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ORIGINAL ARTICLE

Energetics of male field-sport athletes during the 3-min all-out test for linear and shuttle-based running

Mark Kramer[1] · Rosa Du Randt[1] · Mark Watson[2] · Robert W. Pettitt[3]

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Abstract

Purpose All-out, non-steady state running makes for difficult comparisons regarding linear and shuttle running; yet such differences remain an important distinction for field-based sports. The purpose of the study was to determine whether an energetic approach could be used to differentiate all-out linear from shuttle running.

Methods Fifteen male field-sport athletes volunteered for the study (means ± SD): age, 21.53 ± 2.23 years; height, 1.78 ± 0.68 m; weight, 83.85 ± 11.73 kg. Athletes completed a graded exercise test, a 3-min linear all-out test and two all-out shuttle tests of varied distances (25 m and 50 m shuttles).

Results Significant differences between the all-out tests were found for critical speed (CS) [$F(8.97)$, $p < 0.001$), D' (finite capacity for running speeds exceeding critical speed) [$F(7.83)$, $p = 0.001$], total distance covered [$F(85.31)$, $p < 0.001$], peak energetic cost (EC) [$F(45.60)$, $p < 0.001$], peak metabolic power ($\dot{P}$) [$F(23.36)$, $p < 0.001$], average EC [$F(548.74)$, $p < 0.001$], maximal speed [$F(22.87)$, $p < 0.001$] and fatigue index [$F(3.93)$, $p = 0.027$]. Non-significant differences were evident for average $\dot{P}$ [$F(2.47)$, $p = 0.097$], total EC [$F(0.86)$, $p = 0.416$] and total $\dot{P}$ [$F(2.11)$, $p = 0.134$].

Conclusions The energetic approach provides insights into performance characteristics that differentiate linear from shuttle running, yet surprising similarities between tests were evident. Key parameters from all-out linear and shuttle running appear to be partly interchangeable between tests, indicating that the final choice between linear and shuttle testing should be based on the requirements of the sport.

Keywords Aerobic fitness · All-out test · Energetics · Field testing · Shuttle running

Abbreviations

ADP	Adenosine diphosphate
ATP	Adenosine triphosphate
AOT	All-out test
CO_2	Carbon dioxide
CS	Critical speed
$CS_{25\,m}$	Critical speed derived from an all-out shuttle test of 25 m
$CS_{50\,m}$	Critical speed derived from an all-out shuttle test of 50 m
CS_{linear}	Critical speed derived from a linear all-out test (i.e. around a sprint track)
D'	Maximal distance achievable at speed exceeding CS
EC	Energetic cost
ED	Equivalent distance
ES	Equivalent slope
EM	Equivalent mass
g	Gravitational acceleration
GXT	Graded exercise test
H^+	Hydrogen ion
O_2	Oxygen
$\dot{P}$	Metabolic power
P_i	Inorganic phosphate
S_{avg}	Average speed attained

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✉ Mark Kramer
mark.kramer@mandela.ac.za

[1] Human Movement Science Department, Nelson Mandela University, University Way, Summerstrand, Port Elizabeth 6001, South Africa

[2] Psychology Department, Nelson Mandela University, Port Elizabeth, South Africa

[3] Rocky Mountain University of Health Professions, Provo, UT, USA

S_{max} Maximal speed attained during all-out running
$\dot{V}O_{2max}$ Maximal oxygen uptake

Introduction

All-out running and cycling are dependent on both metabolic and mechanical systems (Kenney et al. 2015) which in turn are dependent on adequately developed aerobic and anaerobic bioenergetic pathways. Unlike aerobic metabolism, however, the anaerobic equivalent cannot yet be adequately measured (Mendez-Villnueva et al. 2008; Kenney et al. 2015), which is especially true for all-out or non-constant running, where conventional methods of assessment become more unreliable (Mendez-Villnueva et al. 2008). Hence, validated mathematical approaches have been developed to shed light on sprint activities by focusing on the force or mechanical power that muscle contractions can produce and the inherent whole-body performances associated with such activities (di Prampero et al. 2015; Bundle and Weyand 2012; Buglione and di Prampero 2013; Kenney et al. 2015).

The threshold separating sustainable from non-sustainable running speeds is referred to as the critical speed (CS) (Poole et al. 2016). Although various methods exist to derive the CS parameter for running (Pettitt et al. 2012; Mattioni et al. 2018), the one that has received the least attention since its inception in 2012 is the 3-min all-out test (AOT) for running (linear AOT) (Pettitt et al. 2012; Broxterman et al. 2013). Of specific interest is the duration dependency of running speed, which is characterized by a negative exponential relationship (Bundle et al. 2003; Weyand and Bundle 2005), showing that the greatest speed decrements are observed early on during all-out running (10–30 s), compared to the marginal speed decrements observed at 60–120 s (Bundle and Weyand 2012). A similar relationship was found, although not modelled, when the linear AOT was modified to incorporate 180° directional changes during all-out shuttle running of the same duration (Saari et al. 2017). In that study, CS obtained from a shuttle AOT was similar to CS modelled from three separate shuttle running time-trials of three different distances but was not compared to the CS from a linear AOT nor shuttles of differing distances. Intuitively, CS from linear running would be expected to exceed that of shuttle running or shorter distances, although such research has not yet been conducted. A second parameter typically derived from all-out testing is D', defined as the finite capacity for running at speeds exceeding CS (Jones and Poole 2005). Although it is presently implied that the magnitude of D' is consistent with energetic parameters largely thought to be 'anaerobic' [e.g. muscle (PCr), glycogen], relatively recent evidence shows that D' may be linked to the development of the oxygen uptake ($\dot{V}O_2$) slow-component, suggesting a link between the development of fatigue at speeds above CS and the loss of skeletal muscle efficiency (Vanhatalo et al. 2011). Given the relative ambiguity of the constitution of D', an investigation between all-out testing and the energetic approach may, therefore, be warranted. Modelling of the linear AOT compared to a shuttle AOT may, therefore, shed more light on various mechanistic differences between AOT methodologies and the transferability of parameters for potential training prescription.

