Measured and estimated energy cost of constant and shuttle running in football players

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Abstract

Players in team sports like football often make acceleration and deceleration movements, which are more energetically demanding than running at constant speed. The first aim of the present study was to estimate this difference in associated energy cost. To this end, we compared the actual energy cost of shuttle running to that of running at constant speed. In addition, since measuring oxygen consumption is not feasible during football, the study's second aim was to determine the validity of an indirect approach to estimate energy cost provided by di Prampero et al. (2005) using time-motion data obtained from a tracking system as input. Fourteen male amateur football players performed aerobic constant and continuous shuttle running at six different speeds (range 7.5–10.0 km·h⁻¹) on artificial turf. Measured energy cost was compared to the energy cost estimated with di Prampero's (2005) approach using data from a Local Position Measurement (LPM) system as input. As expected, measured energy cost was significantly higher (~30–50%) for shuttle running than for constant running (P < .001) and this difference increased with speed. For constant running, estimated energy cost was significantly higher (6 to 11%) than measured energy cost, while for shuttle running estimated energy cost was significantly lower (-13 to -16%) than measured energy cost. In conclusion, shuttle running raised the player's energy cost of running compared to constant running at the same average speed. Furthermore, although actual energy cost of constant running was significantly overestimated by di Prampero's approach using LPM data as input, actual energy cost of shuttle running was significantly underestimated.
Introduction

In the past decade, there has been an increased interest in the estimation of workload and energy expenditure of football activities (Carling et al., 2008). Accurate assessment of workload in football training and matches is important in optimizing physical preparation and assessing physical performance of football players (Gaudino et al., 2013; Iaia, Rampinini, & Bangsbo, 2009). Especially in current (international) elite football, with high physical match demands both in frequency and intensity (Wallace & Norton, 2014), coaches and practitioners attempt to optimally load their players to improve or at least maintain player’s physical fitness without getting injured (Carling et al., 2008; Gabbett & Ullah, 2012; Gaudino et al., 2013).

Traditional approaches assessing internal workload (using measures of heart rate, blood lactate and oxygen consumption) (Borresen & Lambert, 2009) are limited reflecting the complex intermittent nature of football and other team sports due to practical and/or methodological reasons (Osgnach et al., 2010). Although these traditional approaches can provide useful estimates of the total energy expenditure of matches, the calculations of instantaneous workload variables over shorter periods are limited.

Newer approaches, which have recently become available because of technological advances (GPS and video and electronic tracking) (Carling et al., 2008), usually focus on the external workload of football. Time-motion data provide detailed (instantaneous) information about distance and speed-related variables of individual players. Lately, it has been argued by several researchers (e.g. Akenhead et al., 2013; Osgnach et al., 2010; Serpiello, McKenna, Stepto, Bishop, & Aughey, 2011; Silva, Magalhaes, Ascensao, Seabra, & Rebelo, 2013; Varley & Aughey, 2013; Varley et al., 2012) that the inclusion of accelerations and decelerations is needed to account for the extra energy spent during fast direction changes, which are common in football and other team sports. However, although most time-motion variables provide a certain indication of workload (e.g. sprint distance) they do not directly represent the energy expenditure or metabolic power of activities.

Recently, an approach introduced by di Prampero et al. (2005) and adapted for football by Osgnach et al. (2010) has made it possible to estimate instantaneous metabolic power of (accelerated and decelerated) running in football by use of time-motion data. The approach has been used by Osgnach et al. (2010) in combination with video tracking and by Gaudino et al. (2013) in combination with GPS tracking to estimate the energy expenditure of football match play and training, respectively. Buglione and di Prampero (2013) also estimated the energy cost of (highly anaerobic) shuttle running using the algorithm in combination with time-motion data of high speed cameras. They compared the energy estimates to energy measurements of a similar but different subject subgroup and concluded that the estimated energy cost was significantly lower than the measured energy cost. To date, however, no study has directly compared di Prampero’s approach to a direct measure of (aerobic) energy expenditure for running involving accelerations and decelerations, such as shuttle running.

