half the speed oscillation (m/s) and δt is the acceleration duration (s). The same applies to decelerations, where negative mechanical work has to be done to decrease the kinetic energy. Due to the fact that muscles consume metabolic energy to perform both work types, with different efficiencies ($eff^+ = 0.25$, $eff^- = 1.25$) (1), we can expect an increase in running cost of transport [$\Delta C = 0.5(\Delta W^+{}_{EXT}/eff^+ + \Delta W^-{}_{EXT}/eff^-)$] of

$$\Delta C = 4.8\frac{\Delta v}{\delta t} \qquad (2)$$

When expressed as extra energy expenditure ($\Delta E = v\Delta C$, $mlO_2 \cdot kg^{-1} \cdot min^{-1}$), for an average speed of 11 km/h and an acceleration phase lasting 3 s, we obtain

$$\Delta E = 14.04\Delta v \qquad (3)$$

As shown in Fig. 3, such a prediction greatly overestimates the pooled experimental data of running on the treadmill and in the field (ΔC = +49.4% rather than +6.3% at the widest speed oscillation). This trend indicates a substantial independency from the oscillation range. Although experimental sessions done in the laboratory were replicated in the field as a precaution against the noninertial frame of reference of the variable-speed treadmill (9), again we found no remarkable differences between the two conditions.

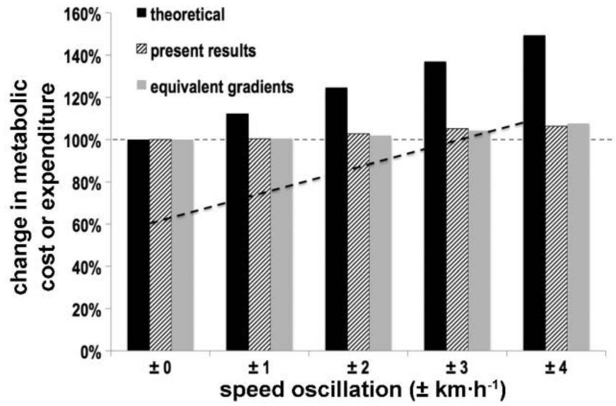

Fig. 3. The change of metabolic cost of running as a function of the speed-oscillation range, with respect to constant speed running. Solid bars represent the predictions from physics (and physiology), hashed bars show the present experimental data (laboratory and field pooled), whereas shaded bars are metabolic estimates obtained by adapting the equivalent gradient theory (4) to the present experimental conditions (see *Eq. 7–10*). The dashed line is just the downward translated trend of the prediction from physics, as to produce 0 increase at the widest speed oscillation. The vertical distance with experimental data represents the "reserve" in terms of inherent energy of constant speed strides that can be used in fluctuating speed cycles.

As in the previous analogous study (9), the present metabolic data of walking are almost constant up to a speed oscillation of ±2 km/h (Table 2).

The rationale to explain this phenomenon for walking has been based on the within-stride mechanical energy fluctuation occurring when moving at constant speed. We can expect that, during accelerative phases, mostly energy increases occur, the reverse being the case for decelerations. Therefore, by separately grouping the mechanical energy increases and decreases of constant-speed strides, we could obtain an equivalent sequence of strides, half of them in acceleration, half in deceleration. The two sequences should imply the same amount of postitive and negative work, thus the same overall metabolic energy expenditure (Fig. 4, *top*). Such an equivalence can be obtained only within a certain speed-change oscillation, and it is based on the physiological energy fluctuation range of the single stride at constant speed. For walking, it was concluded that ±2.5 km/h (and $\delta t = 3$ s) was that limit. Again, in agreement with the previous findings (9), the energy expenditure of speed-oscillating walking ($v \pm \Delta v$, m/s) can be predicted by the proposed equation calculating the average metabolic cost at all the speeds experienced during the cycle, therefore neglecting the energy associated to the speed changes, as:

$$\Delta E = 2.52\, v(\Delta v)^2 \qquad (4)$$

The explanation for running needs a more complex approach. The mechanical energy fluctuation within each stride is partly due to elastic energy stored and successively released by inert body structures, namely tendons, whose action does not affect the metabolic consumption of the runner (Fig. 4, *bottom*). However, the human body is not equiped with anatomical machinery devoted to store elastic energy on a long-term basis (as locusts do, for instance, Refs. 2 and 3), and the dynamics of that portion of the energy fluctuation cannot contribute to set cumulated mechanical energy increases in successive strides, as to correspond to the steady acceleration associated to the same (invariant) metabolic cost. It is necessary, then, to obtain an elastic-free estimate of the mechanical external work (W_{EXT}, J·kg^{-1}·m^{-1}) as