Most research focusing on energetic differences [i.e. energetic cost (EC) and metabolic power ($\dot{P}$)] between linear and shuttle running have used constant speed running (i.e. varying the average running speed required to complete a shuttle) between shuttles of varying distance (i.e. 5, 10, 20 and 25 m) (Buglione and di Prampero 2013; Zamparo et al. 2014; di Prampero et al. 2015; Stevens et al. 2015). To the knowledge of the authors, no study has previously investigated the energetics of all-out running, whether based on linear or shuttle running methodologies. Given the utility of the all-out test for determining both CS, more recently defined as a 'critical metabolic rate' (Poole et al. 2016), as well as D' (likened to 'anaerobic' energetics), the extent to which such parameters differ between linear and shuttle AOTs must be explored further. Similarly, given the lack of statistically significant differences related to the $\dot{V}O_2$ kinetics between all-out linear and shuttle running of the same duration in soccer players (Kramer et al. 2018b), an energetic approach may differentiate between these testing methodologies. Based on the premise that the locomotor patters of linear and shuttle running are inherently different, quantifying the locomotor cost of movement both in terms of EC and $\dot{P}$ would lend itself adequately to the energetic approach. Such research might allow sport scientists the ability to model and predict energetics between linear and shuttle running, with shuttle running being more sport-specific.

The purposes of the present investigation were, therefore, to determine whether an appraisal of EC and $\dot{P}$ could distinguish the physiological loading between linear and shuttle AOTs; to investigate energetic differences between shuttles of varying distances (i.e. 25 m and 50 m) using the AOT methodology; and to determine to what extent the parameters from the various AOTs were interchangeable.

Methods

Participants

Fifteen male field-sport athletes (soccer, $n = 4$; rugby, $n = 11$) volunteered for the study. The characteristics of the players were as follows (means ± SD): age, 21.53 ± 2.23 years; height, 1.78 ± 0.68 m; weight, 83.85 ± 11.73 kg. Prior to participation, all participants completed and signed an informed consent form that included all relevant details pertaining to the tests and testing procedures. The study was approved by the Research Ethics Committee of the Nelson Mandela University in accordance with the principles of the 1975 Declaration of Helsinki.

Experimental design

A repeated measures study design was followed, where participants were required to visit the laboratory on five separate occasions, with all tests being completed following a 24 to 48-h rest period. All tests were completed within a 2-week period.

The first visit served to obtain baseline anthropometric data such as height and weight, as well as familiarizing participants with the testing procedures both for the graded exercise test (GXT), as well as the all-out tests. The second test required participants to perform a laboratory-based square-wave GXT with a verification bout to determine the 'true' maximal pulmonary oxygen uptake rate ($\dot{V}O_{2max}$) and gas exchange threshold (GET). For the third visit, participants were required to complete a 3-min AOT around a 400-m synthetic outdoor sprinting track (linear AOT). The fourth visit required participants to complete a 3-min all-out shuttle test by running repeated 50 m shuttles (50 m AOT). The fifth and final test was a replication of the 50-m AOT, with the exception of completing the shuttles over 25 m distance (25 m AOT). The third through fifth visits were randomized to minimize any potential order effects (Fig. 1).

Experimental procedures

Determination of $\dot{V}O_{2max}$

The GXT was conducted on a motorized treadmill (Woodway 4Front, USA). The ramp protocol consisted of 3 min of walking or slow jogging at a speed of 6 km h^{-1}, followed by a ramp increase in speed of 0.5 km h^{-1} min^{-1} until volitional exhaustion. Once volitional exhaustion was reached, the treadmill speed was reduced to 6 km h^{-1} for 3 min to allow for active recovery, after which the verification bout was initiated to confirm the end-stage $\dot{V}O_2$. For the verification bout, the speed was increased to two stages below the end-stage speed, and subjects were encouraged to continue until volitional exhaustion (usually within 2–3 min), upon which the test was terminated.

Pulmonary gas exchange was measured breath-by-breath during the GXT and verification bouts using a facemask and breathed through low dead-space, low resistance mouthpiece and digital transducer turbine assembly (Metamax 3B, Cortex Biophysik, Leipzig, Germany). Electrochemical cells (O_2) and infrared (CO_2) analyzers housed in the Metamax 3B unit were used to sample the breath-by-breath inspired and expired gas volumes and gas concentrations (Cortex Biophysik). Prior to each test, the analyzers were calibrated using known gas concentrations, and the turbine volume transducer was calibrated using a 3-L syringe (Cortex Biophysik). Heart rate was continuously monitored using wireless telemetry to coincide with the breath-by-breath measurements (Polar H7, Polar Electro Oy, FI-90440, Kempele, Finland). A 'true' $\dot{V}O_{2max}$ was identified using the highest $\dot{V}O_2$ between the GXT and verification bouts, provided the two values differed by less than 3% (Kirkeberg et al. 2011).

Three-minute all-out tests

A stringent warm-up procedure consisting of light jogging and dynamic stretching was followed prior to each all-out test, followed by a 5-min rest period. The linear AOT was completed on a 400-m oval outdoor sprinting track, whereby subjects were instructed to run all-out and to maintain the fastest possible speed at any given instant for the duration of the test. Subjects were fitted with a wrist-worn GPS unit (Garmin Forerunner, Model 305, Taiwan), which yielded

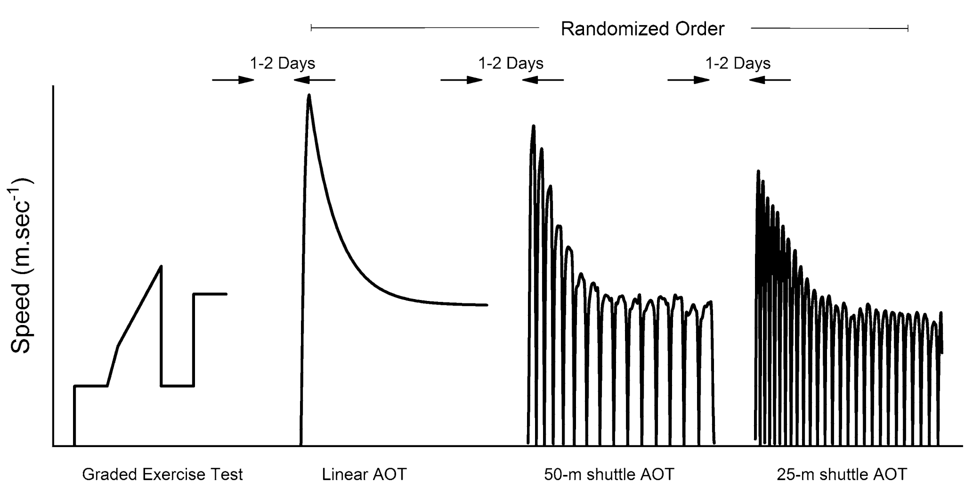

Fig. 1 Schematic representation of the experimental overview for a representative subject. The left-most panel represents the graded exercise test followed by active recovery and severe intensity, verification bout, where exercise time was recorded in minutes (total time of ~14 min). This is followed by the linear AOT, 25 m AOT and 50 m AOT with exercise time recorded in seconds with a randomized testing order. Notice the differences in peak speed, but similar profile of the speed decay

a displacement accuracy of ~3 m, and a speed accuracy of ~0.1 m s^{-1}. Verbal encouragement was provided throughout the test, but no information pertaining to time elapsed or time remaining was provided to discourage pacing. The GPS data were exported to Microsoft® Excel for data acquisition, then exported to OriginPro [OriginPro 2017 (version 94E), OriginLab, USA] for further analysis. The CS is denoted as the average speed over the final 30-s of the test (Pettitt et al. 2012), whereas D' is calculated as the area under the speed-time curve above CS (Broxterman et al. 2013).

