Title: Energy expenditure, metabolic power and high speed activity during linear and multi-directional running

Abstract

Objectives: The purpose of the study was to compare measures of energy expenditure derived from indirect calorimetry and micro-technology, as well as high power and high speed activity during linear and multi-directional running.

Design: Repeated measures

Methods: Twelve university standard team sport players completed a linear and multi-directional running condition. Estimated energy expenditure, as well as time at high speed (> 14.4 $km{\cdot}h^{-1}$) and high power (> 20 $W{\cdot}kg^{-1}$) were quantified using a 10 Hz micro-technology device and compared with energy expenditure derived from indirect calorimetry.

Results: Measured energy expenditure was higher during the multi-directional condition (9.0 ± 2.0 *cf.* 5.9 ± 1.4 $kcal{\cdot}min^{-1}$), whereas estimated energy expenditure was higher during the linear condition (8.7 ± 2.1 *cf*. 6.5 ± 1.5 $kcal{\cdot}min^{-1}$). Whilst measures of energy expenditure were strongly related ($r > 0.89$, $p < 0.001$), metabolic power underestimated energy expenditure by 52% (95% LoA: 20-93%) and 34% (95% LoA: 12-59%) during the multi-directional and linear condition, respectively. Time at high power was 41% (95% LoA: 4-92%) greater than time at high speed during the multi-directional condition, whereas time at high power was 5% (95% LoA: -17-9%) lower than time at high speed during the linear condition.

Conclusions: Estimated energy expenditure and time at high metabolic power can reflect changes in internal load. However, micro-technology cannot be used to determine the energy cost of intermittent running.

Key words: GPS, team sports, physical demands, internal load, acceleration

Introduction

Assessing the external load of team sports, such as relative distance and distance at high speed,[1] has become common practice during training and match-play. This information provides useful guidelines for practitioners when designing match-specific training programmes for individual positions. Furthermore, daily monitoring of training load allows practitioners to alter training volume and intensity to promote training adaptation.[2] However, the use of speed dependant time-motion data has been challenged,[3,4] because it does not account for the physiological load associated with accelerations that occur frequently (~650-1000) in team sports.[5,6] Consequently, the use of distance covered within a predefined speed threshold, such as high intensity running (>14.4 $km \cdot h^{-1}$),[7] is unlikely to accurately quantify an individual's external load.

The use of time-motion data to estimate energy expenditure of accelerated running[3] has the potential to address some of the practical and methodological issues associated with internal load measures. For example, heart rate recordings do not reflect the physiological demands of short duration, high intensity bouts[8] and blood lactate concentration largely depends on the activity undertaken in the 5 minutes before blood sampling.[9] Direct measurements of VO_2 are also unfeasible during training sessions or matches.[3] Therefore, estimations of energy expenditure are typically based on HR data, but is likely to overestimate measured values by ~15-20%.[8,10] Consequently, estimations of energy expenditure which assume that accelerative running on flat terrain is metabolically equivalent to constant speed running up an equivalent slope, have recently been advocated.[3] Energy expenditure is then multiplied by instantaneous speed to calculate metabolic power.[3] In contrast to traditional speed dependant zones, this approach accounts for the metabolic requirement of accelerations and decelerations, which can exceed the metabolic requirement of constant speed running.[11] Indeed, several authors have reported that the distance covered at a high metabolic intensity (>20 $W \cdot kg^{-1}$) during team sport activity was nearly two times the distance covered at high speed.[3,12,13] Accordingly, the quantification of high metabolic power might provide a more suitable reflection of the high intensity demands of team sport activity, which can be used to design match-specific training programmes.