$$W_{EXT} = C_R\, eff - W_{INT} \qquad (5)$$

where C_R is the measured metabolic cost of running at constant speed (i.e., the metabolic equivalent of the elastic-free mechanical work done), *eff* is the maximum expected muscle efficiency, and W_{INT} is the mechanical internal work, necessary to accelerate limbs with respect to the body center of mass during each locomotor cycle. This operation corresponds to removing the internal work from the maximum total mechanical work (= $C_R eff$) that muscles actually do (see Fig. 5). By substituting C_R with the metabolic cost measured in this study at a constant speed of 11 km/h, *eff* with 0.25 (1) and W_{INT} with values for that speed obtained previously (6), we obtain $W_{\mathrm{EXT}} = 0.83$ J·kg^{-1}·m^{-1}. It should be noticed that the units for W_{EXT} (as for all the forms of the cost of transport) correspond to m·s^{-2}, thus the maximum acceleration can be estimated as:

$$0.83\frac{m}{s^2} = \frac{2.5\ m/s}{3\ s} = \frac{9\ km/h}{3\ s} = \frac{\pm 4.5\ km/h}{3\ s} \qquad (6)$$

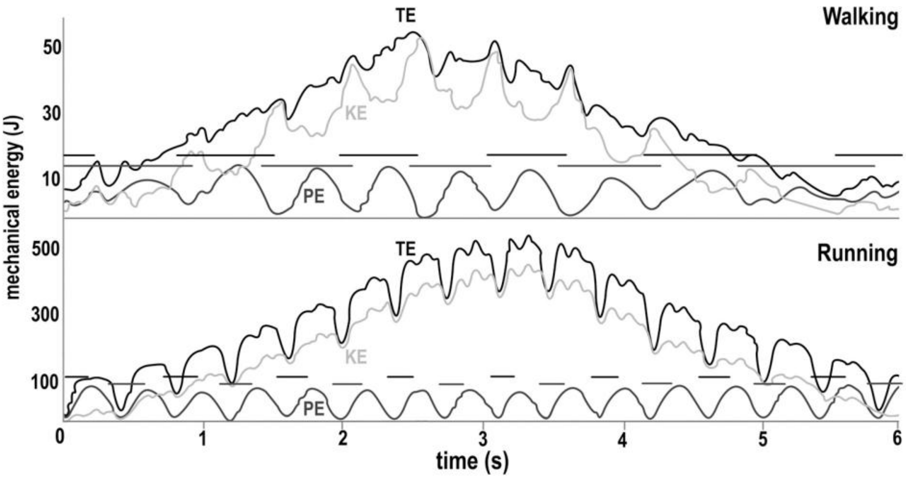

Fig. 4. Time course of the mechanical energies of the body center of mass during walking at 3.5 ± 2.0 km/h (Ref. 9), (*top*) and running at 11.0 ± 4.0 km/h (present data, *bottom*). Curves in ascending order: potential (PE), horizontal kinetic (KE), and total (TE) energy. Horizontal segments represent foot contact duration.

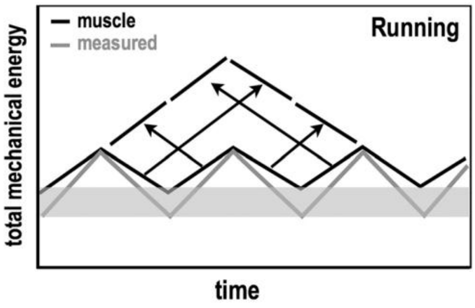

Fig. 5. Graphical explanation of the constancy of the metabolic cost in oscillating-speed running. The increasing portions of the total mechanical energy of each stride (gray curve: measured), after having removed the metabolically free releases of elastic energy from tendons (black curve: muscle), can be cumulated as to represent the accelerating phase of the speed-oscillation cycle. The same applies to the decelerative (decreasing total energy curve) parts, *mutatis mutandis*.

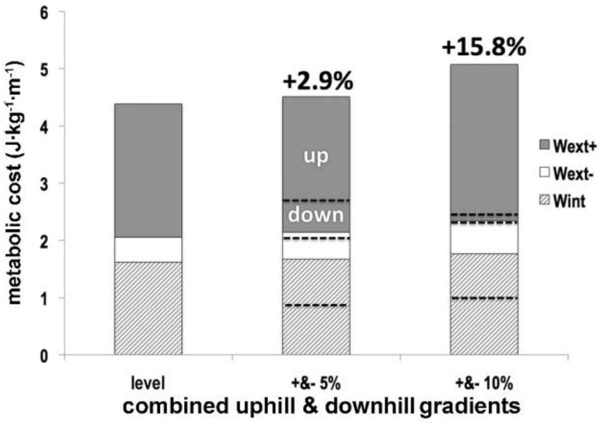

Fig. 7. Mechanical explanation of the present metabolic results according to the adapted equivalent gradient (Ref. 4 and present study), see text for details.