For the 25-m and 50-m AOTs, cones were set up 2 m apart over distances of 25 m and 50 m, respectively. Subjects were then required, depending on the scheduled test, to run all-out over either 25 m or 50 m shuttles. Since no commercially available wrist worn GPS units are available with an adequate sampling frequency (30 Hz minimum is recommended) to accurately measure speed over such short, high-velocity distances, we opted to use a high-speed camera with a sampling frequency of 100 Hz (Sony Cyber-shot DSC-RX10 MK III, Sony, America) to track athlete displacement. To minimize the measurement error, the camera was set up perpendicularly to the line of travel at a distance of 40 m and 80 m for the 25 m AOT and 50 m AOT, respectively. As per the linear AOT, subjects were verbally encouraged throughout the entirety of the test, whilst access to any temporal information was omitted to discourage pacing.

To obtain the desired instantaneous speed and acceleration data from the all-out shuttle tests, the video files were exported to a motion analysis software package (Tracker 4.11.0, Open Source Physics). The automated motion tracking feature was utilized to obtain raw displacement data, which could then be exported to OriginPro for further analysis. Speed data were obtained by numerical differentiation of the displacement data, and acceleration data were obtained by differentiating the speed data. All data were filtered using a fourth-order, zero-lag Butterworth filter with a cut-off frequency of 1–3 Hz (Winter 2009). Peak and average speed data as well as the accelerations and decelerations for each shuttle could be obtained and separately modelled.

Energetics and metabolic power

In a landmark study by di Prampero et al. (2015), the investigators reported that accelerated running was biomechanically equivalent to uphill running at an 'equivalent slope' (ES), which was dictated by the forward acceleration (a_f) of the individual. During a_f, subjects exert a force that is greater than body weight, by an amount that is proportional to a_f, referred to as 'equivalent mass' (EM). Therefore, once a_f is known, ES and EM can be easily obtained as follows: $\mathrm{ES} = a_f/g$, and $\mathrm{EM} = (a_f^2 + g^2)^{0.5}/g$. Minetti et al. (2002) showed that the instantaneous energy cost (EC, J kg^{-1} m^{-1}) of constant speed uphill running is described by the following equation (Eq. 1), which was modified by Osgnach et al. (2010):

$$\mathrm{EC} = (155.4\mathrm{ES}^5 - 30.4\mathrm{ES}^4 - 43.3\mathrm{ES}^3 + 46.3\mathrm{ES}^2 + 19.5\mathrm{ES} + 3.6) \cdot \mathrm{EM} \cdot \mathrm{KT}, \quad (1)$$

where EC is the energy cost of accelerated running, ES is the equivalent slope, with 3.6 (J kg^{-1} m^{-1}) representing the energy cost of running at constant speed on a flat terrain, and KT is the terrain constant [1.29 in the study by Osgnach et al. (2010)]. The metabolic power ($\dot{P}$, W kg^{-1}) can then be calculated by multiplying EC (J kg^{-1} m^{-1}) with the instantaneous speed ($\dot{s}$, m s^{-1}) (Eq. 2):

$$\dot{P} = \mathrm{EC} \cdot \dot{s}. \quad (2)$$

Once the instantaneous EC and $\dot{P}$ were calculated for each AOT, we modelled the peak change in these parameters per shuttle for the 25 m AOT and 50 m AOT). For the linear AOT, however, the EC and $\dot{P}$ were only modelled from the point of peak speed attainment which occurred at approximately 6 s, whereby the remaining performance represents a period of speed decay. Peak EC, $\dot{P}$ and average speed per shuttle (S_{avg}) were found to decrease exponentially per shuttle and could be accurately modelled using the general equation (Eq. 3):

$$y(\delta) = y_0 + A \cdot \mathrm{e}^{-\delta/\tau}, \quad (3)$$

where $y(\delta)$ is the dependent variable of interest (EC, $\dot{P}$ or S_{avg}), δ represents the independent variable which in the present application represents a given shuttle (1, 2, 3… etc.), y_0 is the asymptote of the exponential function, A is the amplitude of the exponential curve and τ is the decay time constant (representing the time taken to reach 63% of the amplitude). For example, the $\dot{P}$ per shuttle would, therefore, be modelled as follows (Eq. 4):

$$\dot{P}(\delta) = \dot{P}_0 + A \cdot \mathrm{e}^{-\delta/\tau}, \quad (4)$$

where $\dot{P}(\delta)$ is the metabolic power per shuttle, and $\dot{P}_0$ represents the asymptote of the metabolic power (Fig. 2).

Having modelled EC and $\dot{P}$ per shuttle turn, as well as the average speed per turn, it was possible to derive and express both EC and $\dot{P}$ as a function of the average speed per shuttle, yielding the following equation (Eq. 5; here $\dot{P}$ is given as an example; see supplementary files for the derivation):

$$\dot{P}\left(S_{avg}\right) = P_0 + A_1\left(\frac{S_{avg}(\delta) - S_0}{A_2}\right)^{\tau_2/\tau_1}, \quad (5)$$

where $\dot{P}(S_{avg})$ is the metabolic power as a function of the average speed for a given shuttle (δ), A_1 and τ_1 are the amplitude and decay time constants of original $\dot{P}$ function, A_2 and τ_2, are the amplitude and decay time constants of the $S_{avg}(\delta)$ function.