Measurements of energy expenditure,[12-16] average metabolic power[12,13,17] and time at high metabolic power[13,15] derived from micro-technology have been documented in several team sports to provide a profile of match and training load. Such measurements have also been strongly correlated with determinants of aerobic fitness,[18] and therefore could provide a more detailed profile of player physical performance, as well as the metabolic demands of training and match-play. However, the metabolic power approach overestimated energy expenditure during constant speed running (~8%),[19] whereas underestimations in energy expenditure and metabolic power were observed during shuttle running (~15%)[19] and a soccer specific drill (~29%),[20] respectively. Changes in movement speed therefore appear to affect the agreement between estimated and measured energy expenditure. Whilst these studies question the validity of this approach, the potential effect of directional changes on estimated energy expenditure and metabolic power remains unclear. The metabolic power approach has the potential to estimate the energy expenditure of a directional change, as the acceleration phase accounts for >80% of the energy requirement of a change of direction.[21] Given the variation in accelerations and decelerations[6] and high speed running[22] performed during match-play, assessing how fluctuations in directional changes influence estimated energy expenditure and metabolic power warrants further investigation. Furthermore, the continuous[19] and low speed movement protocols[19,20] used are likely to under-represent the intense demands of team sport activity, and cannot assess the agreement between activities at high metabolic power and high speed. The use of 4 Hz global positioning systems (GPS) to assess validity,[20] which are unable to accurately detect instantaneous changes in speed,[23] also warrants further investigation using micro-technology with higher sampling frequencies.[19] Thus, the purpose of this study was to compare measurements of energy expenditure derived using micro-technology and indirect calorimetry during linear and multi-directional running. The agreement between high speed and high metabolic power movement demands was also evaluated. It was hypothesized that the energy expenditure of multi-directional running would be higher than linear running. Furthermore, the agreement between measures of energy expenditure as well as high speed and high power activities would increase with the number of directional changes performed.

Method

With approval from the Faculty of Life Sciences Research Ethics Committee at the University of Chester, seven male and five female participants (age: 20.8 ± 2.7 y; stature: 176.0 ± 12.0 cm; mass: 73.3 ± 12.8 kg; VO_{2peak}: 45.2 ± 2.9 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$), volunteered to participate in the study. All participants took part in university standard team sports (rugby, soccer, hockey or netball) and competed in a minimum of one match per month. Based on the physiological characteristics of amateur team sport athletes, participants were required to possess a maximal aerobic capacity > 40 or > 45 $ml{\cdot}kg^{-1}{\cdot}min^{-1}$ for females[24] and males,[25] respectively.

In a repeated measures design, participants completed three visits, separated by 3-7 days. On the first visit, participants completed a 20 m multi-stage fitness test which involved running along a 20 m indoor linear course at a progressively increasing speed (0.5 $km{\cdot}h^{-1}$) until volitional exhaustion. During the test participants wore a pre-calibrated portable gas analyser (Cosmed K4b2, Cosmrd S.r.I, Rome, Italy), so VO_{2peak} could be calculated as the highest VO_2 value recorded over a 30 s epoch. Thereafter participants were familiarized with the procedures for each condition.

In the two subsequent visits, participants completed the multi-directional and linear conditions in a randomised order. Both conditions comprised eight bouts of ~60 s of intermittent activities (jogging and sprinting) followed by 120 s of passive rest. In each condition participants covered 175 m per bout. The multi-directional condition comprised of three 10 m sprints forward interspersed with a 5 m jog backwards. Thereafter, a 2.5 m lateral jog to the right and left was performed, followed by two 10 m sprints forward interspersed with a 5 m jog backwards. This was followed by a 10 m jog forwards, a 2.5 m lateral jog to the right and left into a 35 m sprint forward. Finally, a 5 m diagonal jog, a 15 m jog forwards, a 5 m jog backwards followed by a 20 m sprint forwards was performed during each bout (Figure 1). Conversely, each bout of the linear condition involved 3 x 35 m sprints interspersed with 2 x 35 m jogs along a linear course.

***Insert Figure 1 around here*

The number of directional changes performed during the multi-directional and linear condition was 160 and 32, respectively. Both conditions were performed on an outdoor running track at a similar time of day (± 2 hours). Mean temperature and humidity during the multi-directional (19.0 ± 4.2ºC and 32.5 ± 6.2%) and linear (19.6 ± 4.2ºC and 31.6 ± 3.7%) conditions were similar ($p > 0.05$).

