Title: A new energetics model for the assessment of the power-duration relationship during over-ground running

Authors: C. Vassallo[1*], L. P. Kilduff[1,5], C. Cummins[2,3,4], A. Murphy[2], A. Gray[2], & M. Waldron[1,2,5]

[1]A-STEM, College of Engineering, Swansea University, Swansea, UK

[2]School of Science and Technology, University of New England, NSW, Australia

[3]Carnegie Applied Rugby Research (CARR) centre, Institute for Sport Physical Activity and Leisure, Leeds Beckett University, Leeds, United Kingdom

[4]National Rugby League, Australia

[5]Welsh Institute of Performance Science, Swansea University, Swansea, UK

*Christian Vassallo

Tel: +44 7722335085

Email: christian.vassallo.uk@gmail.com

Abstract

We evaluated the reliability of an over-ground running three-minute all-out test (3MT) and compared this to traditional multiple-visit testing to determine the critical speed (CS) and distance >CS (*D´*). Using a novel energetics model during the 3MT, critical power (CP) and work >CP (*W´*) were also evaluated for reliability and compared to the multiple-visit tests. Over-ground running speed was measured using Global Positioning Systems during fixed-speed trials on a 400 m track to exhaustion, at four intensities corresponding to: i) maximal oxygen uptake ($\dot{V}O_{2max}$) (V_{max}), ii) 110% $\dot{V}O_{2max}$ (110%V_{max}), iii) Δ70% (i.e. 70% of the difference between gas exchange threshold and V_{max}) and iv) Δ85%. The participants subsequently performed the 3MT across two days to determine its reliability. There were no differences between the multiple-visit testing and the 3MT for CS ($P = 0.328$) and *D´* ($P = 0.919$); however, CP ($P = 0.02$) and *W´* ($P < 0.001$) were higher in the 3MT. The reliability of the 3MT was stable ($P > 0.05$) between trials for all variables, with coefficient of variation ranging from 2.0 to 8.1%. The current over-ground energetics model can reliably estimate CP and *W´* based on GPS speed data during the 3MT, which supports its use for most athletic training and monitoring purposes. The reliability of the over-ground running 3MT for power- and speed-related indices was sufficient to detect typical training adaptations; however, it may overestimate CP (~ 25 W) and *W´* (~ 7 kJ) compared to multiple-visit tests.

Key words: Critical power; critical speed; energetics; endurance.

Introduction

The slope of the linear relationship between distance and time (critical speed; CS) and the y-intercept (*D´*) characterise the speed-duration model (Hughson, Orok, & Staudt, 1984). The CS is indicative of the highest rate of oxidative metabolism, below which physiological equilibrium can be maintained and beyond which progressive deviation from homeostasis occurs, resulting in exercise intolerance (Poole, Burnley, Vanhatalo, Rossiter, & Jones, 2016). The *D´* is the finite distance that can be performed above CS (Jones, Vanhatalo, Burnley, Morton, & Poole, 2010). Among athletes whose mode of locomotion is over-ground running, these parameters have been used to profile endurance capacity (Kramer, Clark, Jamnick, Strom, & Pettitt, 2018; Kramer, Watson, Du Randt, & Pettitt, 2019), monitor responses to training interventions (Clark, West, Reynolds, Murray, & Pettitt, 2013; Galbraith, Hopker, Cardinale, Cunniffe, & Passfield, 2014) and determine optimal race or training strategies (Pettitt, 2016; Saari, Dicks, Hartman, & Pettitt, 2019). These applications have been typically based upon estimations of the speed-duration relationship using single-visit tests, of varying composition, in an outdoor setting. The three-minute all-out test (3MT) is the most common among these, typically performed as a maximal sprint effort around an athletics track with no knowledge of elapsed time to discourage pacing (Clark et al., 2013; Kramer et al., 2018; 2019; Pettitt, Jamnick, & Clark, 2012; Saari et al., 2019). Estimations of CS and *D´* from the 3MT compare closely to the traditional multiple-visit testing model, based on both treadmill (Broxterman, Ade, Poole, Harms, & Barstow, 2013) and over-ground running modalities (de Aguiar et al., 2018).

