Liverpool John Moores University

Research Institute for Sport and Exercise Sciences

Phase 2 - Final Report

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The Validation and Application of An Integrated Metabolic Cost Paradigm Using High Frequency GPS Technology In Soccer.

Confidential.

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Lay summary

This research project evaluated the integration of a Global Position System (GPS) with a novel metabolic logarithm to monitor and evaluate the physiological load of players. First, the validity of the indirect GPS metabolic power calculation equation was established and compared to directly determined metabolic power obtained via expired gas analysis during soccer specific movement patterns. Second, to examine the metabolic power of elite players a database was interrogated to model the metabolic requirements of elite player and different positional roles during match play. We find that current performance analysis techniques that utilise speed and distance grossly underestimate the workload players are subject to in match play and fail to adequately quantify the true physiological cost of match play activity relative to the new Metabolic Power paradigm implemented herein. The implications of the present finding to player management are such that workload may be underestimated in games by up to 30%. Where players may have several games per week or a block of games and international duty a reservoir of undetermined player fatigue may accrue that could precede alteration in match performance and increase predisposition to injury .

Executive Summary

This final report details the research activities carried out on the research project entitled 'The validation and application of an integrated metabolic cost paradigm using high frequency GPS technology in soccer.

The terms of reference for the project were:-

1. Determine the metabolic cost of Soccer Specific Activity.
2. Apply these metabolic cost models to match play situations.

The findings outlined in this report are based on several research studies and highlight a number of issues for consideration. The initial research work comprised several initial pilot phases presented in the interim report. The aim of phase one was examine the efficacy of the 10-Hz GPS data capture tool to be used in the assessment of metabolic power during validation of the new metabolic power equations. The second phase of was directed toward examining and re-determining the energy cost equations postulated by Minetti *et al.*, (2002) and modified by Osgnach *et al.*, (2010) so as to alter the energy constant and error terms to reflect the postulated higher energy cost for soccer activity on grass in elite soccer players. Findings indicate that the 10-HZ GPS provide a valid means's of assessing running speed and distance during short duration, low, moderate and higher intensity work intensities with and without change of direction. The 10-Hz GPS system was found to closely mirror the acceleration and deceleration profiles but a bias, which underestimated running speed and distance in the region of approx 2-4% was observed. Further to this initial work we also implemented the methodology of Di Prampero *et al.*, (2005) to determine the metabolic cost of soccer related running activity. This preliminary finding from this work indicated the 10-HZ GPS technology whilst slightly underestimating running velocity is capable of differentiating and resolving metabolic power during exercise of varying intensities where traditional linear and change of direction running tasks are applied. The underestimation is likely to be function of the underestimation inherent in measurement of running speed.

The second phase of research was directed toward establishing the energy cost of running on grass. In examining the previous equations it is apparent that coefficient of determination for energy cost, which was derived from treadmill running, did not reflect the postulated higher energy cost of soccer activity on grass in elite soccer players. In this phase of the research we directly measured the energy cost of constant velocity running on grass in 30 elite professional soccer players using directly measured oxygen uptake via a Cosmed $K4b^2$ portable breath by breath gas analyser and lactate measurement to assess non-aerobic metabolic cost. Results indicate that previous estimates of energy cost of 3.66 kJ·kg·min^{-1} are incorrect and a value of 4.66 kJ·kg·min^{-1} is more reflective of the actual energy cost. Subsequent to the determination of this new energy constant, a new metabolic power equation specific for elite footballers was developed incorporating this data. The energy cost constant facilitated the specific modelling of the energy cost of running on grass and running at different rates of acceleration and deceleration in elite soccer players (Osgnach *et al*., 2010). In the next phase of the research this new equation was Integrated into a 10-Hz GPS model and the energy cost determined during performance of a soccer specific exercise protocol (Figure 2) via integrated software in 20 elite professional soccer players compared to directly measured oxygen uptake via a Cosmed K4b^2 portable breath by breath gas analyser and lactate measurement to assess non-aerobic metabolic cost. The outcomes of this work indicate a small underestimation of metabolic cost via GPS (15. 20 ± 0.75 W·kg^{-1}) of approximately ~4% relative to directly determined parameters (15. 8 ± 1.5 W·kg^{-1}). The final research study took the newly validated Metabolic Power equation and applied it to our database of competitive match play kinematic data from video data capture from the 2011-12 and 2012-13 seasons (295 elite players) as well as GPS derived friendly match play (108 elite players). The principal finding indicate the average metabolic power exerted during match play is approximately 11.2 W·kg^{-1} (reflecting the physiological description of soccer as an aerobic activity with superimposed periods of high intensity activity). The implementation of the metabolic power, equivalent distance, and time spent over 20 W·kg^{-1} concepts indicate that the metabolic load applied to soccer players across all positions is grossly underestimated relative to previous estimates of work load using the traditional (current) speed and distance paradigms. Metabolic Power and associated performance metrics vary across playing positions with an obvious hierarchy of demand expressed; generally Central and wide midfield, followed by wide defenders and attackers had the highest metabolic loads applied with central defender presenting lowest metabolic load apparent across playing positions.

The outcomes of this research are important to UEFA in relation to the following soccer performance issues:

a. A new metabolic cost constant for running on UEFA standard grass pitch in elite soccer players has been quantified for the first time.
b. A metabolic cost paradigm (equation) with direct specificity to elite soccer players is now available and validated.
c. Application of this new metabolic cost paradigm to match play data derived from both video match analysis and integrated GPS technology has highlighted limitations in the use of

current speed and distance match analysis paradigms applied to objectively quantified soccer performance. These limitations are to the to the point that they fail to reflect the quantity and intensity of the metabolic load applied during match play by up to at least ~ 30%.

d. Furthermore, we have established the Metabolic Power requirements during competitive match play for different positional role thus providing for the first time a normative reference ranges for metabolic cost estimates. These estimates may be (are been) utilised to consider general/specific threshold of effort required for the regulation of training intensity, and importantly training load particularly where that training may be orchestrated and assessed via GPS monitoring.

e. These normative ranges having been generated on a large population of elite players may be particularly useful in assessing the efficacy of current training regimen i.e. the small sided game which is a mainstay of physical and technical preparations.

f. Finally, the synergies between the video data capture data, GPS and estimates of metabolic cost during match play opens up a number of possible applications for GPS tracking/monitoring of player readiness in elite and lower tier clubs.

Study 1, Phase 1: Determination of the Energy Cost of Running on Grass in Elite Professional Soccer Players

Soccer match play activity is characterised by repeated bouts of high-intensity running superimposed upon an aerobic background (Bangsbo *et al.,* 2006). Rapid acceleration and deceleration charaterise the movement patterns utilised during match play and training (Di Salvo *et al.,* 2010; Gregson *et al.,* 2010). Previous attempts to assess the metabolic cost imposed by intermittent games play in particular soccer have provided estimates of the metabolic load during match play activities calculated from energy cost paradigms derived from laboratory models of running (Osgnach *et al.,* 2010). In developing this metabolic approach the influence of playing surface on the metabolic power required during soccer has not been directly considered in the original metabolic equations (Minetti *et al.,* 2002). The equation applied by Osgnach *et al.,* (2010) was initially derived from the work of Minetti *et al.,* (2002) which itself was established from treadmill running, however the energy cost of running on grass is assumed to be ~29% higher than that required on a treadmill with a coefficient of multiplication term of 1.29 (KT=1.29) (Pinnington and Dawson, 2001). The incorporation of this into previous work by Osgnach *et al.,* (2010) to account for the differences in energy cost presents a critical issue that may impact the accurate determination of the energy cost of football specific activities. This issue is predicated upon the coefficient of multiplication term developed by Pinnington and Dawson, (2001) been evolved from recreational runners who may not present a suitable kinematic model of running economy that is representative of elite soccer players due to differences in muscle fiber types, fiber recruitment patterns and concomitant metabolic adaptations in energy systems pathways. The coefficient of multiplication (KT = 1.29) may not provide a valid representation of the metabolic constant and remedial error terms required for a representative 'metabolic cost' of running on grass in soccer players. The previous work by Osgnach *et al.,* (2010) whilst innovative failed to undertake the necessary validation of energy cost imposed by this surface change and crucially failed to consider issues around population specificity which may impact upon estimation of the metabolic power required to perform soccer specific movement patterns. To this end the present investigation examined the energy cost of running on grass (EC_r) in elite soccer players, via the incorporation of direct measures of oxygen cost taken on UEFA standard grass playing surfaces.

Objectives:

1. Determine the energy cost (EC_r) of running on a grass pitch conforming to UEFA standards in elite soccer players to determine a new energy constant for this population.

2. Determine the new energy cost logarithm factoring in the new ECr of running on grass determine from objective 1.

METHODS

Participants

Thirty elite level national and international soccer player were recruited; their mean age, height and body mass were 24 ± 3 years, 74.6 ± 6.2 kg and VO_2 peak ~55.2 ± 3.7 $mL·kg^{-1}· min^{-1}$ respectively. Liverpool John Moore's University Research Ethics Committee approved the studies.

Experimental design and protocol for determining the energy cost of elite soccer players running at a constant velocity on grass.

Participants initially underwent assessment of resting oxygen uptake followed by incremental treadmill run to exhaustion to assess maximal oxygen uptake. Assessment of expired gas fractions and ventilation volume was facilitated by assessment with a portable breath-by-breath Cosmed $K4b^2$ gas analyser (Cosmed, Rome, Italy). On a second occasion to evaluate the energy cost of constant-speed running each participant undertook a 'constant velocity' run on a UEFA standard soccer pitch.

All participants were required to run for 6 minutes at 10.29 $km·h^{-1}$ on a UEFA standard grass soccer field. The path of each run was marked with cones every 20 meters with each participant regulating running speed by following a sound signal emitted every 7 seconds so that each 20 m cone was passed as the signal was emitted in order to maintain constant speed. Steady state oxygen uptake was defined as the mean of the last three minutes of the constant speed run.

Calculation of Energy Cost.

The calculation of the ratio between the energy expenditure and the nominal speed:

$$ECr = VO_2/v$$

where VO_2 is the net value (measured minus resting oxygen consumption) assuming an energy equivalent of 20.9 KJ·L O_2 (corresponding to a non-protein respiratory exchange ratio of 0.96), and v is the sub-maximal speed below the anaerobic threshold (assuming that during steady-state exercise performed below the anaerobic threshold, all of the energy turnover is attributed to aerobic metabolism) . One MET was set by convention to 3.5 $mL·kg^{-1}·min^{-1}$. The EC_r above resting; total energy was then divided by the subject's body weight and distance covered in the concerned time, to express EC_r as $J·kg^{-1}·m^{-1}$.

RESULTS

Table 1. Constant velocity energy cost for running on UEFA standard soccer Pitch at 10.29 $km·h^{-1}$ in 30 elite soccer players. Data are Mean ± SD.

Variables:	
VO_2 max ($mL·kg^{-1}·min^{-1}$)	**55.2 ±3.7**
Basal ($mL·min^{-1}$)	**261 ± 22**
VO_2 6 minutes of exercise ($L·min^{-1}$)	**17.2 ± 2.1**
Net VO_2 6 minutes of exercise ($L·min^{-1}$)	**15.6 ± 2.0**
VO_2 Steady State ($L·min^{-1}$)	**2.8 ± 0.38**
ECr grass ($J·kg^{-1}·m^{-1}$)	**4.66 ± 0.43**

DISCUSSION

The main finding of this phase was that in elite professional soccer players, the EC_r of constant velocity running on a UEFA standard natural grass football surface was 4.66 $J·kg^{-1}·m^{-1}$. Sassi *et al.,* (2011) report in a group of amateur soccer players a value of 4.2 $J·kg^{-1}·m^{-1}$, which is lower than present findings. Similarly, Pinnington and Dawson, (2001) and Rodio *et al.,* (2004) report values of 4.56 $J·kg^{-1}·m^{-1}$ and 5.7 $J·kg^{-1}·m^{-1}$ for running on natural grass in recreational runners and sedentary males. Assessment of the EC_r of running on grass has thus provided diverse estimates of EC_r which seem to vary as a function of the shock absorption characteristics and compliance of the surface as well as the population assessed. Our data is clearly contrary to the suggestions of Sassi *et al.,* (2011) that EC_r should not exceed 4.5 $J·kg^{-1}·m^{-1}$, these differences may reside with the elite nature of the current population, the application of a more compliant surface with different shock absorption properties, in addition to the wearing of football boots for test performance. The confluence of such issues may alter running kinematics such that the EC_r requirements of constant speed running are elevated. The central importance of this finding is the establishment of an empirical model of energy cost for movement on grass in elite soccer players; a model that previously had not been quantified. The determination of this new energy constant is central to the determination of the 'Metabolic Power'. Under this 'Metabolic Power' concept in soccer as advanced by Osgnach *et al.,* (2010) their data is modelled upon estimates extrapolated from treadmill running and modified by a multiplication constant to reflect energy cost of moving across a grass surface; present data enhances their model by providing both a surface specific and population specific energy constant. In the second phase of this study this energy constant will be utilized to derive a new metabolic power equation that's reflects these new findings.

Study 1, Phase 2: Determination of a new metabolic power in soccer equation and its validation relative to direct measures of energy expenditure during soccer specific movement patterns.