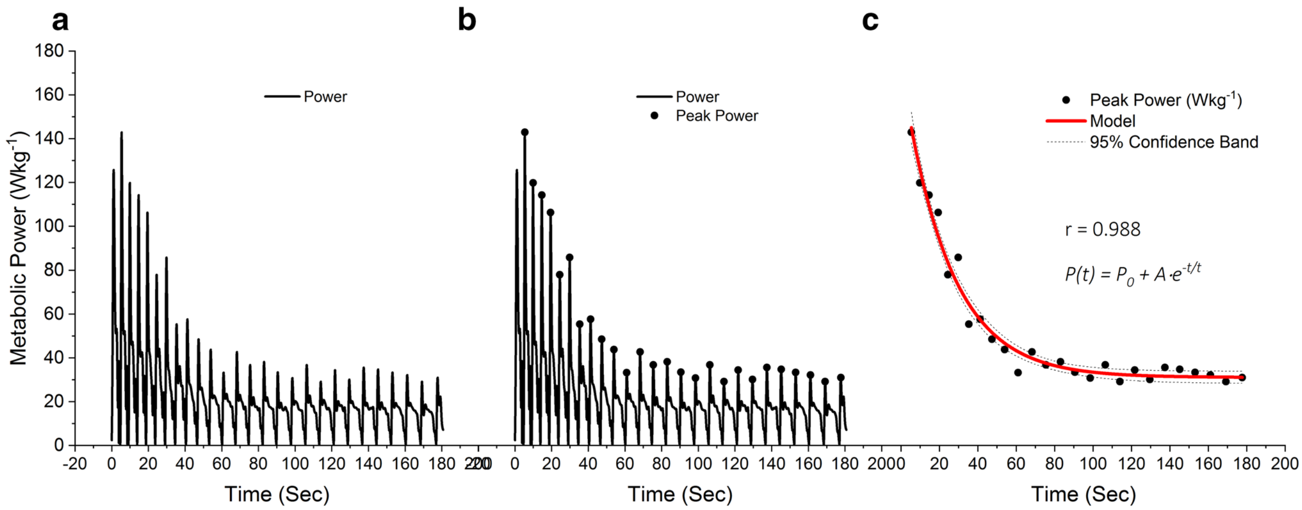

Fig. 2 Modelling process for the exponential decay in peak metabolic ($\dot{P}$) power. **a** The raw $\dot{P}$ as a function of time; **b** the peak $\dot{P}$at each turn, represented by filled dots; **c** the exponential decay model applied to each of the peak $\dot{P}$ points (dotted black lines represent the 95% CI for the model)

Equivalent distance

The equivalent distance (ED) represents the total distance the athlete would have run at steady pace on a solid surface using the total energy spent during the continuous all-out shuttle run (see Eq. 6):

$$\text{ED} = \frac{W_{\text{tot}}}{(\text{EC}_c \times \text{KT})}, \quad (6)$$

where ED is the equivalent distance (m), W_{tot} is the total energy expenditure (J kg^{-1}), EC_c is the EC of running at a constant pace on a flat, solid terrain assumed to be 3.6 J kg^{-1} m^{-1} and KT is the terrain constant, here assumed to be 1.29 (Osgnach et al. 2010). Stated differently, the ED method provides a means by which the additional energy associated with repeated shuttle accelerations and decelerations can be converted into a 'linear' running distance equivalent (measured in meters as opposed to J kg^{-1}), therefore, allowing for more meaningful comparisons to linear running (Osngnach et al. 2010). The ED method, therefore, provides useful insights into the total distance that could be covered theoretically for the shuttle running trials, whereas the raw distance data would misrepresent the actual effort associated with shuttle running.

Statistical analyses

Statistical analyses were conducted using the Statistica package (version 10.1, StatSoft, Dell Software, USA), with all results being presented as mean ± standard deviation (SD) unless otherwise stated. Relationships between selected variables were analysed by Pearson correlation coefficients (r). The correlation coefficients were interpreted on the following criteria: $r < 0.1$, trivial; 0.1–0.3, small; 0.3–0.5, moderate; 0.5–0.7, large, 0.7–0.9, very large; and > 0.9, almost certain (Hopkins et al. 2009). Normality of all distributions was confirmed using the Shapiro–Wilk test. Consistency of measurement was assessed using the intraclass correlation coefficient (ICC α), typical error (TE) and coefficient of variation (CV%). Data derived from all three AOTs were assessed for statistical significance using a one-way analysis of variance (ANOVA), where statistically significant differences were analysed using a post-hoc Scheffè test. Statistical significance was accepted at $p < 0.05$.

Results

Graded exercise test and all-out tests

A 'true' $\dot{V}O_{2max}$ (mean ± SD) of 45.47 ± 4.97 ml kg^{-1} min^{-1} was achieved during the GXT, as indicated by the strong internal consistency between GXT and verification bouts (TE = 0.77 ml kg^{-1} min^{-1}, CV = 1.7%, ICC α = 0.97). Peak speed attained during the GXT was 4.08 ± 0.47 m s^{-1}.

Correlations between $\dot{V}O_{2max}$ and CS parameters from the AOTs were strong for both CS_{linear} ($r = 0.79$, $p < 0.001$) and CS_{50m} ($r = 0.77$, $p < 0.001$) and moderate for CS_{25m} ($r = 0.51$, $p = 0.054$). The total number of shuttle turns initiated during both the 25-m and 50-m AOTs

Table 1 Parameter estimates from the all-out tests

Parameter	Linear AOT	25 m AOT	50 m AOT
AOT parameters			
CS (m s^{-1})	$3.56 \pm 0.67^{b,***}$	$2.90 \pm 0.19^{a,***}$	3.27 ± 0.26
D' (m)	$231.07 \pm 67.29^{b,***},^{c,***}$	$107.21 \pm 38.34^{a,***}$	$134.79 \pm 49.19^{a,***}$
D_{tot} (m)	$876.01 \pm 77.79^{b,***,c,***}$	$631.50 \pm 20.04^{a,***,c,***}$	$730.26 \pm 33.80^{a,***,b,***}$
S_{max} (m s^{-1})	$8.95 \pm 0.92^{b,***,c,**}$	$7.28 \pm 0.59^{a,***}$	$7.82 \pm 0.83^{a,**}$
FI (%)	60.21 ± 6.81	59.91 ± 4.64	57.66 ± 5.96
Energetic AOT parameters			
Peak EC (J kg^{-1} m^{-1})	$13.28 \pm 3.24^{b,***,c,***}$	$32.16 \pm 9.16^{a,***}$	$29.24 \pm 2.74^{a,***}$***
Peak $\dot{P}$ (W kg^{-1})	$65.32 \pm 15.82^{b,***,c,***}$	$113.63 \pm 25.37^{a,***}$	$101.28 \pm 17.91^{a,***}$
Mean EC (J kg^{-1} m^{-1})	$4.63 \pm 0.01^{b,***,c,***}$	$6.19 \pm 0.20^{a,***,c,***}$	$5.47 \pm 0.10^{a,***,b,***}$
Mean $\dot{P}$(W kg^{-1})	22.81 ± 2.06	21.50 ± 1.53	21.82 ± 1.33
Total EC (KJ kg^{-1})	4.06 ± 0.36	3.91 ± 0.28	4.00 ± 0.28
Total $\dot{P}$ (KW kg^{-1})	4.10 ± 0.37	3.89 ± 0.28	3.94 ± 0.24