Despite the increased interest in acceleration and deceleration during running and a
wealth of studies on team sport specific shuttle run tests to assess aerobic fitness (Bangsbo, Iaia, & Krustrup, 2008), only few studies have tried to measure the energy expenditure of accelerated and decelerated running, mainly because of difficulties to achieve steady state exercise (Buglione & di Prampero, 2013). The latter is important because only during steady state exercise energy consumption can be directly obtained from oxygen consumption. Buglione and di Prampero (2013) used a mixed approach to obtain the energy expenditure of shuttle running, combining aerobic measurements with anaerobic energy estimates, because the intensity of their exercise was above the anaerobic threshold. Other studies compared intermittent shuttle running to intermittent in-line running; however, because of relatively high intensities an anaerobic contribution was evident and the extra energy needed for accelerating, turning and decelerating remained unclear (Buchheit, Bishop, Haydar, Nakamura, & Ahmaidi, 2010; Buchheit, Haydar, Hader, Ufland, & Ahmaidi, 2011; Zadro, Sepulcri, Lazzer, Fregolent, & Zamparo, 2011). Hatamoto et al. (2013) studied the energy cost of continuous 180° turning on rather short distances (3–9 m) and low average speeds (4.3–5.4 km·h⁻¹). To our knowledge, the energy expenditure of accelerated and decelerated running for aerobic, continuous submaximal shuttle running has not yet been investigated.

Therefore, the first aim of the study was to assess the additional energy cost of 180° changes of direction during aerobic continuous (10 m) shuttle running compared to constant running. It was hypothesized that the energy cost of shuttle running is higher than for constant running at the same average speed and that the difference between constant and shuttle running increases with speed. Because in practice direct measurement of energy cost is not feasible, the study's second aim was to compare the estimation of energy expenditure by di Prampero’s approach using time-motion data collected with a recently validated tracking system (Stevens et al., 2014) to measured energy expenditure assessed from breath-by-breath respiration during both constant and shuttle running. On the basis of the aforementioned studies (Buglione & di Prampero, 2013; Hatamoto et al., 2013) it was hypothesized that the actual energy cost of constant running is similar to the estimated energy cost, whereas the actual energy cost of shuttle running will be underestimated by di Prampero’s approach.

Method

Subjects

Fourteen healthy amateur football players, who had one match and two to three trainings sessions a week, participated in this study. Subjects had a mean age of 23 ± 2 years (mean ± SD), a height of 183 ± 5 cm, a mean body mass of 78 ± 8 kg and a mean VO₂max of 54 ± 6 mL·kg⁻¹·min⁻¹. They were informed about the experimental protocol before providing their written consent. The study was approved by the Ethics Committee Human Movement Sciences of VU University Amsterdam.
Procedures and experimental design

All measurements were conducted on a ‘FIFA Two Stars’ artificial turf pitch. The experimental protocol consisted of two sessions, separated by at least 30 min. In the first session participants performed 10-m continuous shuttle runs, starting with an average speed of 7.5 km·h⁻¹. Speed was increased by 0.5 km·h⁻¹ every 3 min, until the last stage of running at 10.0 km·h⁻¹ (total duration of 18 min). In the second session participants followed the same protocol for constant running (without abrupt changes of direction), immediately followed by an incremental protocol (increase of 1.0 km·h⁻¹ each minute) until exhaustion to determine maximal oxygen consumption (VO₂max). Constant running was performed on a 160-m track marked with cones; shuttle running turning lines were marked with two cones (1 m width). Running speed was paced by an audio signal; participants had to be at the next cone (constant run) or on the line (shuttle run) at the beep. In this way average speed at each stage would be similar between runs. During the shuttle runs participants had to alternate turning foot and turned with at least one foot on the line.

Gas exchange measurement

Expired air was analysed breath-by-breath using a portable gas analyser (K4b², Cosmed Srl, Rome, Italy). Before the start of each session the gas analyser was calibrated with inspired air (20.93% O₂ and 0.03% CO₂) and a reference gas mixture (16.04% O₂ and 5.01% CO₂); the volume transducer was calibrated using a 3-L syringe. During the tests the gas analyser was placed in a harness on the upper body of the participant. VO₂ data were averaged over 30-s intervals.