Performance analysis in soccer derived from either video or GPS based technology has relied on quantification of distance covered or time spent undertaking running tasks of differing intensities. It has however been argued that such an approach fails to fully appreciate the energy cost of match play such arguments been predicated upon the failure to recognise the critical role repeated acceleration and deceleration during intermittent activity places on the metabolic load each player is subject to (Osgnach *et al*., 2010). Recently the concept of Metabolic Power has come to the attention in relation to more accurately reflecting the actual metabolic load applied during soccer specific activity (Osgnach *et al*., 2010). In their treatise Osgnach *et al*., (2010) adopt the model of Di Prampero *et al*., (2005) and determine the energy cost of acceleration and deceleration, during sprinting activities. Briefly this model is based upon the notion that accelerated running on flat terrain, is mechanically equivalent to running uphill at constant speed, up what is termed an "equivalent slope" (ES) the angle of this slope determined by the forward acceleration. Given that the energy cost of running uphill has been previously determined by Minetti *et al.,* (2002) over a range of slopes, values can then be utilized to obtain the energy cost of acceleration/deceleration during running from the relationship between the energy cost of constant-speed running and slope of the terrain. (Di Prampero *et al*., 2005; Minetti *et al.,* 2002; Osgnach *et al.,* 2010). In adopting the conceptual model of Minetti *et al*., (2002) several limitations as relates to assessment of soccer specific activity are apparent. First, the energy constant derived from the treadmill running i.e. 3.6 kJ as demonstrated in phase one of this document is incorrect and underestimates the energy cost of running on grass in an elite soccer population. Second, in soccer match play rapid acceleration and deceleration are key features of play. The equation presented by Minetti *et al.,* (2002) delimits the calculation of the energy cost of acceleration and deceleration to approximately (+ 4.5 $m{\cdot}s^{-2}$ and - 4.5 $m{\cdot}s^{-2}$) respectively thus not facilitating the accurate calculation of energy cost were such speeds are exceeded; particularly for deceleration. Presently, anomalous data is derived when a player decelerates at speeds of greater than 4.5 $m{\cdot}s^{-2}$ the equation as configured suggests the energy cost of decelerating rapidly is less than that observed at slower rates of deceleration. Osgnach *et al*., (2010) and Savoia *et al*., (2013; unpublished data) suggest greater rates of deceleration (-4 $m{\cdot}s^{-1}$ to -6 $m{\cdot}s^{-1}$) occur in the match play; allowing these incongruities to remain in the calculations may impact upon metabolic cost estimations. It is thus important to address these anomalies in the energy cost constant and in acceleration and deceleration energy cost profile.

Objectives:

2. Derive a new energy cost logarithm factoring in the new ECr of running on grass determine from objective 1 for elite players.
3. Remove anomalies' relating to rapid deceleration present in the original deceleration phase of the equation.
4. Validate this new metabolic power equation relative to directly determined energy expenditure during soccer specific movement patterns in elite players

Objective 2 and 3: Derivation of New Energy Cost Equation.

In order to address these issues it was necessary to modify the equation of Minetti *et al*., (2002) upon which the work of Osgnach *et al*., (2010) was based. To facilitate the modification of the equation it was initially required to alter the previous constant term for running initially described by Minetti *et al*., (2002) [(3.6 ($J{\cdot}kg^{-1}{\cdot}m^{-1}$)] to one reflecting the energy cost to running on UEFA standard natural grass pitch in elite players [(4.66 ($J{\cdot}kg^{-1}{\cdot}m^{-1}$)]. In doing so, the addition of a new constant term 4.66 [($J{\cdot}kg^{-1}{\cdot}m^{-1}$)] modifies and disrupts the essential mathematical slope and shape of the Minetti *et al*.,(2002) model ranging from -45% to 45% and impairs the calculation of metabolic cost. Therefore, to maintain the integrity of the equation's in this range (-45% to 45%) whilst correcting for the underestimation of energy cost that it is created during decelerations (gradients) greater than -45% modification of the slope (%gradient)/energy cost data with different models was required (Figure 1). Following the mathematical model of di Prampero *et al.,* (2005) it is apparent that the fitting of the data with a 4^{th} order polynomial (Figure 1) meets the requirements of the equation i.e. the energy cost constant term is held at 4.66 $J{\cdot}kg^{-1}{\cdot}m^{-1}$ and the error term is minimized (0.11 $J{\cdot}kg^{-1}{\cdot}m^{-1}$) more effectively than either a cubic or parabolic model. Decreasing the order of the polynomial fit for the equation to both a 2^{nd} and 3^{rd} order (2°-3° degree) translates the trend line, shifts it upwards on the y axis, in effect overestimating the directly determined constant term from 4.66 to 4.79 $J{\cdot}kg^{-1}{\cdot}m^{-1}$. The new 'Metabolic Power equation' was thus raised to the fourth degree polynomial, in doing so it:

a. removes the negative inflection point associated with deceleration activity over a -45% gradient apparent in then original Minetti *et al.,* (2002) model.

b. the energy cost of the constant velocity running remains comparable to that directly measured in the 30 elite footballers players on a UEFA standard natural grass pitch (Artemio Franchi stadium, Florence, Italy).

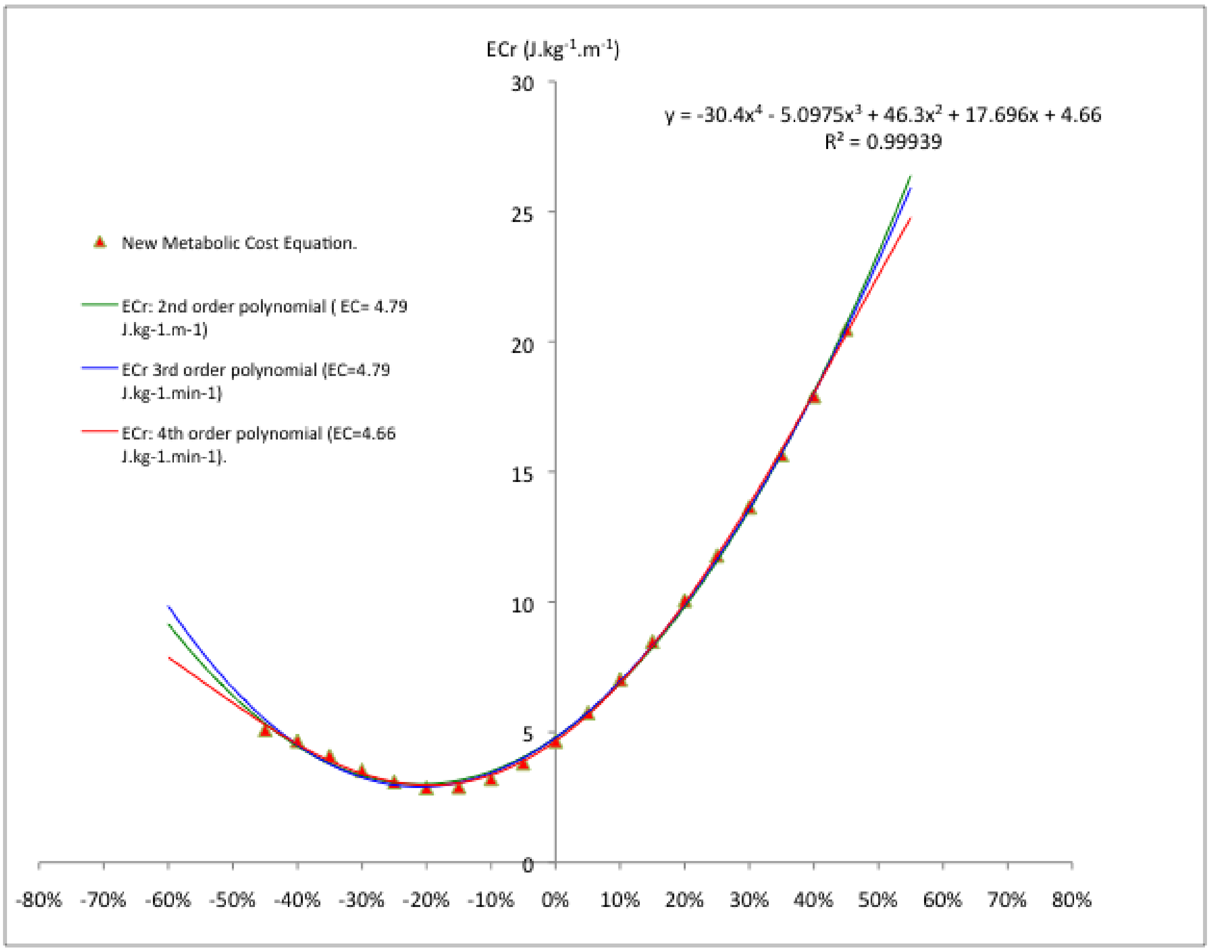

Figure 1 . New metabolic cost paradigm (4th order polynomial fit) relating the energy cost (ECr) of running over grass in elite footballers as a function of the gradient with initial ECr constant at 0% equivalent to 4.66 J·kg^{-1}·min$^{-1.}$ Where y = Energy Cost ; X = Gradient (%):-

$$y = 30.4x^4 - 5.0975x^3 + 46.3x^2 + 17.696x + 4.66 \text{ [new metabolic cost paradigm]}$$

Objective 4: Validation of the 'new metabolic power equation' relative to directly determined energy cost in elite soccer players on UEFA Standard Natural Grass Pitch.

This phase of the report compares the directly determined energy cost required to perform soccer specific movements patterns of differing intensities and complexity relative to the estimates of metabolic power derived from GPS models of energy cost (Minetti *et al*., 2002; Di Prampero *et al*., 2005). Oxygen uptake and derived energy cost [EC_r]) were be determined from a portable breath by breath Cosmed K4b^2 gas analyser to facilitate direct comparison with metabolic power calculated from the EC_r of acceleration and deceleration using a 10 Hz global positioning system (GPS) device (Di Prampero *et al*., 2005; Osgnach *et al*., 2010). In adopting this approach we will validate during an intermittent exercise (soccer) scenario the accuracy of the new metabolic power equation presented in objective 2 and 3 and subsequently integrated into the 10Hz-GPS-interpolation software.

METHODS

Participants

Twenty elite level soccer players from Serie A were recruited to participate in this phase of the study; their mean age, height and body mass were 25 ± 3.2 years, 1.78 ± 0.5 m and 74.5± 6.3kg. Liverpool John Moore's University Research Ethics Committee approved the studies.

Experimental Design.

Players undertook a soccer specific intermittent exercise protocol on several occasions to familiarise and subsequently facilitate physiological data collection. During each trial participant's were fitted with a 10 Hz GPS unit (BT-Q1000eX 10 Hz, Qstarz, Taipei, Taiwan), and a portable gas analyser (COSMED K4b^2 – Rome, Italy), to assess the oxygen uptake directly. At the start and end of each test, blood lactate was collected via Lactate Pro ™ LT-1710 (ARKRAY, Inc – Kyoto, Japan) to assess blood lactate concentrations.

Soccer Specific Movement Circuit.

All 20 elite participants were required to complete a combination of different running conditions incorporated into a soccer specific circuit which were set out on a UEFA standard grass pitch (Figure 2):

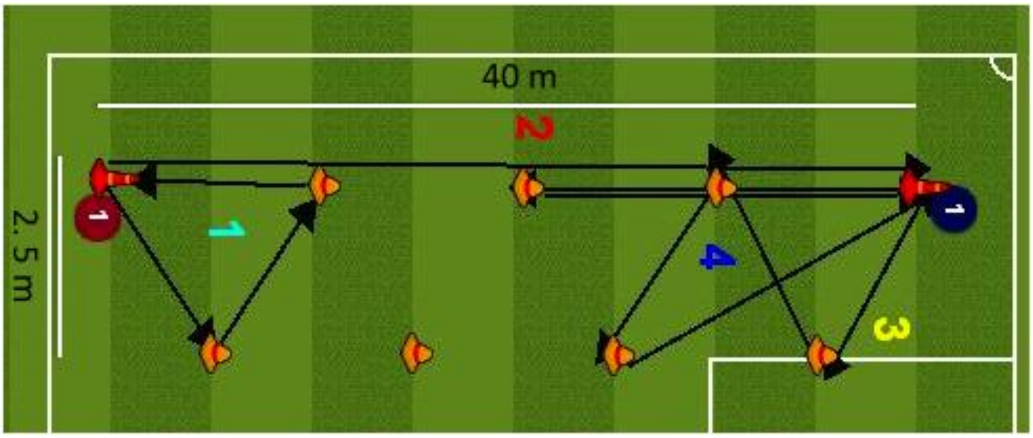

Figure 2. Displacement, direction and angle of change during non-linear soccer specific circuit. Numeral relate to different activity tasks performed sequentially.

The soccer specific protocol used in this validation study takes into consideration central features of soccer related patterns of movement; replicating its intermittent nature by introducing various actions, from maximal to the sub-maximal sprints, shuttles with changes of direction of varying angles. It includes slaloms around cones; including short passive pauses and longer recovery from the maximal sprints. The protocol was divided into 4 phases and repeated for 8 laps to give a total duration of activity of approximately eight minutes (Table 2). All activities commenced from a stationary start position and required participants to come to a complete stop at the end of the marked phase. A trundle wheel was used to measure the exact length of the soccer specific circuit and each participant was familiarised with a sound dictation emitted at set times to regulate running speed. During the circuit an iPod system (iPod nano, Apple, Cupertino, California) was used to emit the pacing bleep every 5 seconds. As a spatial reference multiple markers were positioned at fixed points depending on the running speed required.

Table 2 . Soccer specific protocol activities, distances, duration and recovery profiles.

	Activity	Distance (m)	Intensity($km{\cdot}h^{-1}$) *	Duration (s)	Recovery (s).
1	*Sprint: Triangle Change of Direction > 60^0*	21.18	Max (>26)	~ 4-6"	~ 9-11"
2	Linear Striding	40	14.4 (23)	~10	~ 5"
3	Slalom Run	28.22	10.1 (20)	~ 10	~ 5"
4	Shuttle run	20+20 (40)	14.4 (24)	~ 10	~ 5"

* Exercise intensity expressed as metabolic power is defined in brackets

GPS and Metabolic Power Calculation.

Participants were tracked over the linear-sprints and the soccer specific circuit using a GPS device (BT-Q1000eX 10 Hz, Qstarz, Taipei, Taiwan). Instantaneous velocity measurements were obtained for each trial. The GPS unit was placed on the upper back in a custom-made vest on all participants. The mean ± SD number of satellites during data collection for both the linear (acceleration and deceleration) runs and shuttle run where determined. GPS velocity data (10 Hz) was sampled and synchronized at the first movement recorded above 0 $m{\cdot}s^{-1}$ to account for processing phase delays within the breath by breath output on the Cosmed $K4b^2$. Data were downloaded and analysed using (GPS-Power LagalaColli v9.034 SPINItalia, Roma, Italy;) to establish the time, speed, and distance metabolic power was determined through the methodology of energy cost modelling as previously described and modified according to objective 1 of this study using the new metabolic cost equation (Minetti *et al.,* 2002; Di Prampero *et al.,* 2005)

Direct Assessment of Energy Cost.