D_{tot} is the total distance achieved during each AOT, S_{max} is the maximal speed reached during the AOTs and *FI%* the Fatigue index expressed as a percentage

$^{*}p<0.05$; $^{**}p<0.01$; $^{***}p<0.001$

[a]Significantly different from linear AOT

[b]Significantly different from 25 m AOT

[c]Significantly different from 50 m AOT

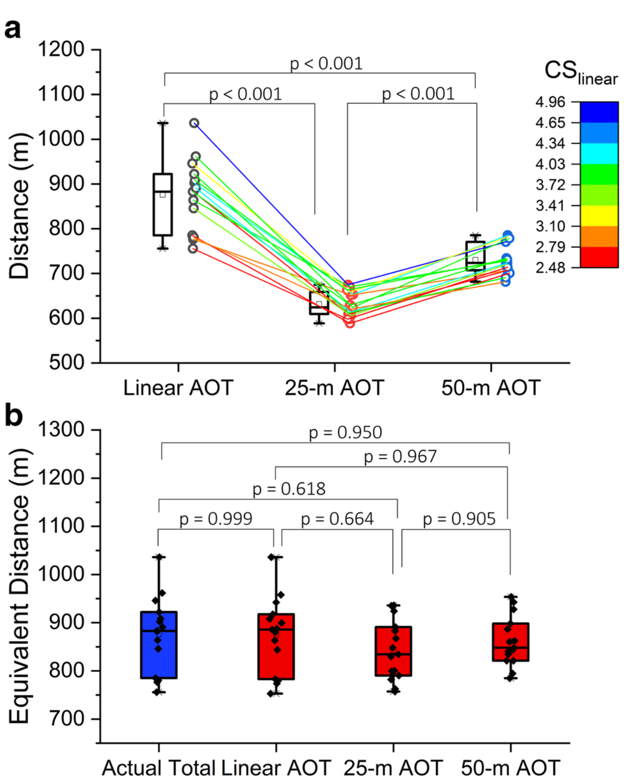

Fig. 3 Actual distance and equivalent distance comparison. **a** A line series plot of total actual distance achieved for the all-out tests with 95% CIs. Athletes are color-scaled according to CS values of the linear AOT. **b** A box plot comparison showing the actual (blue) and estimated (red) total distances calculated using the ED-method

was 26 ± 2 and 14 ± 1, respectively. The results from the AOTs are presented in Insert Table 1 and Fig. 3.

The fatigue index (FI%) represents the speed decrease from S_{max} to CS as a percentage of S_{max} (see Eq. 7):

$$\mathrm{FI}(\%) = 100 \cdot ((S_{max} - \mathrm{CS})/S_{max}). \quad (7)$$

The correlation between the maximum speed attained during the AOTs (S_{max}) and the speed decrement towards CS provides an indication of fatigue (as indicated by FI%). Strong positive correlations were observed between the speed decrease and S_{max} for the linear ($r=0.72$, $p=0.003$), 25 m ($r=0.97$, $p<0.001$) and 50 m ($r=0.97$, $p<0.001$) AOTs, indicating that those participants who achieved greater S_{max} values, also experienced the greatest speed decrements.

Variations in individual performances are visualized more clearly in Fig. 3, highlighting differences in actual distances recorded during the AOTs (panel A) compared to the equivalent distances calculated from both the ED-method (panel B).

The EC (panel A) and $\dot{P}$ (panel B) as a function of speed for the various AOTs are highlighted in Fig. 4. Both EC and $\dot{P}$ increase non-linearly as a function of speed for the shuttle AOTs, but linearly for the linear AOT. Both EC and $\dot{P}$ are significantly more elevated for the 25 m AOT than the 50 m AOT, respectively, for each equivalent speed beyond 4 m s^{-1}.

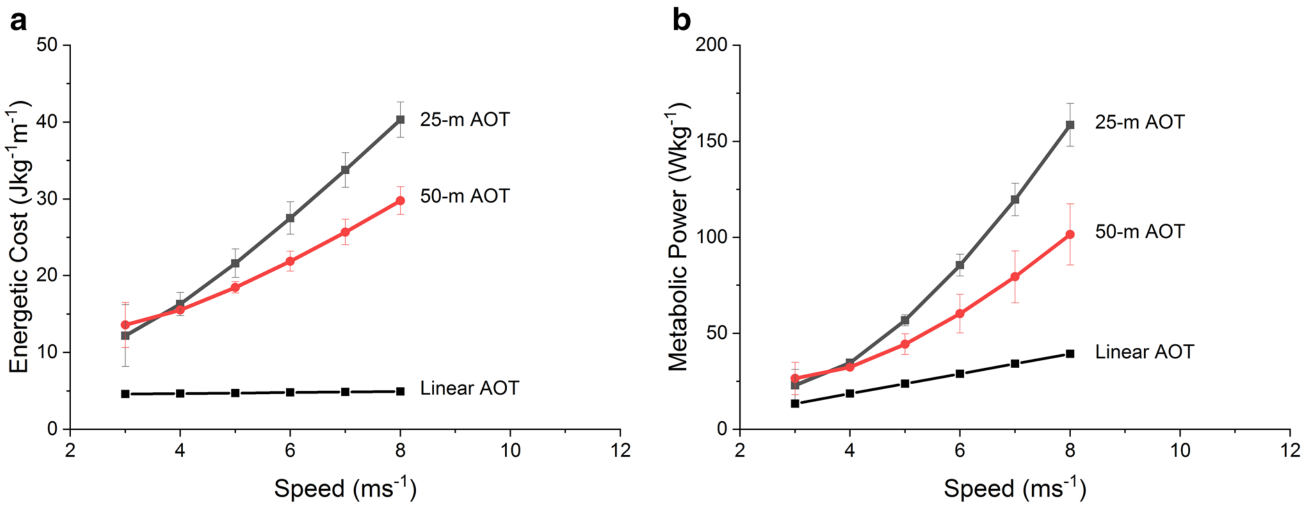

Fig. 4 EC and $\dot{P}$ as a function of average shuttle speed. **a** The EC per unit of average speed for the AOTs; **b** The $\dot{P}$ per unit of average speed for the AOTs, respectively. Take notice that at faster speeds (i.e., >4 m s^{-1}), EC and $\dot{P}$ are proportionately higher for all-out shuttle versus continuous linear running, a relationship more pronounced for 25 versus 50 m switch backs. At slower speeds (~3–4 m s^{-1}), a fixed difference in EC and $\dot{P}$ between shuttle and linear running remains, with no differences between 25 and 50 m switchbacks