Physiological variables

Oxygen consumption (mL·kg⁻¹·min⁻¹) was determined between 1.5 and 2.5 min of every 3-min stage. To obtain the measured energy cost of running first the resting VO₂ (assumed to be 3.6 mL·kg⁻¹·min⁻¹) (McArdle, Katch, & Katch, 2007) was subtracted from measured VO₂ after which the value in millilitres of oxygen per kilogram per minute (mL O₂·kg⁻¹·min⁻¹) was converted to joules per kilogram per minute (J·kg⁻¹·min⁻¹) via the metabolic equivalent of the respiratory exchange ratio (RER) of the respective stage. Finally, the energy cost per minute was divided by the actual running speed, obtained from actual distance covered as explained in the next session, and expressed in joules per kilogram per meter (J·kg⁻¹·m⁻¹). VO₂max was defined as the highest average value of a 30-s window in the incremental test and expressed in millilitres of oxygen per kilogram per minute (mL O₂·kg⁻¹·min⁻¹).

Time-motion measurement

Time-motion data were measured with a local position measurement (LPM) system (10 base stations; version 05.30R; Inmotiotec GmbH, Regau, Austria) positioned around the pitch. LPM
data sampled at 500 Hz were filtered (integrated ‘weighted Gaussian average’ filter set at 85% as recommended by the manufacturer) and resampled at 10 Hz by Inmotio software (version 2.6.9; Inmootec GmbH). The LPM system has recently been validated for football-specific movements and provides acceptable measures of speed, acceleration and deceleration for constant running and 180° turning (Stevens et al., 2014).

For the shuttle running condition, the actual distance covered by the participant’s approximated centre of mass was determined as follows. First, from previous research we know that during submaximal shuttle running distance covered is underestimated by LPM by about 5% (Stevens et al., 2014). To correct for this, the distance assessed by LPM during shuttle running was multiplied by 1.05. Furthermore, during 180° turning the body does not remain vertical, because subjects lean inward towards the other line. Hence, the distance travelled by the centre of mass is less than distance travelled by the feet (10 m), but greater than distance obtained with LPM at the shoulders. To accommodate for this, we modelled the human body as one rigid segment with the centre of mass at 56% of participant’s length and shoulder height at 86% of participant’s length, which located centre of mass at 65% of shoulder height (McConville, Churchill, Kaleps, Clauser, & Cuzzi, 1980). The distance covered by the centre of mass can then be calculated as estimated shoulder distance plus 35% of the difference between nominal distance (travelled by the feet) and estimated shoulder distance. Actual shuttle distance and shuttle speed are shown in Table 3.1.

Estimated energy cost using di Prampero’s approach

Di Prampero et al. (2005) suggested that accelerated running on flat terrain is biomechanically equivalent to uphill running at constant speed. On the basis of the previous study of Minetti et al. (2002) investigating the energy cost of uphill and downhill running they proposed an algorithm to estimate the instantaneous energy cost of accelerated running, which was extended by Osgnach et al. (2010) with a terrain factor for usage in team sports [Eq. 1].

$$C = (155.4 \cdot ES^5 - 30.4 \cdot ES^4 + 43.3 \cdot ES^3 + 463 \cdot ES^2 + 19.5 \cdot ES + 3.6) \cdot EM \cdot KT \tag{1}$$

in which $C$ is the energy cost of accelerated running on the specific terrain (in J·kg⁻¹·m⁻¹) calculated with di Prampero’s approach; ES is the equivalent slope [ES = tan(90-arctan $g/a_f$); $g$ = acceleration due to gravity, $a_f$ = forward acceleration]; 3.6 is the energy cost of running on flat terrain at constant speed; EM is the equivalent body mass: EM = $(a_f^2/g^2+1)^{0.5}$; and KT is a terrain constant [1.29 in the study of Osgnach et al. (2010)]. Because recent research shows that running on ‘FIFA Two Stars’ artificial turf would be around 10% more costly than running on hard surface, the KT used in the present study will be 1.1 (Sassi et al., 2011). The value of 3.6 will be replaced by 4.15, because the latter is the average value measured for the participants in the present study during constant running at 9.5 and 10.0 km·h⁻¹ after correction for terrain (KT = 1.1). Therefore,
the following equation will be used:

\[ C = (155.4 \cdot ES^3 - 30.4 \cdot ES^4 - 43.3 \cdot ES^5 + 46.3 \cdot ES^6 + 19.5 \cdot ES + 4.15) \cdot EM \cdot KT \] \[2\]