The energy costs of soccer specific exercise (EC_r) was determined 24 hrs after the last training bout and ~2-4 h after the last meal; it was evaluated during soccer specific protocol performance. The energy cost of the soccer specific activity protocol was calculated from the ratio of the total metabolic energy expenditure utilised above resting (E in joules) to the distance covered (d in meters). Energy cost above resting was calculated from the sum of the aerobic (Aer), anaerobic alactic (AnAl), and anaerobic lactic (AnLa) energy expenditure. Briefly, energy expenditure derived from aerobic sources was obtained from the integral from the onset of exercise to the end of the soccer specific protocol; the net VO_2 values (averaged over 60 s), as obtained directly during the test minus the pre-exercise resting VO_2 values (~ 3.5 $mL \cdot kg^{-1} \cdot min^{-1}$). Furthermore, contribution from anaerobic alactic (AnAl) energy expenditure was determined from assessment of the VO_2 uptake determined during the first 6 minutes of recovery upon completion of the protocol (fast replenishment). The net VO_2 values obtained from the 4th to 6th minute of recovery were used to estimate the fast alactic O_2 debt, (AnAl) estimates. Finally, the lactic contribution to the overall energy expenditure (AnLa) was estimated after exercise from the net blood lactate [BLa] accumulation above resting, on the basis of an energy equivalent of [BLa] accumulation in blood equating to ~ 3 $mL\ O_2 \cdot kg^{-1} \cdot mM$ (Di Prampero and Ferretti 1999). The overall energy expenditure ECr (Aer + AnAl + AnLa) for the duration of the test (8 minutes) was determined. This value of VO_2 was multiplied by 20.9 based on the assumption that 1-mL O_2 yields 20.9 J, divided by the mass of the subject (kg) and distance covered to yield an estimate of soccer specific protocol EC_r in $J \cdot kg^{-1} \cdot m^{-1}$. Data was converted to $Watt \cdot kg^{-1}$ using the formula:

$$\text{Watt} \cdot \text{kg}^{-1} = EC_r\ (\text{J} \cdot \text{kg}^{-1} \cdot \text{m}^{-1}) * V$$

Where EC*r* is energy cost and v is running velocity. Directly determined estimates where derived and compared with the ECr $Watt \cdot kg^{-1}$ calculated from the new metabolic equation.

RESULTS

Table 3. Physiological and metabolic responses to soccer specific protocol performance in 20 elite players that took the sub-maximal test with the portable Cosmed K4b gas analysis. Data are mean ± SD.

Physiological Measures (n = 20)	Mean ± SD
Gross VO_2 during exercise (mL•min)	25146 ± 3981
VO_2•kgm•in during exercise (net)	39.1 ± 4.1
Net VO_2•kg total during exercise (mL•kg)	304 ± 39
Anaerobic debt (mL•kg)	41.7 ± 5.5
Blood Lactate [BLa](mM)	7.46 ± 1.79
VO_2•kg•min total exercise (debt included)	45.1 ± 4.3
VO_2•kg steady state	41.0 ± 4.7

The difference between the average directly measured metabolic power (Cosmed K4b^2) (15.8 ± 1.5 W·kg^{-1}) and that estimated via the new metabolic power equation (GPS) (15. 20 ± 0.75 W·kg^{-1}) in 20 elite players was ~ 3.7% lower (P>0.05). Individual variation across the players under/over estimates metabolic power from ~ -1.5 W·kg^{-1} to +3.38 W·kg^{-1}. Such variation may exist as a function of difference in running economy, maximal aerobic fitness and efficiency of movement.

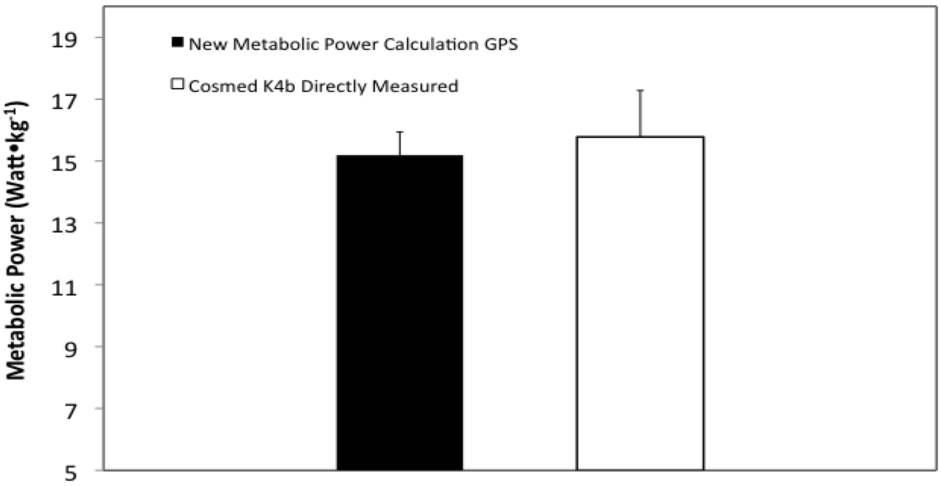

Figure 3. Metabolic power (W·kg^{-1}) derived from direct measurement (Cosmed K4b^2) and indirect assessment using the new metabolic power equation (GPS).

The principal outcomes of this section of the report where:

1. A new metabolic cost equation was determined which introduced a new constant term 4.66 J·kg-^{1}.min-1 and regression prediction equation for the assessment of the EC_r of running on grass in elite soccer players.
2. Estimates of metabolic power using this new equation were derived and compared to metabolic cost measured directly using portable indirect calorimetry (Cosmed K4b^2) during soccer specific movement patterns.
3. The new equation on average under estimates in elite players the metabolic cost by approximately 4%.

Study 2: Metabolic Power in Soccer.

In this section of the report we build upon the initial work outlined in study 1, phases 1 and 2 to apply the 'new metabolic power equation' to a selection of competitive matches from Serie A seasons 2011-12; 2012-13. The matches utilized in our database and referred to in these analyses included 295 professional players with a supplementary analysis of kinematic data from 108 elite players drawn from a number of pre-season Serie A and English Premiership matches (that were analyzed using GPS technology). In the video match analysis data, players were differentiated by role, as suggested by Gregson *et al*. (2010): central defender (n= 79), wide defender (n= 18), central midfielder (n= 86), wide midfielder (n= 45) and attacker (67). In the GPS data set due to the smaller numbers, role differentiation was not undertaken. Data collection in all the competitive games presented occurred via high frequency video cameras sampling at 25-Hz (Amisco, Italy) and spatial resolution analyses to delineate change in position and rate of change (velocity and acceleration) via Cartesian coordinates (K-Sport, Italy).

Energy cost and metabolic power

In order to estimate the energy cost (ECr) and metabolic power (MP) at any given moment within the match play from both the GPS and the video match analysis approach, the equation proposed by Di Prampero *et al*., (2005) based on previous studies of Minetti *et al*., (2002) and then modified within the current report (Objective 1) to evaluate soccer players running on grass was incorporated (EQ. 1).

$$EC\ (y) = 30.4x^4 - 5.0975x^3 + 46.3x^2 + 17.696x + 4.66 \quad [EQ.\ 1]$$

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/af); g = Earth's acceleration of gravity; af = forward acceleration; *EM* is the equivalent body mass: EM = (af2/g2 + 1) 0.5. Metabolic power in $W{\cdot}kg^{-1}$ was calculated by multiplying EC (in $J{\cdot}kg^{-1}{\cdot}m^{-1}$) by running speed (*v;* in $m{\cdot}s^{-1}$) at any given moment (i.e., every 0.1s via both GPS and Video Match Analysis Approach (smoothed from 25Hz to 10 Hz to reflect GPS sampling rate).

Reporting of Metabolic Power.

Characterization of Metabolic power into five power categories: low power (LP; from 0 to 10 $W{\cdot}kg^{-1}$), intermediate power (IP; from 10 to 20 $W{\cdot}kg^{-1}$), high power (HP; from 20 to 35 $W{\cdot}kg^{-1}$), elevated power (EP; from 35 to 55 $W{\cdot}kg^{-1}$), and max power (MP; >55 $W{\cdot}kg^{-1}$) was established. This taxonomy follows the recommendations of Osgnach *et al.,* (2010) and loosely mirrors an activity continuum ranging from standing/walking to maximal sprint activity respectively.

Derived Metabolic Power Parameters.

In addition to the parameters set out above for each player the following parameters were derived:

Average metabolic power

Average metabolic power over the period of match play expressed in $W \cdot kg^{-1}$;

Anaerobic index (AI).

Represents the ratio between the energy expenditure above the metabolic power threshold (TP) selected by the investigator and the total energy expenditure over the whole match: where AI is the anaerobic index, W_{TP} is the energy expenditure over the selected TP ($J \cdot kg^{-1}$), and W is the total energy expenditure ($J \cdot kg^{-1}$). In this study we adopted the criteria of Osgnach *et al.*, (2010) in defining the threshold, TP was considered equal to 20 $W \cdot kg^{-1}$,

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

High Intensity Workload Thresholds (16 $km \cdot h^{-1}$ and 20 $W \cdot kg^{-1}$)**.**

The time spent over 16 $km \cdot h^{-1}$ (TSO 16) which is defined in match analysis approach as High intensity activity (old concept of high-intensity) and Time Spent over 20 $W \cdot kg^{-1}$ (new match analysis approach), Osgnach *et al.,* (2010);

Total Energy Expenditure.

Is expressed as the total energy expenditure over the course of the 90 minutes expressed in kilojoules ($kJ.kg^{-1}$).

Equivalent distance (ED).

One of the most important concepts in performance analysis approach is the equivalent distance (ED). This represents the distance that a player would have run at constant speed using the total energy expended over the 90 minutes of match play where E is the total energy expenditure ($J \cdot kg^{-1}$), and EC is the energy cost of running at constant pace on grass, which is 4.66 $J \cdot kg^{-1} \cdot m^{-1}$ following the value we found in 30 elite soccer players. Equivalent distance index (EDI) represents the ratio between ED (equivalent distance) and TD (total distance) expressed in meters.

Acceleration and Deceleration (%):

In assessing the acceleration and deceleration occurring during match play activity we modified the categorisation reported by Osgnach *et al*., (2010) and reduced it from eight to two categories reflecting:

High acceleration (HI Acc), which is the entire time in %, spent accelerating over 50% of the variation of the maximum possible instantaneous speed;

The high deceleration (HI dec), the percentage time over -2 $m \cdot s^{-2}$ compared to the time spent stopping;

Change of Directions (>30°·min).

Changes of direction are defined as changes in the vector analysis greater than 30° that occur in a minute.

Statistical Analysis.

Present data sets are presented as Mean ± SD.

RESULTS AND DISCUSSION

Soccer match play activity is characterised by repeated bouts of high-intensity running superimposed upon an aerobic background (Bangsbo *et al.,* 2006). Embedded within this ‘physiological’ description of soccer is a requirement for constant accelerations and deceleration. However, reliance on work-rate data emphasising distance covered and the corresponding velocity of movement whilst recognised as a valuable metric may not to adequately represent the ‘true’ metabolic requirements imposed during soccer match play. Principally this view is founded on the notion that these parameters fail to acknowledge the energy cost of accelerations and decelerations and thus the actual energy demands of the match play (Di Prampero *et al*., 2005; Osgnach *et al*., 2010). In the present study, we have taken the updated equations and assumptions (i.e. energy cost of elite soccer players running on grass) upon which the ‘metabolic power approach’ are formulated and applied them in order to assess the metabolic power during soccer match play. Present data indicates the average energy expenditure during elite competitive match play was estimated to be ~ 62.7 ± 8.6 $kJ \cdot kg^{-1}$ equating to a metabolic power of 11.2 ± 1.2 $W \cdot kg^{-1}$ which is slightly higher than the ~ 61.1 ± 6.5 $kJ \cdot kg^{-1}$ (11.2 ± 1.2 $W \cdot kg^{-1)}$ estimates of metabolic power reported by Osgnach *et al*., (2010) (Table 4a). These metabolic estimates are also sensitive to inter-positional variations; such variations are a common finding in studies examining activity patterns using more traditional speed and distance paradigms (Di Salvo *et al*., 2009; Randers *et al*., 2010; Bradley *et al*., 2010 Gregson *et al*., 2010). Consistent with the ability to detect difference in positional roles current data would also seem sensitive to changes in the metabolic power metrics from the first to the second half of match play (Table 4b-c). In relation to the average metabolic power ($W \cdot kg^{-1}$) required over 90 minutes of match play, a positional hierarchy is apparent relative to the central midfielder role; where the central midfielder is 5% > wide midfielder 8% > wide defender 8%> attacker 16% > central defender (Table 4a). Interestingly, the central midfielder role expresses higher metabolic power outputs relative to all other positions across both first and second halves. Indeed average metabolic power in central midfielders in the second half is higher than that seen in the other position during the first half. However, all playing roles (Table 4a) express impaired average metabolic power (-5%), impaired time spent over 16 $km \cdot h^{-1}$(-5%); time spent over 20 $W \cdot kg^{-1}$ (-7%) distance covered at each metabolic power output (Table 7a-c) and time in each metabolic power zone as players progress from first to second halves (Table 4b-c). It is also evident how the time and the distance spent in the power zones between 0-10 $W \cdot kg^{-1}$ (walking, jogging) increase in the second relative to the first half, which may be indicative of the fatigue accumulated during a game (Reilly 2009).

Table 4a. Performance metrics during in season elite soccer competitive match play over 90 minutes for all roles and differentiated by playing position. Data are presented as Mean ±SD.

Activities all matches	All roles (n = 295)	Central Defender (n = 79)	Wide Defender (n = 18)	Central Midfielder (n = 86)	Wide Midfielder (n = 45)	Attacker (n = 67)
Metabolic Power ($W.kg^{-1}$).	11.2 ± 1.2	10.2 ± 0.8	11.2 ± 0.9	12.2 ± 1	11.6 ± 0.9	11.1 ± 1.3
V ($m.min^{-1}$)	115 ± 16	107 ± 7	116 ± 9	126 ± 9	112 ± 31	116 ± 12
Time spent over 16 $km.h^{-1}$ (%)	6.1 ± 1.8	4.2 ± 0.9	5.9 ± 1.4	7.6 ± 1.7	7.1 ± 1.4	6.2 ± 1.6
Time spent over 20 $W.kg^{-1}$ (%)	13.7 ± 2.8	11 ± 1.6	13.7 ± 2	16.2 ± 2.5	14.7 ± 2.2	13.3 ± 2.6
AI %	41.7 ± 4.7	36.7 ± 2.9	42.4 ± 3.1	45.5 ± 4.3	43.5 ± 3.4	41.6 ± 4.1
CoD > 30°. Min^{-1}	17.7 ± 2	18.5 ± 1	17.8 ± 1	18.1 ± 4	17.1 ± 1	16.8 ± 2
HI Acc (%)	4.6 ± 2	4 ± 2.3	4.2 ± 1.1	5 ± 1.6	5.9 ± 3.1	4.5 ± 1.9
HI Dec (%)	12.9 ± 1.9	11.7 ± 1.6	13.3 ± 1.2	14.1 ± 1.8	13.4 ± 1.9	12.5 ± 2
Kilojoule (kJ)	62.75 ± 8.66	56.20 ± 9.57	63.38 ± 5.27	67.65 ± 9.14	65.45 ± 4.89	62.24 ± 6.77

Table 4b. Performance metrics during in season elite competitive soccer match play over the first half (45 minutes) for all roles and differentiated by playing position. Data are presented as Mean ±SD.