During both conditions, energy expenditure was calculated using indirect calorimetry (EE_{VO2}). Specifically, expired air was collected using a breath-by-breath portable gas analyser (Cosmed K4b2; Cosmed Slr, Rome, Italy), which was calibrated before each trial. Energy expenditure was calculated from VO_2 and carbon dioxide production (VCO_2) using the Weir equation.[26] VO_2 during the 120 s rest periods in each condition was included in the analysis to account for anaerobic contributions to total energy expenditure during exercise.[27] It should be acknowledged that micro-technology cannot quantify energy expenditure when an athlete is stationary.[28] However, the comparison of active bouts only would likely underestimate the energy expenditure of high intensity anaerobic activity and lack application to team sport activity that is intermittent in nature. Resting energy expenditure (assumed to be 1.29 $kcal \cdot min^{-1}$ for males and 1.03 $kcal \cdot min^{-1}$ for females)[29] was subtracted from total energy expenditure during each condition to provide net energy expenditure due to exercise (EE_{VO2}).

Estimated energy expenditure (EE_{GPS}) as well as time at high power and high speed were also calculated for both conditions using a MinimaxX GPS unit (Team 2.5, Catapult Innovations, Melbourne, Australia) sampling at 10 Hz. The same GPS device was used throughout the study for all participants to eliminate inter-device variability.[30] Data were subsequently downloaded and analysed (Sprint, Version 5.1, Catapult Sports, VIC, Australia) to calculate EE_{GPS}. Calculations were based on the equations provided by Osgnach and colleagues,[3] which assumes running on a flat terrain is energetically equivalent to uphill running at a constant speed. Time above the equivalent thresholds for high power and high speed (> 20 $W \cdot kg^{-1}$ *cf.* > 14.4 $km \cdot h^{-1}$)[3] were also calculated for comparison. The number of satellites detected by the GPS receiver and the horizontal dilution of precision was 13.7 ± 0.8 and 0.7 ± 0.1 respectively.

Descriptive statistics (mean ± SD) were calculated for all variables. A two-way analysis of variance (ANOVA) was used to determine differences between measurements of energy expenditure and time at high speed and high power during both conditions. Paired sample *t*-tests with a Bonferroni correction were used to follow up any significant effects. Agreement between measures was calculated using Pearson's correlation coefficient (*r*) with 95% confidence intervals (CI) and the 95% limits of agreement (LoA: bias ± 1.96 x SD_{diff}). Due to the presence of heteroscedasticity, ratio LoA were calculated by applying natural logarithmic transformations to the data. Where appropriate, the alpha level was set at $p < 0.05$.

Results

EE_{VO2} and EE_{GPS} during the multi-directional and linear conditions are presented in Table 1. Whilst measurements of energy expenditure between EE_{VO2} and EE_{GPS} were strongly related ($r > 0.89$, $p < 0.001$), they were significantly different ($F = 202.1$, $p < 0.001$). EE_{VO2} was systematically higher during the multi-directional (52%; 95% LoA 20-93%) and linear conditions (34%; 95% LoA 12-59%) when compared to EE_{GPS}.

** *Insert Table 1 around here*

Comparisons between time at high speed and high power during the multi-directional and linear conditions are presented in Table 2. Both measurements were strongly related, but significantly different ($F = 84.9$, $p < 0.001$). Time at high power was higher than time at high speed during the multi-directional condition (41%; 95% LoA 4-92%). Conversely, time at high power was lower than time at high speed during the linear condition (5%; 95% LoA -17%-9%). Furthermore, time at high speed was lower ($t = -10.3$, $p < 0.001$) and time at high power was higher ($t = 2.7$, $p < 0.05$) during the multi-directional condition compared to the linear condition.

** *Insert Table 2 around here*

Discussion

This study has demonstrated that regardless of movement type, energy expenditure derived using micro-technology systematically underestimates energy expenditure measured using indirect calorimetry, despite a strong association between the two measures. Furthermore, measurements of high power and high speed differed during linear and multi-directional running, suggesting the two measures reflect different external loads.

Whilst measurements of EE_{GPS} and EE_{VO2} were strongly related (r > 0.89), EE_{GPS} was underestimated in the multi-directional and linear conditions by ~52% and ~34%, respectively. Therefore, our data reaffirms observations that micro-technology underestimates energy expenditure during intermittent team sport activity.[14,19,20,28] However, this is in contrast to studies showing much smaller underestimations in estimated energy expenditure (~9.4%).[16] These differences are possibly explained by the use of regression equations based on oxygen uptake and accelerometer data during a maximal test to estimate energy expenditure,[16] which do not account for elevations in energy expenditure associated with excess post-exercise oxygen consumption during intermittent activity.[31] Accordingly, the use of varied criterion measures of energy expenditure, and the measurement of energy expenditure during static rest periods appears to affect the agreement with estimated energy expenditure derived from micro-technology. Furthermore, energy expenditure derived from micro-technology should not be used to determine the energy requirement of intermittent exercise.