Using time-motion data from LPM, the metabolic power \( P (W \cdot kg^{-1}) \) can then be calculated by multiplying \( C (J \cdot kg^{-1} \cdot m^{-1}) \) with the instantaneous (i.e. obtained every 0.1 s) speed \( v (m \cdot s^{-1}) \):

\[ P = C \cdot v \] \[3\]

Finally, the average \( P \) between 1.5 and 2.5 min of each stage was divided by the actual running speed of each stage and expressed in joules per kilogram per meter \( (J \cdot kg^{-1} \cdot m^{-1}) \), representing the estimated energy cost.

**Statistical analysis**

All results are presented as means ± SD. General estimating equations (GEE) were performed to analyse the main effect of running mode (constant vs shuttle) for measured energy cost and main effect of method (measured vs estimated energy cost) for both constant and shuttle running. Additional GEE’s were performed including speed and the interaction effect (speed vs running mode or speed vs method) in the model. All analyses were performed in IBM SPSS Statistics for Windows (Version 21.0). Statistical significance was set at \( P \leq .05 \).

![Figure 3.1. Respiratory exchange ratio (RER) for constant running (circles) and shuttle running (triangles) as a function of average speed.](image)
Results

\( \dot{V}O_2 \) reached steady state values between 1.5 and 2.5 min, since the paired delta \( \dot{V}O_2 \) values between the fifth (2–2.5 min) and fourth 30-s block (1.5–2.5 min) were not significantly different from zero (mean of stages across all subjects) during shuttle running (0.3 ± 0.9%) and constant running (0.2 ± 1.0%). Moreover, RER remained below 1.0 in almost all measurements, indicating a predominantly aerobic metabolic contribution, except for six and eight participants in the two highest shuttle-running speeds (Fig. 3.1).

Measured and estimated energy costs for constant and shuttle running are shown in Figure 3.2 and Table 3.1. Measured energy cost was significantly higher for shuttle running than for constant running (main effect = 1.72; 95% confidence interval [CI] = 1.57–1.87, \( P < .001 \)) and the difference between the two running modes increased with speed (interaction effect = 1.42 \times \text{speed}; 95% CI = 1.03–1.81, \( P < .001 \)). For constant running, estimated energy cost was significantly higher (6–11%) than measured energy cost (main effect = 0.34; 95% CI = 0.20–0.48, \( P < .001 \)). For shuttle running, estimated energy cost was significantly lower (-13 to -16%) than measured energy cost (main effect = -0.94; 95% CI = -1.14 to -0.75, \( P < .001 \)). A significant interaction between method (measured or estimated) and running speed was found for both constant (interaction effect = -0.28 \times \text{speed}; 95% CI -0.47 to -0.10, \( P = 0.002 \)) and shuttle running (interaction effect = -0.44 \times \text{speed}; 95% CI -0.76 to -0.12, \( P = 0.006 \)). GEE are described by “\( y = 2.19 + 1.78 \times \text{speed} \)” for measured energy cost of shuttle running and by “\( y = 2.25 + 1.34 \times \text{speed} \)” for estimated energy cost of shuttle running.

![Figure 3.2](image-url)
**Discussion**

The present study was conducted to assess the additional energy cost of 180° changes of direction during aerobic continuous shuttle running compared to running at constant speed, and to compare these measured values of energy cost to values as estimated by di Prampero's approach using time-motion data obtained from (a commercially available) LPM system as input. We found that the extra energy cost needed for 10-m shuttle running at speeds between 7.5 and 10.0 km·h<sup>−1</sup> is 1.3–1.5 times higher compared to constant running at the same average speed and that the difference between the two running modes becomes larger at higher speeds. Moreover, we found that for constant running the actual energy cost is overestimated by di Prampero's approach using LPM data as input, whereas for shuttle running the actual energy cost is underestimated.