Discussion

The present study was the first to calculate the EC and $\dot{P}$ associated with 3-min all-out linear and shuttle-based running. Several novel findings of the study are presented: (1) peak and average EC as well as $\dot{P}$ for all-out shuttle running exceeded linear running; (2) the EC and $\dot{P}$ requirements increased non-linearly with higher average running speed (S_{avg}) during all-out shuttle running for both 25 m and 50 m shuttle distances, but linearly for the linear AOT; and (3) a valid approach for comparing the physiological loading between linear and shuttle AOTs was derived.

Running speeds and, therefore, muscle work, tend to be lower during continuous shuttle running compared to straight-line running, resulting in a reduced percentage of speed decrement (Mendez-Villnueva et al. 2008; Buchheit et al. 2011). A smaller speed decrement for shuttle running was evidenced in the present study whereby the FI% for both the 25 m and 50 m AOTs was significantly lower than for the linear AOT. A lower FI% indicates a narrower difference between maximal running speed and CS, coinciding with the lower D' values observed in the present study for shuttle running in comparison to linear running. Although the exact underlying physiological mechanisms for the narrower FI% and lower D' are not presently understood, the indirect evidence is suggestive of metabolic and neuromuscular perturbations, rather than energy supply limitations (Buchheit et al. 2010).

Movement speed is dependent on the mechanical power that the muscles can produce, which is subject to the product of force and muscle shortening velocity (Allen et al. 2008). The fatigue-inducing mechanisms affecting power output and shortening velocity are inherently different, whereby movements requiring high forces are more influenced by reductions in force production, and those requiring high movement speeds are more impacted by reductions in shortening velocity (Allen et al. 2008). The linear AOT, therefore, poses a unique challenge to the athlete in that it is dependent on both high-power outputs as well as rapid muscle shortening velocities. Most of the experimental evidence is suggestive of the fact that transient increases in (ADP) play a central role in decreased maximal shortening velocities, whereas increases in P_i or H^+ or decreases in $[Ca^{2+}]$ have little impact on this parameter (Funk et al. 1989; Sahlin 1992; Allen et al. 2008). Such findings may be directly extended to the AOT method where Vanhatalo et al. (2011) investigated differences between constant work exercise compared to all-out exercise during cycling. The principal finding of their study was that fatigued muscle fibers incurred a high O_2 cost due in part to either a decreased contribution to externally measured power output or a significantly higher O_2 cost per unit of external work done. The lower contractile efficiency was explained partly by the muscle metabolic perturbations associated with the accumulation of metabolites (e.g. H^+, P_i, ADP and reactive oxygen species).

Direct comparisons between linear and shuttle running are often difficult due to the time lost while accelerating, turning and re-accelerating, which accounted for the differences in total running distance observed in the present study (Buchheit et al. 2010; Buglione and di Prampero 2013; Stevens et al. 2015; Kramer et al. 2018a). It is here that we believe the 'equivalent distance' method, proposed by

Osgnach et al. (2010), would provide useful insights when comparing all-out linear to shuttle running. Raw distance data comparisons of the present study show that the 25 m and 50 m AOTs achieved ~27% and ~17% less distance compared to the linear AOT (Fig. 3a). However, when the time associated with repeated speed changes and turning is accounted for using the ED method, the differences in distance are largely negated (i.e. differences in distances drop to within ~4% and ~2% for the 25 m and 50 m AOTs, respectively; Fig. 3b). The repudiation of overall differences is also reflected in the non-significantly different average $\dot{P}$, total EC and total $\dot{P}$ values recorded for each AOT in the present study, thereby showing comparable physiological loading for the athlete. The comparative physiological loading is commensurate with previous research findings related to the $\dot{V}O_2$ kinetics associated with all-out running (Kramer et al. 2018b). In that study the authors observed no differences in almost all parameters associated with the $\dot{V}O_2$ kinetics during both all-out linear and shuttle running of the same duration. Such findings mirror the ED findings of the present study, highlighting again that the physiological loading between all-out linear and shuttle running may essentially be invariant.

Therefore, the 'true' differences observed between shuttle and linear AOTs may be attributable to unique challenges imposed by shuttle running, such as coordination, agility, balance and flexibility (i.e. neuromuscular rather than physiological) (Buchheit et al. 2010). Within the context of the present study, physiological fatigue factors are considered to be related more to $\dot{V}O_2$ kinetics and peripheral fatigue mechanisms such as muscle fiber efficiency and metabolic perturbations associated with all-out running (e.g. increase in H^+, P_i and ADP), which have been shown to be largely immutable between linear and shuttle running using all-out testing (Burnley et al. 2010; Chidnok et al. 2013; Poole et al. 2016; Kramer et al. 2018b). Alternatively, neuromuscular fatigue factors are related to proprioception and muscle activation/recruitment inherent to the activity (Buchheit et al. 2010; Dittrich et al. 2013; Poole et al. 2016), which, when related to the peak EC and $\dot{P}$ of the present study, were shown to be considerably higher in shuttle running compared to linear running.

It is, therefore, possible that the cumulative effect per shuttle may account for some of the 'lost' energy which cannot be remediated to an appreciable extent. During the initial stages of all-out shuttle running, where speeds were very high (i.e. significantly greater than CS), the differences between linear and shuttle running, as well as between shuttles of different distances (i.e. 25 m vs. 50 m), were most pronounced (i.e. non-linear), but tended to become more homogenous at lower speeds (i.e. ~4 m s^{-1}). Interestingly, the non-linear speed-related differences in EC and $\dot{P}$ were only true for continuous shuttle running, but not for linear running (see Fig. 4). Despite similar speed-time profiles between linear and shuttle running, the EC for the linear AOT exhibited a negligible positive linear relationship, whereas $\dot{P}$ exhibited a more pronounced positive linear relationship. Such a finding is in line with results obtained by Stevens et al. (2015), but in contrast to those by Buchheit et al. (2010), who did not find a speed-dependent relationship between running economy and shuttle running. Our findings may partly be ascribed to differences in shuttle distances and the non-constant high-speed running methodology employed. Although the EC and $\dot{P}$ seem to elicit relatively linear relationships at lower speeds (Hatamoto et al. 2013; Almodhy et al. 2014; Stevens et al. 2015), the extent to which this holds at higher speeds is, therefore, debatable; as shown in our study. It is hoped, therefore, that the high speeds (> 7 m s^{-1} as indicated by S_{max}) recorded in the present study for both linear and shuttle running, as well as the EC and $\dot{P}$ responses to such high speeds, will provide further impetus for future research regarding the underlying physiological mechanisms.