Thus, we can say that the elastic-free external work done at constant-speed (11 km/h) running is equivalent to a speed excursion (acceleration) of ± 4.5 km/h performed in 3 s, and because of this no extra metabolic consumption should be expected within this boundary. This prediction slightly exceeds the widest speed oscillation here investigated, which was limited to 11 ± 4 km/h as to *1*) avoid anaerobic contribution to energy expenditure and *2*) ensure that, at the lowest speed, running could still be performed.

Recently, a new predictive framework has been proposed (4) to infer the metabolic expenditure of sprint running by suggesting the dynamical similarity between level accelerative strides and constant-speed strides on a steep incline. By using a regression of metabolic running cost collected on a wide range of gradients (10), those authors developed an equation that estimates the metabolic cost of running in acceleration by introducing the concepts of equivalent slope (ES) and equivalent mass (EM).

For the purposes of the present study, also decelerations need to be included in the metabolic prediction, thus the proposed equation for the cost of sprint running (C_{sr}, $\mathrm{J \cdot kg^{-1} \cdot m^{-1}}$, Ref. 4),

$$C_{sr} = \left(155.4\, ES^5 - 30.4\, ES^4 - 43.4\, ES^3 + 46.3\, ES^2 + 19.5\, ES + 3.6\right)EM \qquad (7)$$

has been turned into the cost of speed-oscillation running (C_{os}, $\mathrm{J \cdot kg^{-1} \cdot m^{-1}}$)

$$C_{os} = \left(-30.4\, ES^4 + 46.3\, ES^2 + 3.6\right)EM \qquad (8)$$

where, according to the variables here introduced, the equivalent slope is changed into

$$ES = \tan\left(90 - \arctan\frac{g\delta t}{2\Delta v}\right) \qquad (9)$$

and the equivalent mass of the subject into

$$EM = \left[\left(\frac{2\Delta v}{g\delta t}\right)^2 + 1\right]^{0.5} \qquad (10)$$

The simple transformation adopted for the term in brackets in *Eq. 7* [$f(x)$], i.e.,

$$g(x) = \frac{f(x) + f(-x)}{2} \qquad (11)$$

calculates, for a given absolute speed change x, the metabolic cost, per each meter traveled, of running cycles of (half a meter in) acceleration and (half a meter in) deceleration. Because the mathematical form of $f(x)$ is a polynomial function of the gradient (8):

$$f(x) = \sum\nolimits_{i=0}^{\infty} a_i x^i \qquad (12)$$

it can be shown that, due to the above transformation, $g(x)$ (i.e., the term in brackets of *Eq. 8*) will retain just the even degree terms of the original polynomial included in *Eq. 7* (and Ref. 8), i.e.,

$$g(x) = \sum\nolimits_{i=0}^{\infty} a_{2i} x^{2i} \qquad (13)$$

Fig. 6 shows $f(x)\cdot EM$, namely the cost of ascending/accelerating, $f(-x)\cdot EM$, i.e., the cost of descending/decelerating, and the combination of the two, $g(x)\cdot EM$ (i.e., *Eq. 8*), with the abscissas representing both the gradient and the speed oscilla-

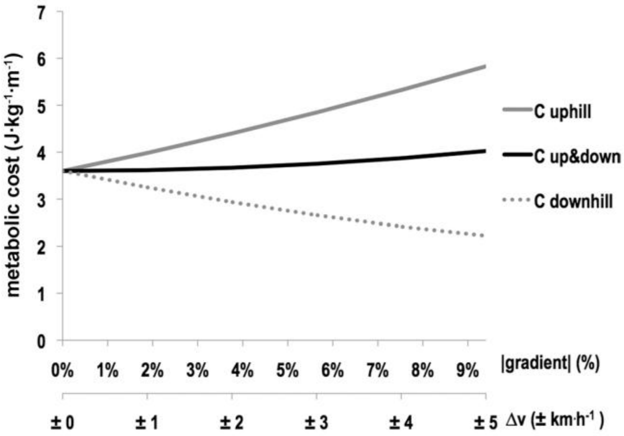

Fig. 6. These curves show the metabolic cost of uphill, downhill, and combined (0.5 m travelled uphill, 0.5 m downhill) as a function of gradient (Ref. 10) or of acceleration/deceleration cycles of 6-s duration (4) up to ±5.0 km/h, according to the theory of equivalent slope of sprint running (Ref. 4 and present study, modified as shown in the present *Eq. 8*).

tion. The equation for C_{os}, independent from the average running speed, predicts the cost of oscillating-speed running according to the equivalent slope theory of acceleration (4). Energy expenditure (E_{os}, $mlO_2 \cdot kg^{-1} \cdot min^{-1}$) for a given average speed (v, m/s) can be estimated as

$$E_{os} = 2.87\left(-30.4\,ES^4 + 46.3\,ES^2 + 3.6\right)EM\ v \qquad (14)$$

When these values are plotted together with experimental data (see Fig. 3) a very close match is found.