The underestimation of energy expenditure was expectedly higher during the multi-directional condition, which might be because of the increase in aerobic[31] and anaerobic[11] metabolism associated with more directional changes (160 *cf.* 32). As the metabolic power approach is based on linear running,[33] the additional energy requirement associated with directional changes might not be accounted for, despite the inclusion of acceleration and deceleration actions within the energy expenditure calculation. Indeed, Stevens et al.[19] reported metabolic power derived energy expenditure was overestimated (6 – 11%) during constant running, whereas underestimations of 13-16% were observed during shuttle running with directional change. Furthermore, the inclusion of backwards and lateral movement in the multi-directional condition might also explain the greater underestimation in EE_{GPS} compared with EE_{VO2}. A greater VO_2 during backwards[34,35] and lateral[34] running, compared to forward running at the same speed has been observed indicating such activities are associated with a greater energy expenditure. Yet, the metabolic power approach is based on forward running,[3] and potentially cannot account for the additional energy requirement of lateral and backwards movement, which reduces the agreement between the two measures. Collectively, these data suggest the agreement between EE_{VO2} and EE_{GPS} is reduced during running with an increased number of directional changes as well as backwards and lateral movement.

Time at high power was ~41% greater than time at high speed during the multi-directional condition, which is consistent with previous reports in team sports (37 – 84%),[12,13] despite a strong agreement between the two measures ($r = 0.85$). Conversely, time at high power was ~5% lower than time at high speed during the linear condition. An improved agreement between time at high speed and high power during linear running, where participants performed fewer accelerations and decelerations, might be anticipated given that the metabolic cost of running at 14 $km \cdot h^{-1}$ is approximately 20 $W \cdot kg^{-1}$.[3] During multi-directional activity, a greater number of accelerations over short distances would limit a participant's ability to attain the high speed threshold.[12,13] Interestingly, time at high power and EE_{VO2} both demonstrated that the multi-directional condition imposed a greater load than the linear condition. Time at high speed did not follow this pattern, suggesting time at high power better reflects changes in internal load during multi-directional activity, when participants are unable to attain the threshold of high speed running. Accordingly, we reaffirm the use of high speed running categories underestimates the metabolic demands of team sport activity.[13] Moreover, the agreement between time at high speed and high power is dependent on the number of acceleration efforts performed, suggesting these two measures represent different external loads.

Whilst we suggest metabolic power is useful for quantifying running load, this study is not without limitations. The comparison of indirect calorimetry inclusive of static rest periods with micro-technology, which cannot quantify energy expenditure when an athlete is stationary,[28] is a potential limitation. However, we deemed it essential to measure energy expenditure during rest periods to quantify the anaerobic contribution to total energy expenditure using EPOC. Whilst this does not account for energy expenditure from rapid anaerobic glycolytic ATP turnover,[36] the lack of a reasonable estimate of anaerobic energy expenditure, such as EPOC, would increase the error in quantifying total energy expenditure.[27] Indeed, previous studies have utilised exercise protocols that were predominately aerobic,[19,20] hence it seemed necessary to implement a protocol that simulated the high intensity running demands typically observed in team sports. Finally, the use of one micro-technology device potentially limits the generalizability of the present findings, despite the use of the same energy expenditure calculation amongst different micro-technology devices.[12,17,20]

Conclusion

We conclude that energy expenditure derived using micro-technology underestimates the energy expenditure of intermittent linear and multi-directional running when compared with indirect calorimetry. Accordingly, EE_{GPS} should not be used to determine the energy cost of intermittent exercise. The agreement between time at high power and high speed appears to be dependent on the number of directional changes performed. This suggests that time at high speed is likely to underestimate the high intensity demands of running incorporating multiple directional changes. Accordingly, we advocate the use of metabolic power parameters to quantify load, but not energy expenditure, during running with multiple directional changes.