The speed-duration relationship has historically been modelled using the performances of endurance athletes (Hughson et al.,1984), who compete at constant speeds in more predictable environments. More recently, its use among athletes competing in sports that are intermittent in nature, such as the majority of team sports, has been considered (Galbraith, Hopker, & Passfield, 2015; Jones & Vanhatalo, 2017; Saari et al., 2019). Team sports typically involve high-intensity bouts, interspersed by rest or periods of low-intensity activity; this in turn leads to frequent surges above and below the CS, the boundary demarcating the heavy and severe exercise intensity domains (Jones et al. 2010). Whilst there are many practical applications of the speed-duration model to team sport athletes, such as assessment of training adaptation (Clark et al., 2013; Kramer et al., 2018), the use of speed to quantify the physiological demands of team sports appears to be limited (Gray, Shorter, Cummins, Murphy, & Waldron, 2018). The intermittent nature of team sports involve frequent acceleration, deceleration and changes in speed, leading to a de-coupling of the relationship between energetic demand and running speed (Polglaze et al., 2018). Consequently, the speed-duration relationship may be limited in classifying exercise intensity. This could have major implications for the accurate monitoring of training load in team sports players. For example, high-intensity (i.e. energy demanding) movements in team sports often occur at low-speed (Gray et al., 2018; Osgnach, Poser, Bernardini, Rinaldo, & di Prampero, 2010). The energy cost of running is elevated by increasing both absolute speed and its rate of change (Buglione & di Prampero, 2013). This has been recently attributed to greater mechanical demands of non-constant speed running, such as deceleration, acceleration and changing direction (Zamparo et al., 2019). Therefore, the suggested application of the speed-duration (rather than power-duration) model to intermittent exercise (Galbraith et al., 2015; Jones & Vanhatalo, 2017) would be unable to capture all energy-demanding aspects of exercise, particularly at low speeds, resulting in poorer estimations of exercise tolerance.

To the authors' knowledge, there has been no investigation of the power-duration relationship during over-ground running. Our recent development of a new over-ground mechanical power model could, therefore, be applied to facilitate characterisation of the power-duration model during over-ground running in team sports athletes (Gray et al., 2018; Gray, Andrews, Waldron, & Jenkins, 2020). Using principles from work-energy theorem, this model algebraically summates positive and negative external work done across body segments using running velocity, alongside known participant characteristics and environmental conditions (Gray et al., 2020). Since work done is explained by a combination of many energy-demanding processes, such as acceleration of the centre of mass (CoM) and movement of the limbs (Zamparo et al., 2019), this model considers factors other than constant horizontal speed achieved by an athlete, better quantifying the demands of intermittent movement. Thus, modelling the power-duration relationship would be more suitable than the speed-duration relationship for monitoring intermittent performance.

However, understanding of the reliability and validity of over-ground power modelling and its utilisation for determining parameters of the power-duration relationship (critical power; CP and the finite work > CP; *W´*) are required prior to further application. Therefore, the aim of the current study was to compare a single visit over-ground running 3MT to traditional multiple-visit procedures to determine parameters of the over-ground speed-duration (CS and *D´*) and over-ground power-duration (CP and *W´*) models. Finally, the test re-test reliability of the 3MT was evaluated for both speed- and power-based parameters.

Methods

Participants

Following institutional ethical approval, nine healthy male participants (age = 24 ± 3 years; body mass = 70.8 ± 6.0 kg; stature = 1.75 ± 0.03 m; maximal oxygen uptake ($\dot{V}O_{2max}$) = 4.4 ± 0.5 L/min) provided written, informed consent to participate in this study. Participants were asked to replicate similar food patterns, refrain from strenuous exercise and not consume alcohol or caffeine 24 h prior to each exercise trial.