This encouraging comparison still does not explain, per se, the reason of the substantial lack of dependency of the metabolic cost on the excursion of speed oscillations. Actually, it has to be noticed that the computing framework proposed by di Prampero and collaborators (4) is only halfway driven by physics, the rest being based on experimental data (10). Those authors established a link between (level) running in acceleration and running on gradients (at constant speed). Thus, to understand the speed range independency of C_{os}, we need to refer to the mechanical determinants of the metabolic cost of gradient running.

A previous investigation (7), by measuring and analyzing the mechanical and metabolic features of gradient running (at constant speeds), explained the reasons for the cost decrease of downhill gradients and for the optimum gradient occurring at −10% of incline. After having removed from the negative and positive work the parts attributable to elastic energy storage and release, respectively, it was noted that those phenomena were the effects of *1*) a residual negative external work in uphill gradients (up to +15%) and of positive external work in downhill gradients (up to −15%), and *2*) the fivefold difference between the muscle efficiency for positive and negative work (see their Fig. 6). For speed-oscillating running, the metabolic equivalent of the positive and negative mechanical external work of matched gradients (−5% and +5%, −10% and +10%) has to be represented as column stacks, together with the one for the internal work (Fig. 7). Further subdivision of each component (horizontal dashed lines) shows the amount of the (metabolically converted) mechanical work measured during uphill and downhill running (shown as up and down, respectively). It can be observed that, despite the partitioning of positive external work (dark gray bar segments) into uphill (acceleration) and downhill (deceleration) parts of the cycle different at all gradients, the sum of the two is almost constant. This applies also to the negative external work (white bar segments), whereas, for internal work, we have both the constancy of the total amount and its partitioning. By looking at the total estimated metabolic cost, as obtained by converting all the forms of mechancal work (7) according to the different efficiencies, we obtain that a combination of −5% and +5% gradients implies a +2.9% change in the metabolic cost with respect to level running. The same calculation leads to +15.8% when a gradient combination of −10% and +10% is simulated. These two figures compare well with the increases found by adapting the predictions from di Prampero (4) to the present experimental protocol, for ES = ±5% (corresponding to Δv = ±2.6 km/h in 3 s) and ES = ±10% (corresponding to Δv = ±5.3 km/h in 3 s), which result as +3.3% and +13.3%, respectively.

The illustrated rationale again confirms the functionally independency of C_{os} within a given speed-change excursion of acceleration/deceleration cycles. When we replace, in Fig. 7, up with acceleration and down with deceleration, it is clearly apparent that the constancy of C_{os} is due, in addition to the different efficiencies of positive and negative work, to the residual deceleration during acceleration phases and the reverse, similarly to what happens in gradient running.

In conclusion, similarly to walking, the substantial constancy of the metabolic cost of running at speed oscillations up to a given span (±4 km/h or ± 1.1 m/s in 3-s ramps) seems to be explained by the inherent mechanical energy fluctuation normally occurring when moving at constant speed (see *Eq. 6* and dashed line in Fig. 3).

In other words, differently from wheeled vehicles, where the absence of energy fluctuations at constant speed makes any speed changes very expensive (hybrid cars were invented to mitigate this problem), legged-body dynamics (ground constraints) makes locomotion expensive even at constant speed, but this allows the use of the same fuel when (limited) speed oscillations are issued. Apart from the relevance of these findings in fundamental biomechanics and bioenergetics of locomotion, we expect that the proposed equations will be used to estimate the metabolic energy expenditure in a variety of field activities and sports, where moderate-speed excursions are present.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS

Author contributions: A.E.M. conception and design of research; A.E.M. interpreted results of experiments; A.E.M., P.G., E.S., and D.C. prepared figures; A.E.M. drafted manuscript; A.E.M., P.G., E.S., and D.C. edited and revised manuscript; A.E.M., P.G., E.S., and D.C. approved final version of manuscript; P.G., E.S., and D.C. performed experiments; P.G., E.S., and D.C. analyzed data.

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