**Measured energy cost of shuttle running**

Previous studies either measured the energy cost of shuttle running at high speeds with a clear anaerobic metabolic contribution (Buchheit, Bishop, et al., 2010; Buchheit et al., 2011; Buglione & di Prampero, 2013; Zadro et al., 2011) or at rather low speeds (Hatamoto et al., 2013). The present study aimed to measure the energy cost of predominantly aerobic (RER < 1.0) shuttle running by means of oxygen consumption. Our results indicated that the energy cost of continuous 10-m shuttle running varied between 5.7 and 6.7 J·kg<sup>−1</sup>·m<sup>−1</sup> for speeds from 2.0 to 2.6 m·s<sup>−1</sup>. This is in line with the results of studies measuring 10-m shuttle running at slightly higher and lower speeds: Buglione and di Prampero (2013) measured 6.9 J·kg<sup>−1</sup>·m<sup>−1</sup> at 2.8 m·s<sup>−1</sup> and data calculated from the equation provided by Hatamoto et al. (2013) using nine turns per minute resulted in a value of 5.2 J·kg<sup>−1</sup>·m<sup>−1</sup> at 1.5 m·s<sup>−1</sup> (the latter calculated from VO<sub>2</sub> using 20.9 J·mL O<sub>2</sub>·s<sup>−1</sup>). Moreover, in our study the energy cost of shuttle running increased linearly with speed, indicating that running economy (in mL O<sub>2</sub>·m<sup>−1</sup>) decreased linearly with speed. This is in contrast with the results of Buchheit et al. (2011), who found no speed dependency of running economy for (20-m) shuttle running. It could well be that the shorter (10-m) shuttles in our study elevated the metabolic demand and therefore amplified the relationship between speed and energy cost.
of shuttle running. A decreased running economy of shuttle running at higher speeds can be related to the fact that at higher speeds the number of necessary turns increase and the cost of every turn, including deceleration and acceleration, is higher at higher speeds (Hatamoto et al., 2013). It remains unclear whether the linearity of energy cost with speed in our study holds at higher intensities (RER > 1.0), because both exercise at high intensity and fatigue have been found to decrease (muscle) efficiency and therewith energy cost may increase in a non-linear manner (Bangsbo, Krstrup, Gonzalez-Alonso, & Saltin, 2001; Jones et al., 2011).

The present study measured the energy cost of submaximal aerobic shuttle running. In football training various drills, such as small-sided games, also involve continuous accelerations and decelerations. Although in football the anaerobic energy cost can be high at certain periods of the game (Bangsbo, Mohr, & Krstrup, 2006), aerobic metabolism predominates during football and plays an important role during both constant running as well as accelerated and decelerated running (Buchheit et al., 2011; Reilly, 1997). Participants spent more time in high acceleration and deceleration zones (above 1.5, 2.5 and 3.5 m·s⁻²) during the aerobic shuttle running activity of the current study than football players during high intensity 6v6 small-sided games (unpublished data), indicating that the measured aerobic shuttle running activity in the current study is relevant even for high-intensity football activity.

*Estimated energy cost of constant running*

The present study is the first to directly compare measured energy cost of constant and shuttle running with the energy cost as estimated by di Prampero’s approach using data from a commercially available tracking system. The energy cost of constant running was overestimated by approximately 8% using di Prampero’s approach. This can be explained by the fact that, during (non-treadmill) constant running the speed of a person is never perfectly constant. The measured energy cost for “constant” running in this study, on average 4.15 J·kg⁻¹·m⁻¹, includes the energy cost of actual small accelerations and decelerations of the participant. In di Prampero’s equation extra energy cost is calculated for these accelerations and decelerations on top of the ‘constant’ 4.15 J·kg⁻¹·m⁻¹. In addition, LPM measures falsely small fluctuations in speed during constant running when compared to a gold standard (Stevens et al., 2014). Moreover, these extra accelerations and decelerations can partly account for the overestimation of the energy cost of constant running as estimated using di Prampero’s equation. Furthermore, the difference between measured and estimated energy cost declined significantly with speed. This can possibly be explained by our exclusion of the resting metabolism in the calculation of energy cost, because the relative contribution of resting metabolism increases with a decrease of speed.