Activities all matches (1st Half)	All roles (n = 295)	Central Defender (n = 79)	Wide Defender (n = 18)	Central Midfielder (n = 86)	Wide Midfielder (n = 45)	Attacker (n = 67)
Metabolic Power ($W.kg^{-1}$).	11.5 ± 1.3	10.3 ± 0.8	11.6 ± 0.9	12.5 ± 1.2	11.6 ± 1.2	11.3 ± 1.4
V ($m.min^{-1}$)	116 ± 21	108 ± 8	112 ± 27	125 ± 24	121 ± 10	112 ± 27
Time spent over 16 $km.h^{-1}$(%)	6.1 ± 2	4.1 ± 1	6.2 ± 1.5	7.7 ± 2.1	7.1 ± 1.6	6.2 ± 1.9
Time spent over 20 $W.kg^{-1}$(%)	14.2 ± 3.2	11.2 ± 1.8	14.4 ± 2	16.8 ± 3	14.8 ± 2.9	13.8 ± 3.1
AI %	41.9 ± 5.3	36.5 ± 3.3	43.1 ± 3.4	45.9 ± 5	43.8 ± 4	41.8 ± 5.1
CoD > 30°. Min^{-1}	17.5 ± 2	18.7 ± 2	17.8 ± 2	17.6 ± 1	16.7 ± 2	16.6 ± 2
HI Acc (%)	4.6 ± 2.2	4 ± 2.3	4.3 ± 1.1	5.1 ± 1.8	6.2 ± 3.5	4.5 ± 1.9
HI Dec (%)	12.9 ± 2.4	11.7 ± 1.9	13.6 ± 2.4	14.2 ± 2.3	13.3 ± 2.6	12.5 ± 2.4

Table 4c. Performance metrics during in-season elite competitive soccer match play over the second half (45 minutes) for all roles and differentiated by playing position. Data are presented as Mean ±SD.

Activities all matches (2nd Half)	All roles (n = 295)	Central Defender (n = 79)	Wide Defender (n = 18)	Central Midfielder (n = 86)	Wide Midfielder (n = 45)	Attacker (n = 67)
Metabolic Power ($W.kg^{-1}$).	11 ± 1.3	10 ± 0.8	10.9 ± 1.2	11.9 ± 1.1	11.6 ± 1.1	10.8 ± 1.3
V ($m.min^{-1}$)	113 ± 17	105 ± 7	113 ± 11	123 ± 9	121 ± 10	109 ± 21
Time spent over 16 $km.h^{-1}$ (%)	5.8 ± 1.9	4.1 ± 1	5.6 ± 1.7	7.4 ± 1.8	6.8 ± 1.8	5.8 ± 1.7
Time spent over 20 $W.kg^{-1}$ (%)	13.2 ± 3	10.7 ± 1.8	13 ± 2.5	15.4 ± 2.5	14.6 ± 2.5	12.7 ± 2.8
AI %	41 ± 5.2	36.3 ± 3.6	41.3 ± 4.7	44.7 ± 4.6	42.7 ± 4.5	40.7 ± 4.6
CoD > 30°. Min^{-1}	17.4 ± 2	18.1 ± 2	17.5 ± 2	17.1 ± 1	17.3 ± 2	16.7 ± 2
HI Acc (%)	4.5 ± 2.1	3.9 ± 2.4	4.1 ± 1.7	4.9 ± 1.7	5.6 ± 3	4.5 ± 1.9
HI Dec (%)	12.8 ± 2.4	11.6 ± 2.1	12.9 ± 2.7	13.9 ± 2.1	13.4 ± 2.6	12.4 ± 2.1

Metabolic power ($W{\cdot}kg^{-1}$) is useful in ascribing a more sensitive estimate of the physical loads imposed on players; with more effective estimates of work completed during match play subsequent regulation of training and recovery may be precisely controlled by support staff. However, whilst useful to physiologist as a metric of work ($W{\cdot}kg^{-1}$) it may not translate effectively to applied practitioners in soccer. Therefore, we have applied the concept of equivalent distance (ED) (Osgnach *et al.*, 2010) to reflect the quantity (distance covered) but also the quality (acceleration/deceleration profile) of match related activity in a simple metric and ratio that essentially equates how far a player could run at a constant velocity using the total energy expenditure spent in a match compared to the actual distance covered. The concept of ‘distance covered’ is well embedded in the toolbox of the performance analysts, coaches and managers as a marker of effort, such that's its removal from the lexicon of performance analysis may be difficult to achieve. Therefore, incorporation of the ED in terms readily understood by practitioners may be advantageous in simply expressing an aspect of the metabolic power concept. Using this ED and Equivalent Distance Index (EDI) (Table 5a), to represent activity over the full 90 minutes of competitive match play and first versus second half play it is readily apparent that there exists a gulf between the actual distance covered in a match [Total Distance (TD)] and that represented by the ED approach. Incorporating the effect of acceleration and deceleration across the match activity suggests players (all roles) have effectively expended enough energy to have covered an additional ~ 3 kilometres further than the TD metric would indicate. In essence, ED provides a ‘true’ representation of actual energy expenditure in a match play situation (Osgnach *et al*., 2010). When expressed as the EDI, players are easily observed to be to be running ~ 30% further than that expressed in the TD metric. Positional variations in the ED and the EDI differentiate player activity: Central Midfielder > Wide midfielder > Wide defender ≥ Attacker > Central defender (Table 5a). Such a hierarchy is reflective of the positional variation of work rate observed in other studies (Di Salvo *et al*., 2009; Bradley *et al*., 2010). Examination of the ED and EDI performance metrics (Table 5b-c) indicate that they are reduced from the 1st to 2nd half reflecting a reduction in match related work activities reported by others (Reilly *et al*., 2009; Di Salvo *et al*., 2009; Bradley *et al*., 2010).

Table 5a. Equivalent distance (ED), Total distance (TD), Equivalent distance index (EDI) and running velocity in elite soccer player over 90 minute match play and differentiated by position. Data are presented as Mean ±SD.

Activities all matches	All roles	Central Defender	Wide Defender	Central Midfielder	Wide Midfielder	Attacker
	(n = 295)	(n = 79)	(n = 18)	(n = 86)	(n = 45)	(n = 67)
V (m.min^{-1})	115 ± 16	107 ± 7	116 ± 9	126 ± 9	112 ± 31	116 ± 12
TD (m)	10350 ± 1440	9630 ± 630	10440 ± 810	11340 ± 810	10080 ± 2790	10440 ± 1080
ED (m)	13465 ± 1859	12060 ± 2054	13601 ± 1132	14517 ± 1962	14046 ± 1050	13357 ± 1454
EDI (%)	130%	125%	130%	128%	139%	128%

Table 5b. Equivalent distance (ED), Total distance (TD), Equivalent distance index (EDI) and running velocity in elite soccer player over the first half (45 minutes) of competitive match play and differentiated by position. Data are presented as Mean ±SD.

Activities all matches (1st Half)	All roles	Central Defender	Wide Defender	Central Midfielder	Wide Midfielder	Attacker
	(n = 295)	(n = 79)	(n = 18)	(n = 86)	(n = 45)	(n = 67)
V (m.min^{-1})	116 ± 21	108 ± 8	112 ± 27	125 ± 24	121 ± 10	112 ± 27
TD (m)	5220 ± 945	4860 ± 360	5040 ± 1215	5625 ± 1080	5445 ± 450	5040 ± 1215
ED (m)	6548 ± 748	5922 ± 472	6611 ± 506	7147 ± 668	6624 ± 665	6470 ± 799
EDI (%)	125%	122%	131%	127%	122%	128%

Table 5c. Equivalent distance (ED), Total distance (TD), Equivalent distance index (EDI) and running velocity in elite soccer player over the second half (45 minutes) of competitive match play for all roles and differentiated by position. Data are presented as Mean ±SD.

Activities all matches (2nd Half)	All roles (n = 295)	Central Defender (n = 79)	Wide Defender (n = 18)	Central Midfielder (n = 86)	Wide Midfielder (n = 45)	Attacker (n = 67)
V ($m.min^{-1}$)	113 ± 17	105 ± 7	113 ± 11	123 ± 9	121 ± 10	109 ± 21
TD (m)	5085 ± 765	4725 ± 315	5085 ± 495	5535 ± 405	5445 ± 450	4905 ± 945
ED (m)	6212 ± 908	5718 ± 473	6231 ± 664	6553 ± 1395	6636 ± 601	6115 ± 734
EDI (%)	122%	121%	123%	118%	122%	125%

Traditional match analysis approaches have centred upon representing the external load applied during match play in terms of distance covered or time spent undertaking work activity at different running speeds or in running speed zones (Reilly *et al*., 2009; Di Salvo *et al*., 2009; Bradley *et al*., 2010). This approach has been instrumental in yielding insights into the physical requirements of soccer match-play performance (Gregson *et al*., 2010). However, a critical limitation to these models is their failure to consider the variances in running speed that occur during acceleration and deceleration phases of match activity and crucially the subsequent variances in energy expenditure such changes elicit. It must be understood that metabolic cost can be high even when players are presumed to be moving at relatively slow running speeds, due simply to the rate of acceleration and deceleration that occurs within that movement sequence. For example, where a player was to commence running at 9 $km{\cdot}h^{-1}$ the associated energy cost would approximate to 10 $W{\cdot}kg^{-1}$ however, if that players accelerates by 1 $m{\cdot}s^{-2}$ metabolic cost can increase to 20 $W{\cdot}kg^{-1}$, acceleration by 2.5 $m{\cdot}s^{-2}$ can cost 35 $W{\cdot}kg^{-1}$ and 3.5 $m{\cdot}s^{-2}$ can elicit ~ 55 $W{\cdot}kg^{-1}$. Players accelerate and decelerate more than 1000 times during a match with almost 700 changes of direction, meaning that constant velocity movement is rare. Different acceleration and deceleration profiles can thus elicit different metabolic demands, which are disassociated from a corresponding notional running speed. Di Salvo *et al*., (2009), have differentiated 'in game' sprint related activities based on velocity profiles. We contend that predicated on present findings such a velocity-based approach might add little to the understanding and appreciation of high intensity activity in soccer given the previously mentioned discordance between metabolic power and running speed profile. Examination of the current data relating to the time spent in higher metabolic power activities 20-55 $W{\cdot}kg^{-1}$ (Table 6a) suggests greater durations undertaking higher MP activities in those players engaged in all wide positions (wide defenders and wide midfield) and attackers. In addition, the role of central midfield players would seem particularly prominent in undertaking activities requiring high levels of energy expenditure. Such prominence may exist as a function of need to defend against attacks and rapidly switch to an offensive role. Central defenders fulfil a reactive role reacting to counteract the movements of the opposing players necessitating rapid and frequent changes of direction and accelerations, over short distances, which may explain the observed metabolic power and ED data.

Table 6a. Time (s) spent at different Metabolic Power ($W \cdot kg^{-1}$) requirements in elite soccer player over 90 minutes of competitive match play and differentiated by playing position. Data are presented as Mean ± SD.

Time at Met. Power	All roles	Central Defender	Wide Defender	Central Midfielder	Wide Midfielder	Attacker
	(n = 295)	(n = 79)	(n = 18)	(n = 86)	(n = 45)	(n = 67)
0-10 $W \cdot kg^{-1}$(s)	3441 ± 355	3724 ± 191	3471 ± 224	3140 ± 389	3386 ± 252	3491 ± 323
10-20 $W \cdot kg^{-1}$ (s)	1259 ± 243	1159 ± 217	1264 ± 159	1381 ± 194	1319 ± 124	1177 ± 325
20-35 $W \cdot kg^{-1}$ (s)	507 ± 103	421 ± 65	504 ± 70	582 ± 105	547 ± 88	486 ± 91
35-55 $W \cdot kg^{-1}$ (s)	178 ± 42	138 ± 21	180 ± 29	211 ± 46	190 ± 29	174 ± 36
>55 $W \cdot kg^{-1}$ (s)	86 ± 23	66 ± 14	91 ± 19	100 ± 27	92 ± 17	89 ± 20

Table 6b. Time (s) spent at different Metabolic Power ($W \cdot kg^{-1}$) requirements in elite soccer player over the first half (45 minutes) of competitive match play and differentiated by playing position. Data are presented as Mean ±SD.

Time at Met. Power	All roles	Central Defender	Wide Defender	Central Midfielder	Wide Midfielder	Attacker
(1st Half)	(n = 295)	(n = 79)	(n = 18)	(n = 86)	(n = 45)	(n = 67)
0-10 $W \cdot kg^{-1}$(s)	1601 ± 152	1732 ± 97	1587 ± 92	1475 ± 133	1599 ± 133	1615 ± 155
10-20 $W \cdot kg^{-1}$ (s)	632 ± 86	584 ± 63	626 ± 64	691 ± 64	614 ± 72	616 ± 104
20-35 $W \cdot kg^{-1}$ (s)	250 ± 53	204 ± 34	251 ± 30	292 ± 46	258 ± 54	240 ± 49
35-55 $W \cdot kg^{-1}$ (s)	86 ± 23	65 ± 12	88 ± 16	105 ± 23	91 ± 17	85 ± 22
>55 $W \cdot kg^{-1}$ (s)	41 ± 12	31 ± 8	45 ± 11	49 ± 13	45 ± 11	42 ± 12

Table 6c. Time (s) spent at different Metabolic Power ($W \cdot kg^{-1}$) requirements in elite soccer player over the second half (45 minutes) of competitive match play for all roles and differentiated by playing position. Data are presented as Mean ± SD.