Interestingly, the peak $\dot{P}$ for both the 25 m and 50 m AOTs in the present study exceeded the peak values of medium level sprinters during a 100 m dash (Tables 1, 2). Such high $\dot{P}$ values were only sustained for approximately three shuttle lengths during the 25 m AOT but dissipated more quickly for the 50 m AOT. Such findings attest to the extreme accelerations and decelerations experienced by athletes during all-out shuttle running, yet despite this, athletes exhibited similar CS and lower fatigue indexes for shuttle running compared to linear all-out running (see Table 1). It

Table 2 Summary of energetic cost and metabolic power

	Mean		Peak	
	EC (J kg^{-1} m^{-1})	$\dot{P}$ (W kg^{-1})	EC (J kg^{-1} m^{-1})	$\dot{P}$ (W kg^{-1})
Sprinters[a]	10.7	61.0	43.8	91.9
Usain Bolt[a]	18.4	105.0	104.4	199.0
Marathon[b]	3.48–3.72	–	–	–
Soccer[c,d]	5.71–6.71[c]	9–16[d]	–	–
Rugby[d,e]	5.88–6.07[d]	7.8–10.0[e]	–	–
Aus Football[f]	–	9.2–10.9	–	–
25 m shuttle[g]	6.19	21.50	32.16	113.63
50 m shuttle[g]	5.47	21.82	29.24	101.28

[a]di Prampero et al. (2015)
[b]Tam et al. (2012)
[c]Stevens et al. (2015)
[d]Cummings et al. (2016)
[e]Buchheit et al. (2015)
[f]Coutts et al. (2015)
[g]Present study

is possible that the lower peak speeds attained during shuttle running 'balance' the higher energy cost of the repeated shuttle turns, thereby essentially equating both the EC and $\dot{P}$ for linear and shuttle running. Evidence for the energetic equivalence is revealed in the total EC and $\dot{P}$ calculated for the various all-out tests, which were statistically non-significantly different.

Similarly, the mean EC and $\dot{P}$ results of the present study compare favourably to studies focusing on the energetics of soccer, rugby and Australian football (Osgnach et al. 2010; Coutts et al. 2015; Cummings et al. 2016). The implications are, therefore, that the linear, 25 m and 50 m AOTs, as methods of assessment, encompass a broad range of EC and $\dot{P}$ values that span not only all-out sprinting, but also match-play demands inherent to rugby and soccer. The AOT methodology, therefore, shows substantial utility as a testing tool as is evidenced by its diverse application to high-intensity sports such as rowing, swimming, cycling and running (Jones and Vanhatalo 2017).

Despite the similarities and differences between linear and shuttle running portrayed in the current study, it is presently unclear which method of testing would yield the most useful training-specific parameters for sports such as soccer, rugby and hockey. The high EC and $\dot{P}$ exhibited during the early stages of shuttle running may impart adaptations that would be conducive to the development of agility or rapid accelerations; both attributes being considered favourable adaptations for soccer and rugby. Conversely, given the high correlation between CS_{linear} and $\dot{V}O_{2max}$, it may be true that training based on CS and D' parameters derived from linear all-out running may induce more favourable adaptations for the development of aerobic fitness compared to parameters derived from all-out shuttle running. Surprisingly, the data may suggest that the 50 m AOT could potentially offer the most viable middle-ground in terms of adaptations from both linear and shuttle running. It is clear however, that differences between all-out linear and shuttle running are not attributable to physiological mechanisms but are most likely ascribed to differences in neuromuscular loading. Evidently, additional research is needed to arrive at the optimum shuttle running training distances and the associated adaptations for given sport demands. Finally, more expedient methods of data acquisition for shuttle running need to be developed, potentially by utilizing high-fidelity GPS systems capable of recording speed at higher sampling rates (e.g. ≥ 20 Hz).

Conclusion

Although the inherent differences between all-out linear and continuous shuttle running were statistically non-significant for certain parameters (i.e. similar mean ED, mean $\dot{P}$, total EC and total $\dot{P}$), the inter-individual performance variations may negate the interchangeable nature of the parameters between AOTs. A high CS in the linear AOT does not guarantee CS transferability to the 25 m or 50 m AOTs. Similar observations were made for other parameters such as D' and total distances covered. It would also appear that the CS methodology provides a useful method for comparing both all-out linear and shuttle running not only due to the parameters derived from the model, but also its broader ability to provide useful metrices such as 'equivalent distance'. Even so, given the differences in the CS and D' parameters derived from each test, it is unclear at this stage which version of the test would yield more optimal training results during a sport-specific intervention. The fatigue inducing mechanisms for shuttle running appear to be related more to neuromuscular factors rather than the physiological loading revealed in the present study. The choice of which test to implement for field-sport athletes should, therefore, be centered on test-specificity; the linear AOT may be more suited for the assessment of physiological loading, whereas the shuttle AOTs, specifically the 50 m AOT, may be better suited for the assessment of neuromuscular adaptation. More research in this field is, therefore, merited.