*Estimated energy cost of shuttle running*

The energy cost of shuttle running was underestimated by about 15% by the ‘di Prampero’ approach in combination with the LPM time-motion data. There are three possible explanations
for this underestimation. First, for movements including 180° turning, LPM underestimates distance by about 5% (Stevens et al., 2014). If we correct for this by multiplying the estimated energy cost with 1.05, the underestimation of energy cost would decrease from 15% to 10%. Second, part of the underestimation could be due to the ‘di Prampero’ equation, because the algorithm is based on measurements of experienced (endurance) mountain runners. The energy cost during running at constant speed are known to be lower in experienced runners compared to professional and recreational football players (Sassi et al., 2011). During uphill and downhill running (set equal to accelerated and decelerated running at an equivalent slope) the differences in energy cost may increase between experiences mountain runners and football players (Minetti et al., 2002). If the equation would account for this increased energy cost, the underestimation of actual energy cost would possibly decrease below 10%. Third, as already discussed in detail by di Prampero et al. (2005), the equation for calculating the instantaneous energy cost of running has several assumptions leading to uncertainties in applicability of the equation at especially high speeds and accelerations. However, the shuttle running activity in our study was largely aerobic exercise and did not include maximal accelerations and decelerations. Therefore, the consequences of these assumptions in the equation are expected to be limited for the activities in the present study.

Although the above explanations remain speculative, it is important to note that others using the di Prampero’s equation have found even larger underestimations of energy cost. The underestimation of energy cost of shuttle running in our study (~15% at 2.0 to 2.6 m·s⁻¹) was lower as found by Buglione and di Prampero (2013) (~30% at 4.0 m·s⁻¹). In addition to differences in protocol, intensity of exercise and the method used to obtain the measured energy cost, the differences between studies could be due to the different methods used to obtain the time-motion data used as input for di Prampero’s equation. It is important to realize that factors such as validity of the tracking technology used, sample and export frequency, and filtering of the signals influence the time-motion data to an important extent and therewith influence the outcome of di Prampero’s equation. Although there may have been small underestimation of distance, speed and acceleration in the present study, it is important to note that accuracy will decline even further when using low sampled GPS (time-motion) data as input (Portas et al., 2010), especially when turns would be executed at higher intensities. In contrast, improvement of current tracking technology may help to further increase accuracy of metabolic power estimation in daily practice.

**Practical implications**

Trainers and practitioners often use football-specific exercises during training, such as small-sided games, since these exercises have the advantage that physical, technical and/or tactical skills are trained simultaneously. More accurate estimations of energy cost and metabolic power during both these training exercises and matches can improve planning of daily and weekly training load. In addition, more accurate estimations of energy cost can help to optimize
dietary intake. The estimated metabolic power and energy cost by the di Prampero's approach in combination with LPM time-motion data are possibly better indicators of training intensity and training load than workload variables based on distance covered. It is not clear yet whether and to which extent it is possible to compare the energy cost and metabolic power between different running activities. Comparison of estimates of energy cost and metabolic power might be possible within players performing the same activity, for example to detect fatigue. However, practitioners should be careful to make comparisons between players with different playing positions and therefore different movement characteristics.

**Conclusions**

Compared to constant running, aerobic continuous 10-m shuttle running increases energy cost up to 50% at 2.6 m·s\(^{-1}\) and probably even more at higher speeds. Di Prampero’s approach in combination with LPM time-motion data partly accounts for the extra energy needed for accelerations and decelerations in comparison to estimating energy cost of running based solely on distance covered. However, the total energy costs are probably still somewhat underestimated.