Time at Met. Power	All roles	Central Defender	Wide Defender	Central Midfielder	Wide Midfielder	Attacker
(2nd Half)	(n = 295)	(n = 79)	(n = 18)	(n = 86)	(n = 45)	(n = 67)
0-10 $W \cdot kg^{-1}$(s)	1647 ± 217	1782 ± 107	1683 ± 133	1492 ± 309	1593 ± 130	1686 ± 176
10-20 $W \cdot kg^{-1}$ (s)	580 ± 102	539 ± 72	569 ± 88	615 ± 135	635 ± 67	560 ± 97
20-35 $W \cdot kg^{-1}$ (s)	225 ± 57	188 ± 45	224 ± 41	256 ± 62	259 ± 43	213 ± 57
35-55 $W \cdot kg^{-1}$ (s)	80 ± 22	64 ± 11	82 ± 18	94 ± 27	88 ± 18	78 ± 17
>55 $W \cdot kg^{-1}$ (s)	39 ± 13	30 ± 8	41 ± 13	45 ± 16	42 ± 11	41 ± 10

The metabolic power approach applied in this work indicates that the definition of what constitutes a high intensity match play activity may need to be redefined. Table 4a presents observations defining the time spent in 'high intensity activities' across both 90 minutes of match play and on a half by half basis observed from the perspective of the 'old' running speed and new 'metabolic power' based approaches. Data indicates that the 295 elite players spent approximately 6% of the total match time working at an intensity exceeding the 16 $km \cdot h^{-1}$ threshold previously defined in literature as indicative of high intensity running (Osgnach *et al.*, 2010). However, when defined using the new metabolic power approach players spend ~ 14 % of the match time at power outputs exceeding (20 $W.kg^{-1}$), which are defined as high intensity based on the acceleration into and deceleration out of the movement. Furthermore, examination of the 108 elite players assessed via GPS monitoring (Table 8) based on these same criteria i.e. time spent at a work intensity exceeding 16 $km{\cdot}h^{-1}$ and power output exceeding (20 $W{\cdot}kg^{-1}$), was approximately 5.1% and 11.4% respectively. In essence, the use of speed threshold data clearly underestimates by ~50% the work rate of the players or alternatively it may also be viewed that players are performing 50% more high intensity work than is attributed by running speed. Support for this view may be seen in the Anaerobic index (AI%) metric, which indicates approximately ~40% of total energy expenditure came from anaerobic sources (Table 4a). These have findings have implications in terms of implementing recovery strategies from games and the scheduling of games. Squad rotation/selection policies prevalent in many premiership teams are generally implemented in periods of fixture congestion and/or prioritisation of competitions so as to allow the effective distribution of match play around a squad. Implementation of such schemes are based on diverse factors including the managers/coaches sense of 'player fatigue'; present match-play data indicating substantially elevated metabolic power requirements presents an empirical basis and a putative case to suggest coaches sense of 'player fatigue' may have a sensitivity that traditional work rate analysis tracking lacks the resolution to detect. Although, for those key players selected on a continual basis it would indicate that very careful recovery management in the inter-game periods are required.

Table 7a. Distance (m) covered at different Metabolic Power ($W{\cdot}kg^{-1}$) requirements in elite soccer player over 90 minutes of competitive match play and differentiated by playing position. Data are presented as Mean ±SD.

Distance at Met. Power	All roles (n = 295)	Central Defender (n = 79)	Wide Defender (n = 18)	Central Midfielder (n = 86)	Wide Midfielder (n = 45)	Attacker (n = 67)
0-10 $W{\cdot}kg^{-1}$(m)	4298 ± 397	4568 ± 248	4351 ± 247	4023 ± 524	4186 ± 330	4341 ± 305
10-20 $W{\cdot}kg^{-1}$ (m)	3673 ± 626	3226 ± 396	3606 ± 506	4106 ± 636	3809 ± 441	3580 ± 636
20-35 $W{\cdot}kg^{-1}$ (m)	1823 ± 490	1363 ± 465	1811 ± 297	2170 ± 431	2082 ± 415	1778 ± 350
35-55 $W{\cdot}kg^{-1}$ (m)	709 ± 179	530 ± 92	713 ± 123	852 ± 195	797 ± 136	701 ± 147
>55 $W{\cdot}kg^{-1}$ (m)	365 ± 100	271 ± 56	382 ± 81	428 ± 116	413 ± 77	379 ± 87

Table 7b. Distance (m) covered at different Metabolic Power (W·kg^{-1}) requirements in elite soccer player over the first half (45 minutes) of competitive match play and differentiated by playing position. Data are presented as Mean ±SD.

Distance at Met. Power (1st Half)	All roles (n = 295)	Central Defender (n = 79)	Wide Defender (n = 18)	Central Midfielder (n = 86)	Wide Midfielder (n = 45)	Attacker (n = 67)
0-10 W·kg^{-1}(m)	2031 ± 172	2160 ± 128	2040 ± 145	1921 ± 173	1965 ± 158	2043 ± 160
10-20 W·kg^{-1} (m)	1819 ± 309	1585 ± 197	1793 ± 218	2066 ± 235	1780 ± 261	1783 ± 337
20-35 W·kg^{-1} (m)	899 ± 299	702 ± 145	904 ± 127	1046 ± 260	986 ± 236	877 ± 192
35-55 W·kg^{-1} (m)	343 ± 97	245 ± 49	350 ± 64	422 ± 98	384 ± 76	342 ± 92
>55 W·kg^{-1} (m)	172 ± 56	124 ± 30	188 ± 44	206 ± 57	201 ± 46	178 ± 62

Table 7c. Distance (m) covered at different Metabolic Power (W·kg^{-1}) requirements in elite soccer player over the second half (45 minutes) of competitive match play and differentiated by playing position. Data are presented as Mean ±SD.

Distance at Met. Power (2nd Half)	All roles (n = 295)	Central Defender (n = 79)	Wide Defender (n = 18)	Central Midfielder (n = 86)	Wide Midfielder (n = 45)	Attacker (n = 67)
0-10 W·kg^{-1}(s)	2034 ± 239	2153 ± 118	2074 ± 129	1891 ± 390	1982 ± 156	2067 ± 155
10-20 W·kg^{-1} (s)	1643 ± 356	1454 ± 217	1616 ± 272	1816 ± 417	1742 ± 515	1598 ± 321
20-35 W·kg^{-1} (s)	824 ± 214	664 ± 132	802 ± 163	952 ± 243	975 ± 209	788 ± 185
35-55 W·kg^{-1} (s)	321 ± 90	246 ± 47	322 ± 71	379 ± 111	366 ± 78	312 ± 72
>55 W·kg^{-1} (s)	166 ± 55	124 ± 33	172 ± 49	193 ± 71	182 ± 49	172 ± 45

It is to this process of player's physical management that new technology such as GPS has a significant contribution to make. Whilst semi-automated video capture technology is available to elite level clubs that would allow relatively easily monitoring of match related energy expenditure its implementation in second tier clubs is generally limited. Present data (Table 8) presents performance metrics from 108 elite professional soccer players whose metabolic power and work profiles have been determined by GPS in interclub pre-season challenge games. It is interesting to note that GPS technology estimates whilst derived from different games to the video match analysis; present a series of metrics approximately similar albeit slightly lower than the competitive games. In particular, the lower rate of high intensity activity is noteworthy, but not unexpected. Such differences may reflect the less competitive nature of pre-season friendly matches relative to the importance of competitive in season matches (Table 8). It remains for direct comparison of GPS and Video match analysis system to be reported in order to assess agreement between technological approaches. However, it would be an interesting task to apply GPS in these 2nd tier championship clubs during the competitive season as a means of monitoring physiological load in conjunction with the metabolic power paradigm. These preliminary observations suggest that independent of the data capture method metabolic power in elite match play may be somewhat similar.

Table 8. Comparison of performance metrics obtained during preseason friendly soccer match play (GPS derived) relative to in season competitive match play as determined by video analysis. Data are presented as Mean ±SD.

Parameters	Friendly matches (GPS).	Competitive matches (Video Analysis).
	All roles	All roles
	(n = 108)	(n = 295)
Metabolic Power ($W.kg^{-1}$).	11.0 ± 0.7	11.2 ± 1.2
V ($m.min^{-1}$)	112 ± 13	115 ± 16
Time spent over 16 $km.h^{-1}$ (%)	5.1 ± 1.6	6.1 ± 1.8
Time spent over 20 $W.kg^{-1}$ (%)	11.4 ± 2.3	13.7 ± 2.8
AI %	40.6 ± 3.2	41.7 ± 4.7
CoD > 30°. Min^{-1}	17.1 ± 1.6	17.7 ± 2
HI Acc (%)	4.2 ± 1.1	4.6 ± 2
HI Dec (%)	10.4 ± 1.8	12.9 ± 1.9
Kilojoule (kJ)	59.22 ± 6.28	62.75 ± 8.66
TD (m)	10080 ± 1170	10350 ± 1440
ED (m)	12708.2 ± 1347	13465 ± 1859
EDI (%)	126%	130%

Conclusion

As suggested by Gregson *et al*., (2010) and Osgnach *et al*., (2010), it is essential to attach importance to the activities of the game of football. Using the new metabolic power approach, we support the assertions of Osgnach *et al*., (2010) that the demands of soccer match play are more appropriately represented by the Metabolic Power (MP) approach. We extend the Osgnach *et al*., (2010) conceptual work to indicate that metabolic power is impacted upon by the positional demands of the game and is sensitive to differentiate metabolic power difference between first and second half in match play profiles, however further detailed analysis is required. Furthermore, we present for the first time GPS derived metabolic power data from elite players in match play situations, which approximate that seen, when data is determined via gold standard video data capture. Such observation may provide for the extension of the metabolic power approach beyond the traditional video capture system to GPS focused capture where athletic trainers may wish to derive a more holistic workload model for each player. It is critical, that these performance metrics be further examined in relation to collective tactics/formations and therefore the energy cost in conjunction with understanding the temporal dynamics of metabolic power during phases of possession with and without the ball. Such issues have been considered with speed and distance paradigms, however given the gross underestimation of game requirements these need to be re-examined. Further extension and analysis on the database will be useful to better understand the specific requirements of the game. Classic match analysis approaches have initiated and brought about positive changes in professional practice in soccer. They have introduced objective quantification and evaluation of match play and linked the regulation of training to the perceived physical demands of match play. The metabolic power approach customised to elite soccer players presented in this report represents an evolution in the tools available to the coach/trainer and performance analysts that will assist in refining this process.

Acknowledgements.

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Appendix A.

Phase 1

Interim Report

December 2012

The Validation and Application of An Integrated Metabolic Cost Paradigm Using High Frequency GPS Technology In Soccer.

Liverpool John Moores University

Research Institute for Sport and Exercise Science

Phase 1 Interim Report
December 2012

The Validation and Application Of An Integrated Metabolic Cost Paradigm-Using High Frequency GPS Technology In Soccer.

Prepared by

Dr Dominic A Doran
Dr Neil Chester
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Confidential.

Executive Summary

This update briefing documents details the work to date on the research project entitled 'The validation and application of an integrated metabolic cost paradigm using high frequency GPS technology in soccer. This work is important for UEFA in that is sets out the preliminary GPS and metabolic cost validation work in order to provide a means of assessing the metabolic cost of soccer activity as detailed below.

The terms of reference for the project are :-

1. Determine the metabolic cost of Soccer Specific activity
2. Apply those metabolic cost models to match play situations.

The findings outlined in this report are based on the preliminary research completed to date and highlight a number of issues for consideration. Study one is comprised of several initial phases. The aim of phase one was firstly to validate the assessment of speed and distance measures derived from high frequency 10 Hz-GPS technology relative to a gold standard laser determined measures. In particular the efficacy of GPS assessment of linear acceleration and deceleration in conjunction with change of direction was considered in addition to validation of distance covered on an a linear soccer specific circuit. Further to this, examination of the coincidence between metabolic power calculation derived from 10 Hz-GPS and gold standard laser determined measures during acceleration and deceleration tasks with and without change of direction. This early phase examined the efficacy of the 10 Hz-GPS to be used in the assessment of metabolic power in match play. The second phase of study one was directed toward examining the energy cost equations postulated by Minetti *et al.*, (2002) and modified by Osgnach *et al.*, (2009) so as to alter both the coefficient of determination and error terms to reflect the postulated higher energy cost for soccer activity on grass in elite soccer players.

Preliminary finding indicate that the 10 Hz-GPS provide a valid means's of assessing running speed and distance during short duration, low, moderate and higher intensity running with and without change of direction. However, as with previous reports relating to lower frequency (1 Hz, 4Hz and 5 Hz) the current 10 Hz-GPS system demonstrates a bias which slightly underestimates both running speed and distance; this error term is in the region of approx 2-4% absolute difference in these variables. The 10 Hz-GPS closely mirror the acceleration and deceleration profiles determined at 100 Hz via Laveg laser system as indicated by the high correlations across all tasks (Table 1), something present data on 4 Hz systems indicate they do not adequately achieve. Further to this initial work we also implemented the methodology of Di Prampero *et al.*, (2005) to determine the metabolic cost of running. This approach was applied to shuttle running activity at sub-maximal and self-determined maximal running speeds with 180^{o} change of direction to assess coincidence between metabolic power estimates from the 10Hz-GPS during acceleration and deceleration relative to the laser system. Findings indicate a high degree of association (R^2 = 0.998) between GPS relative to laser derived metabolic power over and out and back 20 meter shuttle run. Data indicted that 10 Hz-GPS relative to the Laser provided very similar estimates of metabolic power of 22.79 ± 0.3 vs 23.26 ± 0.3 ($W \cdot kg^{-1}$) with a mean difference between system estimates of metabolic power of 0.47 ± 0.07 ($W \cdot kg^{-1}$) at sub-maximal speed. During high intensity running metabolic power estimates were assessed as 31.84 ± 2.4 vs 32.17 ± 2.5 ($W \cdot kg^{-1}$) for 10Hz-GPS and laser respectively with a mean difference 0.33 ± 0.11($W \cdot kg^{-1}$). This preliminary finding indicate the 10 Hz-GPS technology whilst underestimating slightly is capable of differentiating metabolic power during varying exercise intensities where traditional linear and change of direction running tasks are applied. The underestimation is likely to be function of the underestimation inherent in measurement of running speed.