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Compliance with ethical standards

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References

Allen DG, Lamb GD, Westerblad H (2008) Skeletal muscle fatigue: cellular mechanisms. Physiol Rev 88(1):287–332

Almodhy M, Beneke R, Cardoso F, Taylor MJD, Sandercock GRH (2014) Pilot investigation of the oxygen demands and metabolic cost of incremental shuttle walking and treadmill walking in patients with cardiovascular disease. BMJ Open 4:e005216

Broxterman RM, Ade CJ, Poole DC, Harms CA, Barstow TJ (2013) A single test for the determination of parameters of the speed–time relationship for running. Resp Physiol Neurobiol 185(2):380–385 **(PMID: 22981969)**

Buchheit M, Bishop D, Haydar B, Nakamura FY, Ahmaidi S (2010) Physiological responses to shuttle repeated sprint running. Int J Sports Med 31:402–409

Buchheit M, Haydar B, Hader K, Ufland P, Ahmaidi S (2011) Assessing running economy during field running with changes of direction: application to 20 m shuttle runs. Int J Sports Physiol Perform 6(3):380–395

Buchheit M, Manouvrier C, Cassirame J, Morin JB (2015) Monitoring locomotor load in soccer: is metabolic power, powerful? Int J Sports Med 36:1149–1155

Buglione A, di Prampero PE (2013) The energy cost of shuttle running. Eur J Appl Physiol 113:1535–1543

Bundle MW, Weyand PG (2012) Sprint exercise performance: does metabolic power matter? Exerc Sport Sci Rev 40(3):174–182

Bundle MW, Hoyt RW, Weyand PG (2003) High-speed running performance: a new approach to assessment and prediction. J Appl Physiol 95:1955–1962

Burnley M, Vanhatalo A, Fulford J, Jones AM (2010) Similar metabolic perturbations during all-out and constant force exhaustive exercise in humans: a (31)P magnetic resonance spectroscopy study. Exp Physiol 95(7):798–805

Chidnok W, DiMenna FJ, Fulford J, Bailey SJ, Skiba PF, Vanhatalo A, Jones AM (2013) Muscle metabolic responses during high-intensity intermittent exercise measured by ^{31}P-MRS: relationship to the critical power concept. Am J Physiol Regul Integr Comp Physiol 305:R1085–R1092

Coutts AJ, Kempton T, Sullivan C, Bilsborough J, Cordy J, Rampinini E (2015) Metabolic power and energetic costs of professional Australian football match-play. J Sci Med Sport 18(2):219–224

Cummings C, Gray A, Shorter K, Halaki M, Orr R (2016) Energetic and metabolic power demands of national rugby league match-play. Int J Sports Med 37(7):552–558

di Prampero PE, Botter A, Osgnach C (2015) The energy cost of sprint running and the role of metabolic power in setting top performances. Eur J Appl Physiol 115:451–469

Dittrich N, de Lucas RD, Maioral MF, Diefenthaele F, Guglielmo LG (2013) Continuous and intermittent running to exhaustion at maximal lactate steady state: neuromuscular, biochemical and endocrinal responses. J Sci Med Sport 16(6):545–549

Funk C, Clark A Jr, Connett RJ (1989) How phosphocreatine buffers cyclic changes in ATP demand in working muscle. Adv Exp Med Biol 248:687–692

Hatamoto Y, Yamada Y, Fuii T, Higaki Y, Kiyonaga A, Tanaka A (2013) A novel method for calculating the energy cost of turning during running. Open Access J Sports Med 4:117–122

Hopkins WG, Marshall SW, Batterham AM, Hanin J (2009) Progressive statistics for studies of sports medicine and exercise science. Med Sci Sports Exerc 41(1):3–12

Jones AM, Poole DC (2005) Oxygen uptake kinetics in sport, exercise and medicine. Taylor and Francis, New York, **(PMC3880088)**

Jones AM, Vanhatalo A (2017) The 'critical power' concept: applications to sports performance with a focus on intermittent high-intensity exercise. Sports Med 47(1):S65–S78

Kenney WL, Wilmore J, Costill D (2015) Physiology of sport and exercise, 6th edn. Human Kinetics, Champaigne

Kirkeberg JM, Dalleck LC, Kamphoff CS, Pettitt RW (2011) Validity of 3 protocols for verifying. Int J Sports Med 32:266–270 **(PMID: 21271494)**

Kramer M, Clark IE, Jamnick N, Strom C, Pettitt RW (2018a) Normative data for critical speed and D' for high-level male rugby players. J Strength Cond Res 32(3):783–789 **(PMID: 28542091)**

Kramer M, Watson M, Du Randt R, Pettitt RW (2018b) Oxygen uptake kinetics and speed-time correlates of modified 3-minute all-out shuttle running in soccer players. PLoS One 13(8):e0201389

Mattioni MF, Fontana FY, Pogliaghi S, Passfield L, Murias JM (2018) Critical power: how different protocols and models affect its determination. J Sci Med Sport 21(7):742–747

Mendez-Villnueva A, Hamer P, Bishop D (2008) Fatigue in repeated sprint exercise is related to muscle power factors and reduced neuromuscular activity. Eur J Appl Physiol 130:411–419

Minetti A, Moia C, Roi GS, Susta D, Ferretti G (2002) Energy cost of walking and running at extreme uphill and downhill slopes. J Appl Physiol 93(3):1039–1046

Osgnach C, Poser S, Bernardini R, Rinaldo R, di Prampero PE (2010) Energy cost and metabolic power in elite soccer: a new match analysis approach. Med Sci Sports Exer 42(1):170–178

Pettitt RW, Jamnick N, Clark IE (2012) 3-min all-out exercise test for running. Int J Sports Med 33:426–431

Poole DC, Burnley M, Vanhatalo A, Rossiter HB, Jones AM (2016) Critical power: an important fatigue threshold in exercise physiology. Med Sci Sport Exerc 48(11):2320–2334

Saari A, Dicks ND, Hartman ME, Pettitt RW (2017) Validation of the 3-min all-out exercise test for shuttle running prescription. J Strength Cond Res. https://doi.org/10.1519/JSC.0000000000002120

Sahlin K (1992) Metabolic factors in fatigue. Sports Med 13:99–107

Stevens TGA, de Ruiter CJ, van Maurik D, van Lierop CJW, Savelsbergh GJP, Beek PJ (2015) Measured and estimated energy cost of constant and shuttle running in soccer players. Med Sci Sports Exerc 47(6):1219–1224

Tam E, Rossi H, Moia C, Berardelli C, Rosa G, Capelli C, Ferretti G (2012) Energetics of running in top-level marathon runners from Kenya. Eur J Appl Physiol 112:3797–3806

Vanhatalo A, Poole DC, DiMenna FJ, Bailey SJ, Jones AM (2011) Muscle fiber recruitment and the slow component of uptake: constant work rate vs. all-out sprint exercise. Am J Physiol Regul Integ Comp Physiol 300:R700–R707

Weyand PG, Bundle MW (2005) Energetics of high-speed running: integrating classical theory and contemporary observations. Am J Physiol Regul Integr Physiol 288:R956–R965

Winter DA (2009) Biomechanics and motor control of human movement, 4th edn. Wiley, New Jersey

Zamparo P, Zadro I, Lazzer S, Beato M, Sepulcri L (2014) Energetics of shuttle runs: the effects of distance and change of direction. Int J Sports Physiol Perform 9:1033–1039