Practical implications

- Measures of energy expenditure derived using the metabolic power approach can be used to reflect changes in internal load, however it cannot be used to determine the energy cost of intermittent exercise.
- The agreement between measured energy expenditure and energy expenditure derived using the metabolic power approach is affected by the number of directional changes and the amount of backwards and lateral movement performed.
- Time at high power can provide a more suitable measure of external load in comparison to time at high speed, during running with multiple accelerations performed over short distances.

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Table 1. Agreement between EE_{VO2} and EE_{GPS} during the multi-directional and linear conditions

Table 2. Agreement between time at high power and high speed during the multi-directional and linear conditions

Figure 1. Schematic representation of the multi-directional running condition. Each X indicates a change of direction.

Table 1. Agreement between EE_{VO2} and EE_{GPS} during the multi-directional and linear conditions

Condition	EE_{VO2} kcal (kcal·min^{-1})	EE_{GPS} kcal (kcal·min^{-1})	Mean difference ± SD difference (kcal)	*r*	95% CI	Ratio LoA
Multi-directional	213.5 ± 44.2 (9.0 ± 2.0)	140.9 ± 30.9 (5.9 ± 1.4)	72.6 ± 23.0	0.89*	0.69 to 0.99	1.52 x/÷ 1.27
Linear	199.9 ± 47.8 (8.7 ± 2.1)	148.9 ± 34.6 (6.5 ± 1.5)	51.0 ± 19.5	0.95*	0.86 to 0.99	1.34 x/÷ 1.19

** Denotes a significant correlation ($p < 0.05$). EE_{VO2} = energy expenditure from indirect calorimetry, EE_{GPS} = energy expenditure from GPS*

Table 2. Agreement between time at high power and high speed during the multi-directional and linear conditions

Condition	Time at high power (s)	Time at high speed (s)	Mean difference ± SD difference (s)	*r*	95% CI	Ratio LoA

Multi-directional	118.4 ± 11.7	85.5 ± 18.7	32.9 ± 11.1	0.86*	0.55 to 0.97	1.41 x/÷ 1.36
Linear	111.5 ± 10.4	117.4 ± 5.9	-5.9 ± 7.6	0.71*	0.40 to 0.90	0.95 x/÷ 1.15

** Denotes a significant correlation (p < 0.05).*

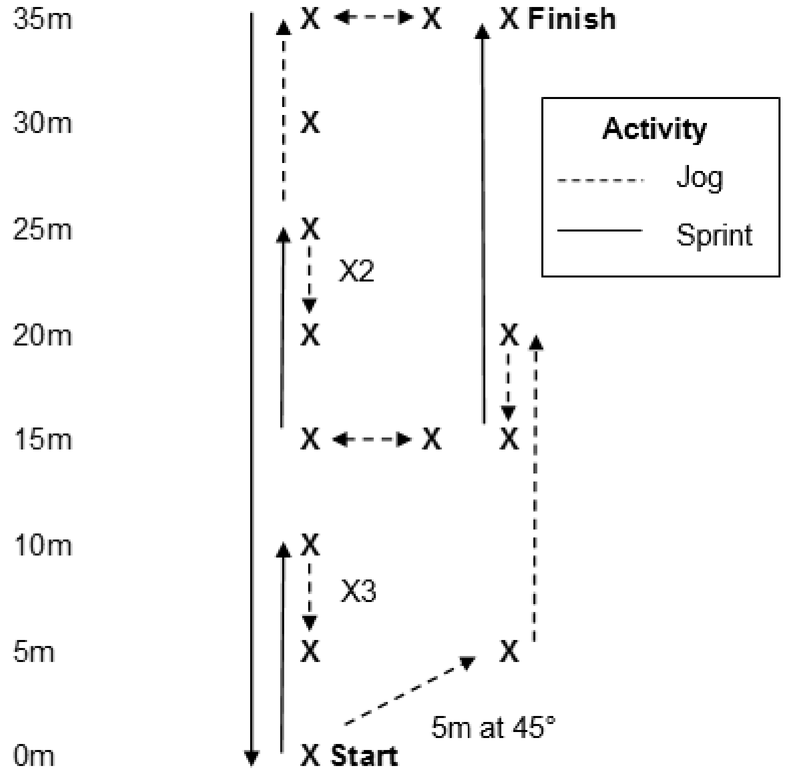

Figure 1. Schematic representation of the multi-directional running condition. Each X indicates a change of direction.