The second phase of study one was directed toward examining the energy cost equations initially postulated by Minetti *et al.*, (2002) and modified by Osgnach *et al.*, (2009). In examining the previous equations it is apparent that coefficient of determination for energy cost, which is derived from treadmill running, is not applicable and does not reflect the higher energy cost of soccer activity on grass in elite soccer players. In this phase we measured the energy cost of constant velocity running in 17 elite professional soccer players using directly measured oxygen uptake via a Kosmed K4 portable breath by breath gas analyser. Data indicate that previous estimates of energy cost of 3.66 $J \cdot kg^{-1} \cdot m^{-1}$ is incorrect and a value of 4.67 $J \cdot kg^{-1} \cdot m^{-1}$ is more reflective of the true cost (Di Prampero *et al.*, 2005; Osgnach *et al.*, 2009). Several equations with different order polynomial fits have been derived based on this preliminary population data to iron out certain congruities in the early equations regarding the influence changes in body angle during acceleration and deceleration may have on metabolic power estimates. The data is confirmative of the necessity to modify the initial equation as applied by Osgnach *et al.*, (2009). This process is ongoing.

The data contained herein is preliminary and will be subject to further detailed statistical analysis as sample size is increased. Research activity on all aspects of study one is continuing; the validation of energy cost of running on grass is currently being extended from the 17 elite players to over 30. In parallel we have a highly trained but non-elite population of semi professional and varsity players under assessment using the same methodology. This data is not included in this report but will form part of the final submission. Continuing in parallel with this data collection has been the collection of further GPS match play data which has expanded our historical database that forms the final phase of research project upon which the new equation will be applied.

Conclusions

Our key observations would indicate that the current terms of reference initially supplied in the grant on target. We have assessed the validity of the new 10Hz-GPS technology, reliability data analysis is ongoing will be added to this assessment in the final report. We have determined a new energy cost constant that suggests previous estimates are incorrect for elite players and underestimate the true cost on UEFA standard pitches. We have developed a ‘NEW preliminary metabolic power’ equation that is being applied to elite professional, semi professional and high fitness varsity players. We continue to evolve and extend the GPS database for the player’s match play database across positions.

Background.

Several studies have examined the validity (accuracy) of GPS systems however these assessments have been determined predominately during steady-state movements, using systems that have a lower rate sampling frequency. Whilst faster GPS systems (5 Hz and 10 Hz) have been validated for team sports, some doubts continue to exist on the appropriateness of GPS for measuring short high-velocity linear and change of direction movements that are common in intermittent team games (Coutts *et al.*, 2010).

It is clear however, that in order to improve tracking accuracy particularly for higher velocity movements, higher GPS sampling frequencies would be clearly advantageous. Castellano *et al.*, (2011) and Varley *et al.*, (2011) have confirmed that 10-Hz GPS devices are more accurate on linear runs of 15 and 30 m, however performance in team sports is rarely linear. The ability to accelerate, decelerate and change direction at several ranges of speed and distance is critical to performance (Jennings *et al.*, 2010a). For this reason it is important that evaluation and validation of multidirectional and soccer-specific activities with high sampling frequency (10 Hz) GPS is undertaken. In previous validation studies GPS has been compared to timing lights, which only provide an estimate of average velocity over a measured distance which negates their effective use for assessing acceleration and deceleration. Consequently during GPS validation the use of Laser measurement systems similar to those used to track car velocities would facilitate the assessment of both acceleration and deceleration giving high sampling frequency of ~100 Hz. In the present study we have utilised a new low cost 10-Hz high frequency GPS system (BT-1000ex, Qstarz, Taiwan).

The initial pilot study presented below was conceptualised in order to establish its validity relative to a gold standard Laser system sampling at 100 Hz per second and to compare it to a current 4-Hz GPS system in order to examine the influence of sampling rate on the assessment of the rate of acceleration and deceleration.

<u>Study One. (Part A)</u>

Objectives:

1. Determine the coincidence of running speeds derived from a LAVEG Sport Laser "gold standard" to those off a 4 Hz and 10 Hz-GPS system.
2. Comparison of the accuracy of the distances measured with Laveg Sport Laser and 10-Hz GPS at different exercise intensities.

3. Evaluate the measurement error obtained from 10 Hz-GPS derived distance covered on a non-linear measured soccer specific circuit at different running speeds;

4. Determine and verify the metabolic power calculated from running speed during linear acceleration and deceleration runs with change of directions derived from a 10 Hz-GPS and Laveg Laser system using the approach of Di Prampero *et al.,* (2005) .

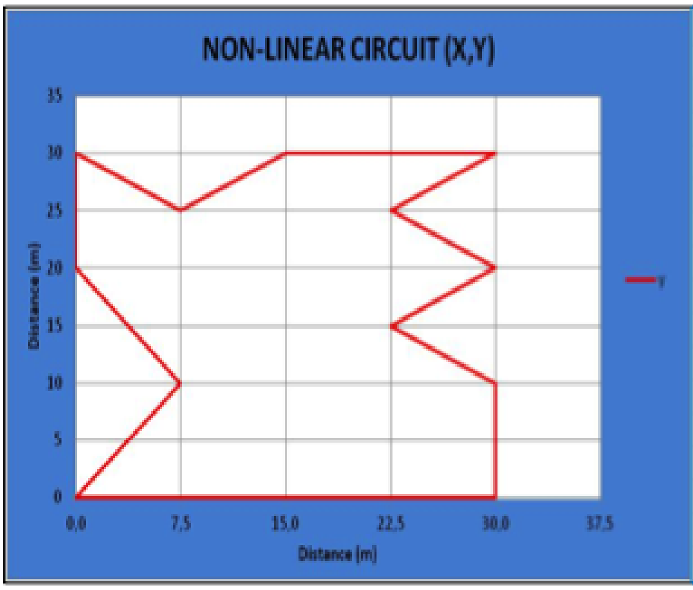
Methods.

Participants.

Ten male students who participate regularly in varsity level soccer volunteered and provided written consent to participate in this study. Their mean age, height and body mass were 21 ± 2 years, 1.74 ± 6 m, and 74 ± 5 kg respectively. This population whilst not elite provide a validation sample trained in soccer specific activity to undertake the trial.

Experimental design and protocol [GPS validation]

All participants were required to complete 4 different running conditions: 1-2) Linear (straight)-line sub-maximal run over a marked 30 meters course with low-moderate acceleration and deceleration, 3-4) sub-maximal shuttle run over 20 meters keeping time with a beep sound to regulate running speed and 5) high-intensity accelerations and decelerations over 50 meters. Additionally each participant undertook linear and change of direction tasks running 6 laps of a measured soccer specific circuit (Figure 1), which was set out on a synthetic sports surface. This was designed to simulate the kinematics velocity and changes of direction experienced during soccer. All activities commenced from a stationary start position and required participants to come to a complete stop at the end of the marked course. A trundle wheel was used to measure the exact length of the soccer specific circuit and each participant was familiarised with a sound signal emitted at set times to regulate running speed. During the non-linear circuit an iPod system (iPod nano, Apple, Cupertino, California) was used to emit the pacing signal (bleep) every 5 seconds. As a spatial reference multiple markers were positioned at fixed points depending on the running speed required. Running speeds commenced at 2.5 m·s^{-1} and increase to 3.3 m·s^{-1} and 4.1m·s^{-1} over two consecutive laps.



x	y	direction	angles (°)	distance (m)
0,0	0,0			
30,0	0,0	90	90	30,00
30,0	10,0	0	56	10,00
22,5	15,0	304	113	9,01
30,0	20,0	56	113	9,01
22,5	25,0	304	113	9,01
30,0	30,0	56	146	9,01
15,0	30,0	270	34	15,00
7,5	25,0	236	67	9,01
0,0	30,0	304	124	9,01
0,0	20,0	180	37	10,00
7,5	10,0	143	74	12,50
0,0	0,0	217		12,50
				total (m)
				144,08

Figure 1. Displacement, direction and angle of change during non-linear soccer specific circuit.

Participants were tracked over the linear-sprints and the soccer specific circuit using GPS devices (BT-Q1000eX 10 Hz, Qstarz, Taipei, Taiwan; VX Log™ 225, Visuallex Sport, Lower Hutt, New Zealand). During straight-line and linear shuttle running simultaneous measurement with a laser speed gun sampling at 100 Hz (LAVEG LDM-300c sport, Jenoptik AG, Jena, Germany) was performed to act as a gold standard. The measurement error for the Laveg laser pertaining to distance travelled has been identified as 0.10 ± 0.06 m over 100 m (Arsec & Locatelli, 2002) with a coefficient of variation of up to 0.2% over 10, 30, 50, 70 m (Harrison *et al.*, 2005). The laser was positioned behind the participants at the starting point of the linear runs and aligned with the centre of the participants back to ensure acquisition of laser signal. Instantaneous velocity measurements were obtained for each trial. The GPS units were placed approximately 20 cm apart on the upper back in a custom-made vest on all participants. The mean ± SD number of satellites during data collection for both the linear (acceleration and deceleration) runs and shuttle run where determined. Laser velocity data (100 Hz) was resampled to 10 Hz and 4 –Hz for comparison with the respective GPS device and synchronized at the first movement recorded above 0 m·s^{-1} to account for processing phase delays inherent with GPS system. Data were downloaded and analysed using several forms of conversion software (GPS Power, SPINItalia, Roma, Italy; LAVEG V3.9, Jenoptik, Jena, Germany; QSports v3.74, Qstarz, Taipei, Taiwan; VX View^{TM}, VX Sport, Lower Hutt, New Zealand) to establish the time, speed, distance and metabolic power.

Metabolic Power Calculation.

Metabolic power was determined through the methodology of energy cost modelling (Minetti *et al.,* 2002; Di Prampero *et al.,* 2005) to use the running speed data to determine an estimate of metabolic power determined concurrently from the Laser and 10 Hz-GPS data. Using 20 m shuttle runs with 180^0 change of direction at sub-maximal speeds and maximal speeds with tight changes of direction.

Energy cost calculation.

The calculation of the ratio between the energy expenditure and the nominal speed:

$$ECr = VO_2/v$$

where VO_2 is the net value (measured minus resting oxygen consumption) assuming an energy equivalent of 20.9 KJ·L O_2 (corresponding to a non-protein respiratory exchange ratio of 0.96), and *v* is the sub-maximal speed below the anaerobic threshold (assuming that during steady-state exercise performed below the anaerobic threshold, all of the energy turnover is attributed to aerobic metabolism) . One MET was set by convention to 3.5 mL·kg^{-1}·min^{-1}. The EC_r above resting; total energy was then divided by the subject's body weight and distance covered in the concerned time, to express EC_r as J·kg^{-1}·m^{-1}.

Statistical analysis.

Descriptive statistics for the data under consideration are presented as mean ± SD. The strength of association between individual laser (gold standard) and 10-Hz GPS estimates of running speed was assessed using Pearson (r) correlation analysis. A least squares regression approach was used to assess the validity of the 10 Hz-GPS, where the laser estimates of running speed were regressed against each 10 Hz-GPS estimate separately for each running speed (Batterham 2004; Hopkins 2004; Hopkins 2010). The potential for any fixed bias was assessed by determining whether the intercept for the regression was different from zero. Similarly, to identify if proportional bias was present the slope of the regression line was assessed to determine if it was different from 1. The random error was quantified using the standard error of the estimate from the regression. Visual inspection as recommended by Hopkins et al., (2004) of the residual plots (standardised residual on standardised predicted) was carried out to determine if the random error was uniform along the range of measures taken.

Results

Satellite data acquisition.

The mean ± SD number of satellites acquired during data collection for the linear runs (acceleration and deceleration) and shuttle runs were 10.77 ± 0.85, while during the non-linear circuit it was 10.60 ± 0.90. The mean horizontal dilution of position (HDOP) during data collection was 0.89 ± 0.10 and 0.88 ± 0.08 respectively for straight-line linear acceleration and decelerations as well as the shuttle run and non-linear soccer specific circuit.

Influence of GPS Sample frequency: Comparison of 4Hz vs 10Hz-GPS vs Laser system.

Running Speed.

In order to evaluate the influence of GPS data acquisition sample rate on measurement of linear acceleration and deceleration running speed a comparison of 4Hz and 10 Hz-GPS relative to the gold standard laser was undertaken. Figure 2 presents the typical response to linear acceleration and decelerations across all GPS systems (n=4). The path in blue indicates the 10 Hz-GPS while the green path highlights the 4 Hz-GPS. The trends indicated are replicated across all linear running speeds, whilst distance measures are acceptable the ability of the 4 Hz-GPS system to track change in acceleration and deceleration was poor relative to the greater accuracy displayed with the 10-Hz high sample frequency GPS system. Indeed it is apparent that the 4 Hz-GPS loses accuracy even during the interval of time at which running pace is almost constant. To that end we removed the 4 Hz-GPS from all further work due to its inability to facilitate measurement of acceleration and deceleration phases. Remaining data compare 10 Hz-GPS running speed and distance to laser derived data only (Figure 4).

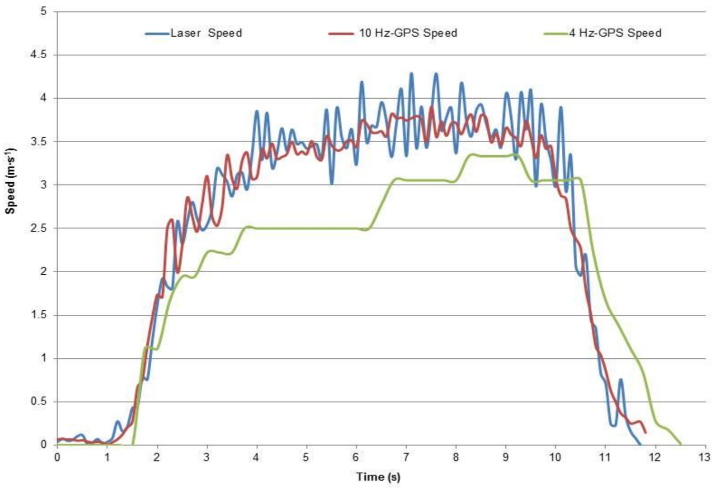


Figure 2. Comparison of typical running speed response curve for 10 Hz-GPS vs 4 Hz-GPS vs Laser during linear acceleration and decelerations over 30 m at moderate intensity.

Linear Acceleration and Deceleration Distance Ran.

During each linear 20, 30 and 50 m acceleration and deceleration run the mean values of laser derived relative to 10 Hz-GPS derived distance covered at different running speeds where; 2.5 $m{\cdot}s^{-1}$ were 30.33 ± 0.77 m vs 29.50 ± 0.87 m (-0.027%); 3.3 $m{\cdot}s^{-1}$ were 30.22 ± 0.91 m vs 29.45 ± 0.98 m (-0.025%); 4.38 $m{\cdot}s^{-1}$ were 50.47 ± 0.40 m vs 49.27 ± 0.84 m (-0.024%); shuttle run 39.26 ± 0.52 m vs 38.55 ± 0.46 m (0.018%) respectively. In all case the GPS underestimated distance covered.

Soccer Specific Circuit Distance Ran.

Total distance covered as determined by 10 Hz-GPS on each of the non-linear circuits relative to the actual measured distance i.e.144.08 m at 2.5 $m{\cdot}s^{-1}$ was 140.84 ± 2.27 m, (-2.25%); at 3.33 $m{\cdot}s^{-1}$ 136.01 ± 3.69 (-5.6%); at 4.16 $m{\cdot}s^{-1}$138.8 ± 2.38 m (-3.67%). The 10 Hz-GPS underestimated the criterion distance on the soccer specific circuit (Figure 3).

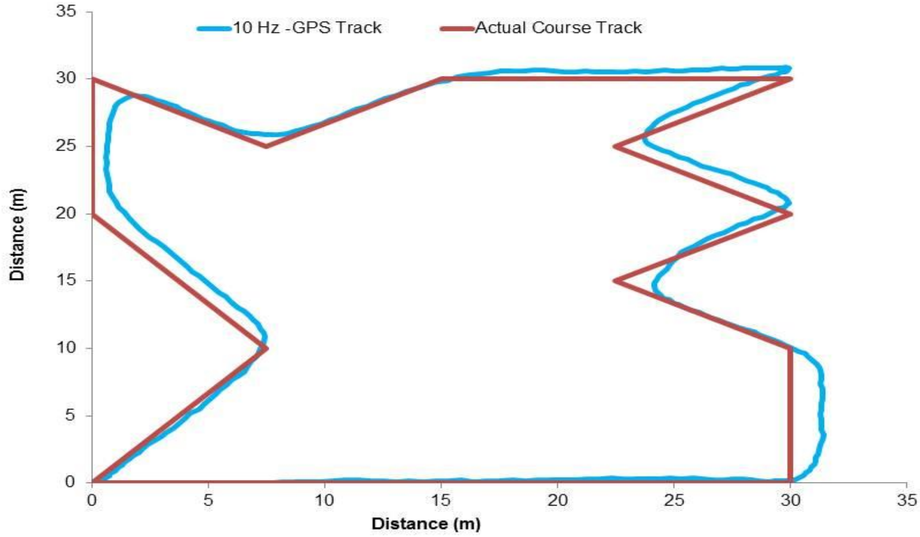


Figure 3. Comparison of distance covered between actual and 10 Hz-GPS transit path during linear and non-linear soccer specific circuit at $3.33 m \cdot s^{-1}$.

Least squares regression analysis of laser vs 10-Hz GPS derived running speed.

The relationship between linear running speed with and without 180^{o} change of direction and 10 Hz-GPS was explored using least squares regression analysis in order to identify if any bias (proportional or fixed) was present and to quantify the random error. The slopes, intercepts and the standard error of estimates (SEE) are presented (Table 1). The random error were relatively similar across the different movement tasks with the smallest value being $0.018 m \cdot s^{-1}$ for the low intensity run and increasing as speed increased and change of direction were introduced to $0.07 m \cdot s^{-1}$. The potential for any bias was assessed by visual inspection of the regression line an example of which is presented (Figure 5). Using a 10 Hz - GPS showed a small amount of fixed bias with the regression line above the line of unity. The slopes and positions of the regression lines for all tasks provides strong evidence for the presence of fixed bias that result in slight underestimation of running speed. 10 Hz-GPS was highly correlated with laser-derived speeds across all running tasks.

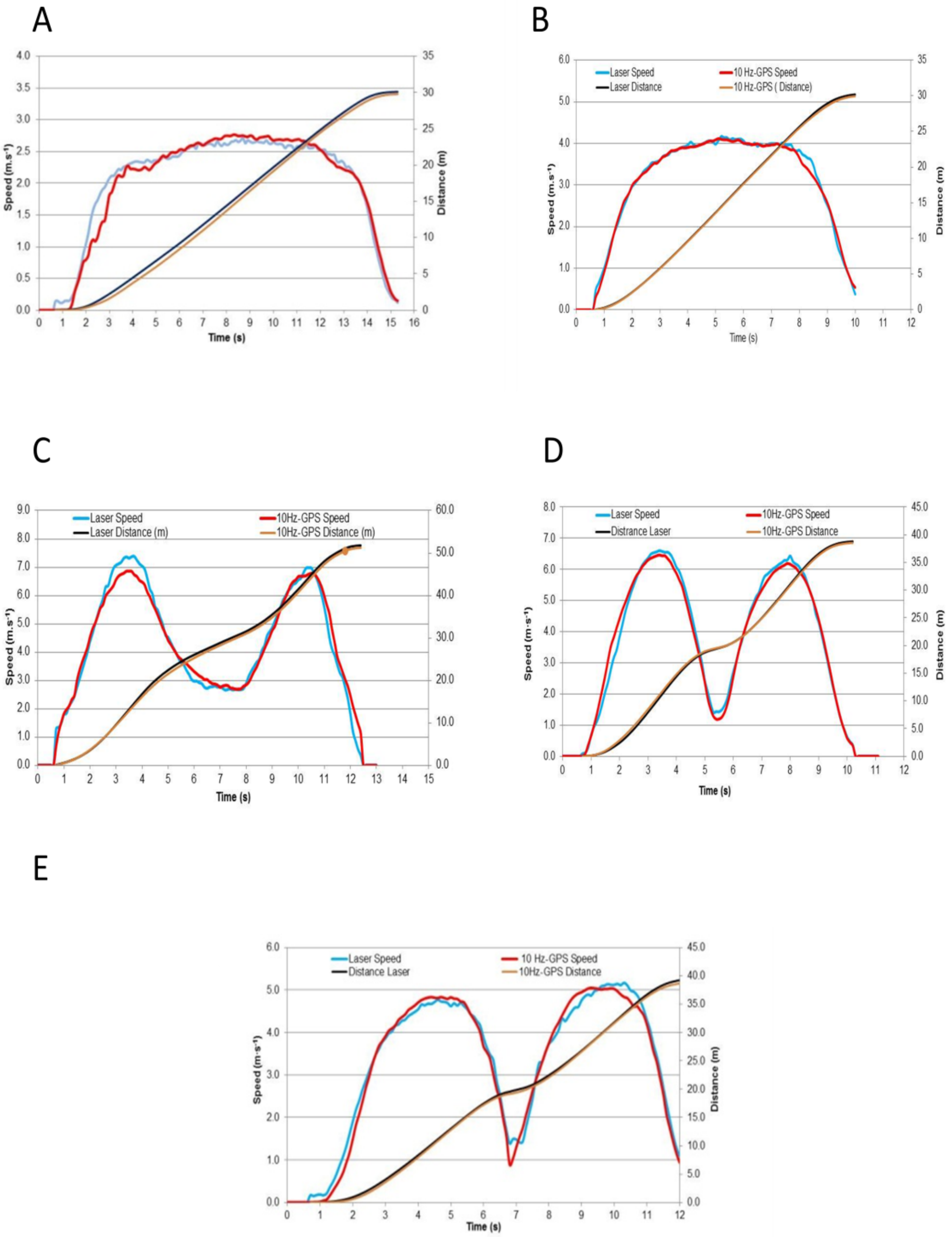


Figure 4. Comparison of typical running speed and distance measurements derived from a 10 Hz-GPS relative to Laser during linear acceleration and decelerations at low intensity over 30m (Panel – A), Moderate Intensity over 30m (Panel-B), high intensity over 50m (Panel–C) sub-maximal 20 m shuttle run with 180^{o} change of direction (Panel-D) high intensity 20 m shuttle run with 180^{o} change of direction (Panel-E).

Table 1. Least squares regression analysis (R) of the slopes, intercepts, standard error of estimate (SEE) and 95% confidence interval (95% CI) between Laser and 10 Hz-GPS running speed ($m·s^{-1}$) and metabolic power ($W·kg^{-1}$) in varsity soccer players.

Running Speed.	10 Hz -Laser ($m·s^{-1}$) Mean ±SD	10 Hz-GPS ($m·s^{-1}$) Mean ± SD	Laser –GPS Δ ($m·s^{-1}$) Mean ± SD	% Diff	Slope	Intercept	SEE	R
Low Intensity	2.15 ± 0.6	2.10 ± 0.60	0.062 ± 0.01	-2.9	0.93 (0.75-1.31)	0.14 (-0.138 - 0.51)	0.018	0.98
Moderate Intensity	3.29 ± 1.3	3.20 ± 1.3	0.095 ± 0.05	-2.9	1.11 (0.88-1.34)	0.269 (-1.01 - 0.48)	0.052	0.96
50 m linear Acc/Dec.	3.98 ± 1.8	3.86 ± 1.81	0.11 ± 0.07	-2.9	0.88 (0.73-1.04)	0.560 (-0.04 - 1.16)	0.067	0.97
20 MST linear with 180^0 COD	3.40 ± 1.4	3.31 ± 1.4	0.08 ± 0.07	-2.5	0.80 (0.36-1.25)	0.729 (-0.75- 2.21)	0.074	0.82
Metabolic Power 20 m sub-max ($W·kg^{-1}$)	23.26 ± 0.3	22.79 ± 0.3	0.47 ± 0.07	-2.1%	-	-	-	-
Metabolic Power 20m max sprint ($W·kg^{-1}$)	32.17 ± 2.5	31.84 ± 2.4	0.33 ± 0.11	-1.1%	.998 (0.96 -1.01)	.737(0.90 – 1.38)	0.239	0.99

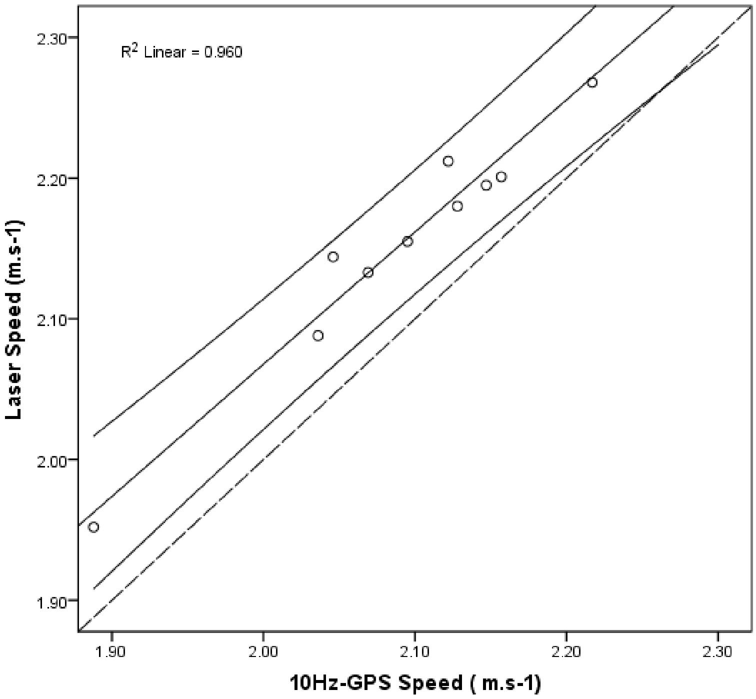


Figure 5. Least Squares regression analysis plot (R) of the slopes, intercepts, standard error of estimate (SEE) and 95% confidence interval (95% CI) between Laser and 10 Hz-GPS running speed ($m{\cdot}s^{-1}$) at low intensity in varsity soccer players. (Note the underestimation of speed as indicated by the points lying above the line of unity [broken line] indicating a fixed bias. The example illustrated suggests that its underestimates relative to the laser by a margin of -0.06 $m{\cdot}s^{-1}$, in conjunction with a small SEE 0.018 $m{\cdot}s^{-1}$.

Metabolic Power.

Metabolic power was derived for each 20, 30 and 50 m acceleration and deceleration run the mean values of laser derived relative to GPS derived metabolic power at different running speeds sub-maximal and high intensity where determined (Figure 6). Metabolic power ($W{\cdot}kg^{-1)}$ is presented in Table 1. Present data shows high degree of convergence between metabolic power estimates. Data indicted that 10 Hz-GPS relative to the Laser provided similar estimates of metabolic power of 22.79 ± 0.3 vs 23.26 ± 0.3 ($W{\cdot}kg^{-1}$) with a mean difference between system estimates of 0.47 ± 0.07 ($W{\cdot}kg^{-1}$) at sub-maximal speed. During high intensity running metabolic power estimates were assessed as 31.84 ± 2.4 vs 32.17 ± 2.5 ($W{\cdot}kg^{-1}$) for 10-Hz GPS and laser respectively with a mean difference 0.33 ± 0.11($W{\cdot}kg^{-1}$). Figure 6 presents the association between 10 Hz-GPS and laser derived metabolic power (Di

Prampero *et al.*, 2005). Figure 7 present the typical response of running speed and metabolic power determined by 10 Hz-GPS and laser (Di Prampero *et al.*, 2005).

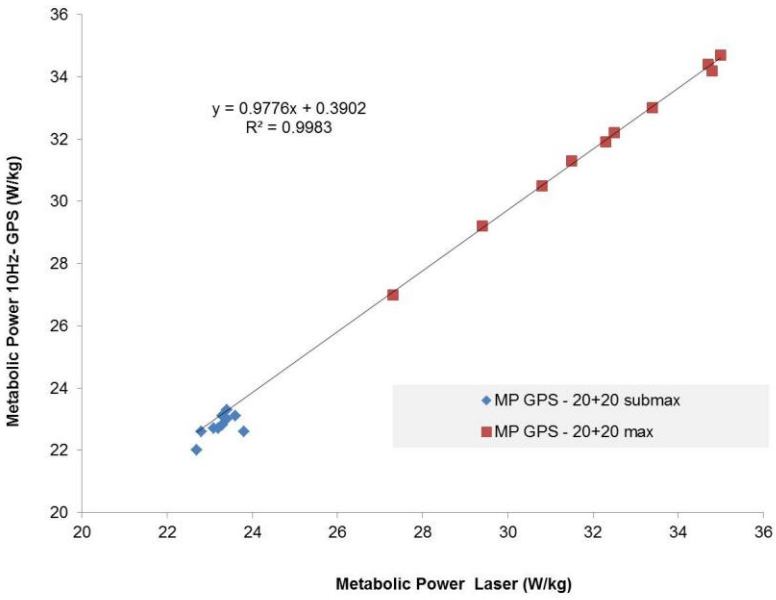


Figure 6. Regression analysis of typical 10 Hz-GPS to laser derived metabolic power estimates during linear acceleration and decelerations with 180^{o} change of direction over 40 m (20m + 20m shuttle run). Note maximal speed distribution reflects the heterogeneity of the population assessed and the small sample size assessed to date.

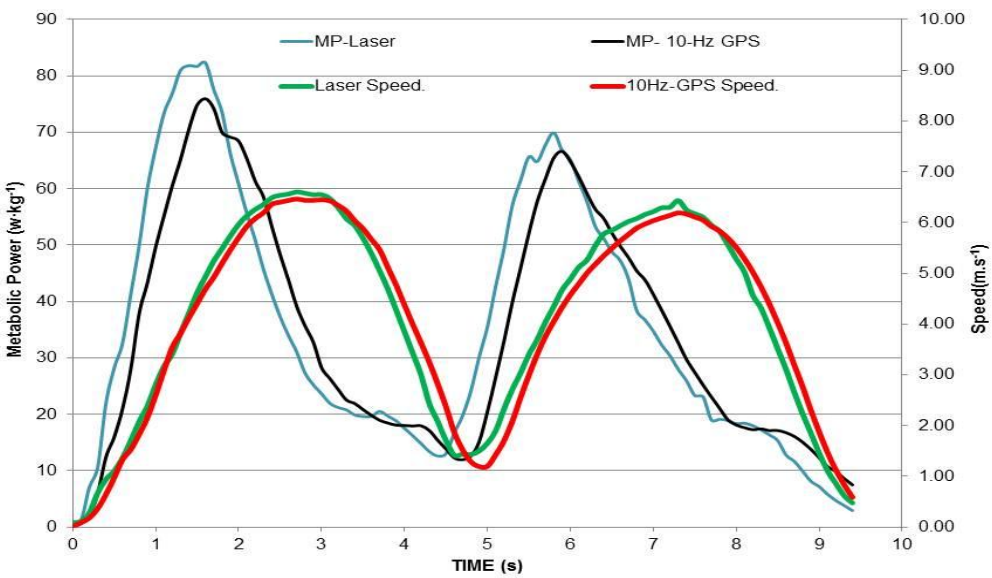


Figure 7. Comparison of metabolic power (W·kg^{-1}) derived from a 10 Hz-GPS to gold standard laser during linear acceleration and decelerations with 180^{o} over 40 m (~ 6.5 m·s^{-1}).

Discussion.

Di Salvo *et al*., (2010) and Gregson *et al*., (2010) reported that the ability to execute sprints over short distances repeatedly during football fare important in football performance. Petersen *et al*. (2009) have shown that these key football specific movements may be missed when recording at lower GPS sampling frequencies i.e. 1 Hz, however utilising a higher sampling rate of 5 Hz does allows for more accurate data representing short high speed movements (Jennings *et al*., 2010a; Portas *et al*., 2010). The preliminary findings in this report further support this general notion; doubling sampling rate from 5 Hz to 10 Hz improves the accuracy of running speed and distance travelled measurements. This finding is in line with the observation of others (Castellano *et al.*, 2011; Varley *et al.*, 2011). A critical threshold for GPS tracking technology resting at 10-Hz may therefore exist. In the present work the use of 4 Hz-GPS proved unworkable in our hands. A disassociation of the 4 Hz-GPS with the laser and 10 Hz-GPS ability to track acceleration, constant velocity and deceleration over short distances was apparent. This contrasts the typical responses seen with 10 Hz-GPS during the acceleration and declaration phases as indicated in Figure 4 where the 10 Hz-GPS and laser system importantly track acceleration and decelerations accurately. The error rates of less than 4% from laser derived criterion speed values when translated to a game specific context would most likely not be enough to affect assessment and classification of movement or metabolic cost during game specific activities. However it is important to note the presence of fixed bias indicates the 10Hz-GPS slightly underestimates running speed relative to the laser at all velocities. This finding is consistent with other reports from GPS systems sampling at lower frequency and may reflect the satellite offsets built into the systems.

Unlike Jennings *et al*. (2010a) who has indicated that as running speed increases the accuracy of running speed and distances measures declines present data indicate as speed increases the accuracy is maintained during linear and change of direction tasks with the 10 Hz- system. The maintenance of tracking accuracy with 10 Hz-GPS during shuttle running tasks with 180^{o} change of direction running is contrary to that noted by Portas *et al*., (2010) who suggests during football specific football specific movement patterns with tight turns (180^{0} turn) 5 Hz system are unable to resolve the task with sufficient accuracy. Current data indicate that with a 10 Hz sampling frequency shuttle run tasks at varying speeds with 180^{0}

change of direction provide for an underestimation, of running speed and distance which is <4%.

The ability to detect changes in acceleration and deceleration as well as distance ran is based on adequate GPS signal quality been received. In the present study to quantify the quality and accuracy of the GPS signal, we report the satellite lock and the Horizontal Dilution of Precision (HDOP) which can be considered the sum of all the errors that may impact upon GPS signal quality (Witte and Wilson, 2005). The main factors influencing HDOP are the number of visible satellites and their position in relation to the receiver unit (Williams and Morgan 2009). Values range from 1-50 with 1 indicating ideal scenarios were a satellite is locked directly overhead with others providing a systematic array spread equidistant around the horizon. Variation from this indicates increasing unreliability (Witte and Wilson, 2005). Satellite lock and HDOP is critical information that should be reported during the data collection process for all future work, any data collected with less than 5 satellites lock and a HDOP of greater than 2.5 should be considered inaccurate and should be avoided (Hewitt, Doran and Close, 2012; unpublished data LJMU Football Exchange). Present work indicates during linear acceleration and decelerations and non-linear soccer specific circuit an average satellite lock of 10.77 ± 0.85 and 10.60 ± 0.90 with an average HDOP of 0.89 ± 0.10 and 0.88 ± 0.08 respectively.

In the context of having shown that acceleration and deceleration can be mapped accurately with the 10-Hz GPS system. This part of the preliminary investigation compared the metabolic power required to perform soccer specific shuttle running patterns of differing intensities derived from GPS modelling versus Laser modelling of We further applied the methodology of energy cost modelling to use the running speed data to determine an estimate of metabolic power determined concurrently from the Laser and 10-Hz GPS systems (Minetti *et al.,* 2002; di Pampero *et al.,* 2005). Using 20 m shuttle runs at sub-maximal speeds with tight changes of direction we determined the metabolic cost derived from both system. Finding indicates a high degree of correlation in terms of metabolic cost estimates between both systems (Table 1). Additionally the system was able to differentiate sub-maximal from maximal running metabolic power estimates (Figure 6). Generally, the GPS relative to laser demonstrated an underestimation of metabolic power of approximately 0.47 ± 0.3 $W.kg^{-1}$ at sub-maximal running speed and 0.33 ± 0.1 $W.kg^{-1}$at high intensity.

Conclusions.

These preliminary reports indicate that an increased GPS sample frequency (rate) provides a valid means of assessing running speed during rapid acceleration and deceleration that occur during linear runs and runs with tight change of directions relative to a 100-Hz laser system. During the soccer specific circuit comprising short linear runs as well as tight and more gradual change of direction tasks the distance measured and running speed was acceptable. Predicated upon this preliminary sample analysis the following conclusion may initially be considered;

1. Associated with 10-Hz GPS some errors of running speed are apparent on the linear circuits equating to about 2-4%; there appears a fixed bias, which systematically underestimates running velocity and distance.
2. 10 Hz-Gps would appear to accurately track the path of movement and the angular changes occuring during a varietey of changes of direction tasks (CoD);
3. The calculation of metabolic power during sub-maximal and maximal runs with 180° change of direction COD indicate no unacceptable bias.

This study has been further updated in terms of sample population size and is reported in detail in the phase 2 final report

Study One. (Part B) :

Determination of metabolic cost of running on grass in elite Professional Soccer Players.

Background

Soccer match play activity is characterised by repeated bouts of high-intensity running superimposed upon an aerobic background (Bangsbo *et al.,* 2006). Rapid acceleration and deceleration charaterise the movement patterns utilised during match play and training (Di Salvo *et al.*, 2010). Previous attempts to assess metabolic cost in intermittent games play in particular soccer have provided estimates of the metabolic load applied during match play activities (Osgnach *et al.,* 2009). In developing this metabolic approach the influence of playing surface on the metabolic power required during soccer had not been directly considered in the original metabolic equation (Minetti *et al.*, 2002). The previous work i.e. Osgnach *et al.*, (2010) whilst innovative failed to undertake this necessary validation work and crucially failed to consider the impact playing surface has on the metabolic power required to perform soccer specific movement patterns. The equation applied by Osgnach *et al.*, (2009) was initially derived from the work of Minetti *et al.*, (2002) which itself was established from treadmill running, however the energy cost of running on grass is assumed to be ~29% higher than that required on a treadmill (Pinnington and Dawson, 2001). The incorporation of a coefficient of multiplication term (KT = 1.29) into previous work by Osgnach *et al.*, (2010) presents a critical issue that may impact accurate determination of the energy cost of football specific activities. This issue is predicated upon THE coefficient of multiplication term was developed by Pinnington and Dawson, (2001) in 13 recreational runners during a study to determine the energy cost of running on grass. This constant was subsequently applied by Di Prampero *et al.*, (2005) in his new energetic sprint approach [Equation 2]; this means that the group examined by Pinnington and Dawson, (2001) may not present a suitable model of running economy for elite soccer players due to differences in metabolic adaptations in energy systems and muscle metabolic pathways thus the coefficient of multiplication (KT = 1.29) added from running on treadmill (Minetti *et al,* 2002) [Equation 1] to running on grass during soccer specific activity (Osgnach *et al.*, 2009) [Equation 3] may not provide a valid representation of the metabolic constant and remedial error terms required for a representative or 'true metabolic cost' of running on grass. Incorporation of direct measures taken on UEFA standard playing surfaces grass will act to minimise estimation errors in metabolic cost due different playing surfaces. This investigation will determine the energy cost of running on grass (EC_r) in elite soccer players, which is a critical constant term for the new metabolic cost paradigm.

(Equation 1) $Cr_i = 155.4i^5 - 30.4i^4 - 43.3i^3 + 46.3i^2 + 19.5i + 3.6$

(Minetti *et al.,* 2002)

(Equation 2) $C_{sr} = 155.4ES^5 - 30.4ES^4 - 43.3i^3 + 46.3i^2 + 19.5i + 3.6$

(Di Prampero *et al.,* 2005)

applied on soccer (grass)

(Equation 3) $C_{sr} = [(155.4ES^5 - 30.4ES^4 - 43.3ES^3 + 46.3ES^2 + 19.5ES + 3.6)EM]1.29$

(Osgnach *et al.*, 2009)

Objectives:

3. **Determine the energy cost of running on a grass pitch conforming to FIFA 2 stars standards in elite soccer players.**

Methods.

Participants

Seventeen elite soccer national and international elite level player were recruited; their mean age, height and body mass were 27 ± 3 years, 1.77 ± 3 m and 75.9 ± 5.2 kg and VO_2 peak ~55.3 ± 3.7 mL·kg^{-1}· min^{-1} respectively. Liverpool John Moores University Research Ethics Committee approved the studies.

Experimental design and protocol

Participants initially underwent assessment of resting Oxygen uptake followed by incremental treadmill run to assess maximal oxygen uptake. Assessment of expired gas fraction and ventilation volume was facilitated by assessment with a portable breath-by-breath Cosmed K4b^2 gas analyser (Cosmed, Rome, Italy). On a second occasion each participant undertook a constant velocity run on a UEFA standard soccer pitch. All participants were required to run for 6 minutes at 10.29 km·h^{-1} on a UEFA standard soccer field. The path of each run was marked with cones every 20 meters with each participant regulating running speed by following a bleep emitted every 7 seconds so that each 20 m cone was passed as the signal was emitted in order to maintain constant speed. Steady state oxygen uptake was defined as the mean of the last three minutes of the constant speed run. The calculation of the ratio between the energy expenditure and the nominal speed:

$$ECr = VO_2/v$$

where VO_2 is the net value (measured minus resting) assuming an energy equivalent of 20.9 KJ/L O_2 (corresponding to a non-protein respiratory exchange ratio of 0.96), and v is the sub-maximal speed below the anaerobic threshold. One MET was set by convention to 3.5 millilitres of oxygen per minute for every kilogram of body mass. The ECr above resting total energy was then divided by the subject's body weight and distance covered in the concerned time, to express ECr as J·kg^{-1}·m^{-1}

Discussion.

The main finding of the present study is that in elite professional soccer players, the EC_r of running on a UEFA standard natural grass football surface was 4.67 $J{\cdot}kg^{-1}{\cdot}m^{-1}$. Sassi *et al.,* (2011) report in a group of amateur soccer players a value of 4.2 $J{\cdot}kg^{-1}{\cdot}m^{-1}$, which is lower than present findings. Similarly, Pinnington and Dawson, (2001) and Rodio *et al.,* (2004) report values of 4.56 $J{\cdot}kg^{-1}{\cdot}m^{-1}$ and 5.7 $J{\cdot}kg^{-1}{\cdot}m^{-1}$ for natural grass in recreational runners and sedentary males. Assessment of the EC_r of running on grass has provided diverse estimates of EC_r which seem to vary as a function of the shock absorption characteristics and compliance of the surface as well as the population assessed. Our data is clearly contrary to Sassi *et al.,* (2011) suggestions that EC_r should not exceed 4.5 $J{\cdot}kg^{-1}{\cdot}m^{-1}$ differences may reside with the elite nature of the current group, the application of a more compliant i.e. standardized soccer surface in addition to wearing football boots for test performance. The confluence of such issues may alter running kinematics such that the EC_r requirements of running are elevated. Interestingly, recent unpublished data indicates that EC_r may vary as a function of training specificity change in elite players. The EC_r of running in elite players increased by 13.5 % from 4.31 ± 0.38 $J{\cdot}kg^{-1}{\cdot}m^{-1}$ pre season to 5.12 ± 0.43 $J{\cdot}kg^{-1}{\cdot}m^{-1}$ mid competitive season (December). It is therefore important that further assessments of changes in ECr with training in these elite populations are quantified.

Conclusion.

The present findings indicate that elite soccer players running on international standard pitch show an elevation in energy cost of running. This elevation exceeds the constants previously applied in the energy cost model of Minetti *et al.*, (2002) and Osgnach et al., (2009). This new data has facilitated the development of a new Beta EC*r* equation for the determination of metabolic power in soccer players. The further validation and implementation will be presented in the final report.

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