Study design

Participants visited the testing facility on seven occasions, each separated by between 48 and 72 h. During visit one, participants were tested for their $\dot{V}O_{2max}$ and the gas exchange threshold (GET) using a graded exercise test on a treadmill, as well as being familiarised to all track-based tests. On visits 2-5, the participants completed fixed-speed over-ground running trials to exhaustion (T_{lim}) at four randomised intensities, expressed relative to the running speeds attained at GET (V_{GET}) and $\dot{V}O_{2max}$ (V_{max}). Accordingly, these were i) $\dot{V}O_{2max}$ (V_{max}), ii) 110% $\dot{V}O_{2max}$ (110%V_{max}), iii) Δ70% (i.e. 70% of the difference between GET and V_{max}) and iv) Δ85%. All speeds were determined from treadmill tests to elicit exhaustion within 2 and 15 min (Triska, Karsten, Nimmerichter, & Tschan, 2017). On visits 6 and 7, the participants performed all-out 3MT on a 400 m running track to evaluate the test re-test reliability between days. The CP, CS, *W´* and *D´* determined from the 3MT on visit 7 were compared to those determined by the multiple-visit method. Visit 7 was selected as it represented the most familiarised visit.

Procedures

Preliminary testing

After a 5-min warm-up at 5 km/h, the participants performed a graded exercise test to exhaustion on a recently calibrated, motorized treadmill (HP Cosmos Pulsar; HP Cosmos Sports and Medical, Nussdorf-Traunstein, Germany). The test began at 6 km/h and was conducted at a fixed gradient of 1% to simulate air resistance (Jones & Doust, 1996). Treadmill speed was increased by 0.5 km/h each minute, until volitional exhaustion. V_{max} was determined as the velocity that corresponded to $\dot{V}O_{2max}$, which was adjusted (V_{max} = stage speed (km/h) + time completed (s) / 60 × 0.5) when a stage of the test was not completed. Respiratory gases were collected and measured breath-by-breath (Jaeger Vyntus CPX, Hoechberg, Germany), with $\dot{V}O_{2max}$ determined as the highest 30-s mean value. The $\dot{V}O_2$ and $\dot{V}CO_2$ data were used to plot the GET, based on a combination of the V-slope method (Beaver, Wasserman, & Whipp, 1986) and ventilatory equivalents (Caiozzo et al., 1982). The treadmill velocity corresponding to the GET and V_{max} were used to determine the Δ70% and Δ85% for subsequent T_{lim} trials. Two-thirds of the ramp rate was deducted from GET and V_{max} velocities, accounting for mean $\dot{V}O_2$ time response during constant work-rate exercise (Whipp, Torres, Davis, & Wasserman, 1981).

Over-ground power- and speed-duration relationship determined from multiple visits

For each trial, a 10-Hz GPS device (FieldWiz, ASI, Lausanne, Switzerland) was fitted between the participant's shoulder blades and secured to the body within a harness to restrict movement artefacts. The FieldWiz GPS device has provided comparable (CV = 2.0-5.6%; ICC = > 0.8) and reliable (CV = 0.8-2.2%; ICC = > 0.9) measures of peak velocity and total distance during linear and multidirectional motion (Willmott, James, Bliss, Leftwich, & Maxwell, 2019) in relation to a previously validated device (Varley, Fairweather, & Aughey, 2012). Participants completed a series of four randomized constant speed tests to T_{lim} on the inside lane of a 400 m outdoor synthetic track at a similar time of day (± 3 h). The intensities were all suitable to achieve T_{lim} between ~ 2 and 15 min (Jones & Vanhatalo, 2017). The mean temperature and relative humidity were 12 ± 6 °C and 54 ± 19 %, respectively, with wind speeds of 7 ± 5 km/h, with 14 km/h the highest recorded. The speed of each trial was regulated by a combination of cones placed at 10 m intervals around the inside of the athletics track and an audio file, which delivered a ‘beep’ sound at a pre-determined frequency. The participants were asked to control their running speed, such that the audio tone corresponded to their feet intersecting with each 10 m cone. The frequency of the audio tones was modulated between each trial to match the intended speed of each participant. The audio file was delivered to the participants through wireless headphones on a continuous loop. All trials began with a low-cadence walk (1.5 m/s), and audio tones were increased every ~ 20 s until the prescribed speed was attained. The participant’s audio track was synchronised to an external device, permitting monitoring of the participants’ pacing throughout the trials. This process was practiced during the familiarisation (visit 1). The trial was terminated upon volitional exhaustion or an inability to maintain the required speed for ten consecutive 10 m intervals. In this instance, T_{lim} was recorded from the start of the test to the first missed cone. A handheld stopwatch was used to measure T_{lim}. Participants were not informed of elapsed time and no verbal encouragement was provided. If a cone was missed, the participant was verbally warned and instructed to slowly progress their speed to avoid sharp accelerations. If the participants were unable to reach the necessary speed in the subsequent 10 cones, the previous criteria were applied. Calculation of the CP or CS and *W´* or *D´* was based on linear regression of the work done (W) (equation 1) or distance covered (D) (equation 2) *vs.* T_{lim} (Monod & Scherrer, 1965) as follows:

$$\mathrm{W} = \mathrm{CP} \times \mathrm{T}_{\mathrm{lim}} + W' \qquad \text{(equation 1)}$$

$$\mathrm{D} = \mathrm{CS} \times \mathrm{T}_{\mathrm{lim}} + D' \qquad \text{(equation 2)}$$

Where W is in kJ, T_{lim} is in s and D is in m.

Over-ground power- and speed-duration relationships determined from the 3MT

Visits 6 and 7 each comprised a 3MT. Both protocols were preceded by a standardised warm-up, comprising walking, jogging, dynamic stretching and one 10 m sprint. Participants were instructed to perform a sustained all-out sprint effort in an anticlockwise direction on either of the two outermost lanes of a six lane 400 m athletics track. The start line was randomly altered between visits. Strong verbal encouragement was provided by investigators situated around the perimeter of the track, although no information on elapsed or remaining time was given to discourage pacing. The 3MT was terminated once 185 s had elapsed, in order to ensure a complete 180-s data segment was obtained. The mean speed achieved during the final 30 s of the test was determined as CS, while the distance (m) > CS (*D´*) was calculated according to equation 2. Speed data derived from GPS was modelled to determine mechanical work (J) and over-ground power (W). Critical power (W) was determined by the mean power output during the last 30 s, while *W´* (kJ) was calculated as work performed (kJ) > CP, according to equation 1.

Modelling over-ground power

For each outdoor trial (visits 2-7), raw velocity data (10 Hz) were downloaded from the GPS device and exported to Microsoft Excel (Microsoft Corp., Redmond, USA). From this, estimations of work and power were made using an energetics model, previously applied to running-based sports (Cummins, Gray, Shorter, Halaki, & Orr, 2016; Furlan et al., 2015; Gray et al., 2018), with its underpinning theory validated (Gray et al., 2020; Zamparo et al., 2019). Drawing upon principles of work-energy theorem, and established relationships between running speed and the body's kinematics (Gray et al., 2018; 2020), this model provides estimates of mechanical work done in J and mechanical power (P) in W on a sample-by-sample basis during over-ground running. This model partitions total mechanical work (W_{total}) done into external work (W_{ext}) and internal work (W_{int}), where W_{ext} is work done to accelerate the centre of mass (CoM) with respect to the environment and W_{int} is work associated with the acceleration of body segments with respect to the CoM. Therefore, total mechanical work (J) is given by:

$$\mathrm{W_{tot}} = \mathrm{W_{ext}} + \mathrm{W_{int}} \qquad \text{(equation 3)}$$

Additionally, work done can be positive or negative. When the kinetic (KE) and/or potential energies (PE) of a mass are increased, positive work (W_+) is done; when decreased, negative work (W_-) is done. During over-ground running the CoM is also accelerated in the horizontal (W_{hor}) and vertical (W_{vert}) planes (Cavagna et al., 1964), whilst also being subject to air resistance (W_{air}) (di Prampero, 1986). Thus, external work done ($J{\cdot}kg^{-1}$) is given by:

$$\mathrm{W_{ext} = W_{hor} + W_{vert} + W_{air}} \qquad \text{(equation 4)}$$

Using an equation from Minetti (1998), internal work (W_{int}) is modelled from velocity, stride frequency, duty factor (the percentage of the stride cycle in which a single limb is in the stance phase) and a constant reflecting the inertial properties of the limbs. In the absence of uneven terrain, varying loads or changes in wind direction and speed, body mechanics are tightly coupled with forward velocity in running (Gray et al., 2019; 2020). As such, stride frequency and duty factor are readily modelled from GPS derived running velocity, enabling the subsequent determination of work done to swing the limbs around the CoM (W_{limbs}). Thus, internal work done ($J{\cdot}kg^{-1}$) is given by:

$$\mathrm{W_{int} = W_{limbs}} \qquad \text{(equation 5)}$$

Therefore, starting with knowledge of forward running speed, total work done (W_{tot} in J) and P (W) were derived by dividing work done by the sample duration (0.1 s) to produce a P - time curve. This modelling was applied to raw velocity data for visits 2-7.

Statistical analysis

All statistical analyses were performed using Statistical Package for Social Sciences (SPSS, version 22; SPSS, Inc., IL, USA). Following tests of normality, paired *t*-tests were used to compare the CS, *D´*, CP and *W´* of the multiple-visit and 3MT, as well as the test re-test of the 3MT. The absolute error of the method comparison and the reliability data was evaluated using the coefficient of variation (CV) (Atkinson & Nevill,

1998) along with associated 95% confidence intervals. Significant differences were identified when $P < 0.05$.

Results

Comparison of the 3MT to multi-visit tests

Parameters for each participant are presented for the multiple-visit tests (Table 1) and the 3MT (Table 2). There were no systematic differences identified between the multiple-visit tests and the 3MT for the CS (3.7 ± 0.2 vs. 3.6 ± 0.4 m/s, $P = 0.328$) and *D´* (145 ± 38 vs. 144 ± 29 m, $P = 0.919$), respectively. However, there were differences between the multiple-visit tests and 3MT for the CP (424 ± 29 vs. 450 ± 46 W, $P = 0.020$) and *W´* (19 ± 6 vs. 25 ± 8 kJ, $P < 0.001$), respectively. These values were descriptively higher in the 3MT in seven out of the nine participants. The CV (± 95 CI) for all variables were as follows: CS = 4.4 ± 2.9 %; *D´* = 12.5 ± 5.1 %; CP = 5.1 ± 1.9 %; *W´* = 20.8 ± 10.3 %.

Table 1. Multiple-visit testing parameters derived from the linear distance- and work-time models to characterise the speed- and power-duration relationships. SEE = Standard error of the estimate for *D´* (m) and *W´* (kJ), respectively.

	T_{lim} (s)				**Distance-Time Model**				**Work-Time Model**			
Partici-pant	**Δ70 %**	**Δ85 %**	**V_{max}**	**110% V_{max}**	**Multi-visit CS (m/s)**	**Multi-visit *D´* (m)**	**r^2**	**SEE (m)**	**Multi-visit CP (W)**	**Multi-visit *W´* (kJ)**	**r^2**	**SEE (kJ)**
1	605	341	239	108	3.7	99	1.000	7.9	430	13	1.000	0.4
2	870	606	298	188	4.0	176	0.998	62.8	397	22	0.997	7.5
3	843	600	290	176	3.6	199	0.999	45.5	440	28	1.000	5.4
4	823	620	264	155	3.5	187	0.996	82.8	450	25	0.997	9.8
5	881	670	310	162	4.0	156	0.999	42.7	478	23	0.999	5.8
6	595	412	189	125	3.7	103	0.999	32.9	385	11	0.999	2.8
7	770	457	225	109	3.8	106	0.999	35.8	415	13	0.999	3.3
8	774	443	219	111	3.6	127	0.999	39.2	419	16	0.999	3.8
9	797	495	241	119	3.7	149	1.000	30.9	402	18	1.000	2.8
Mean	773	516	253	139	3.7	145	0.999		424	19	0.999	
SD	105	112	41	31	0.2	38	0.001		29	6	0.001	

Table 2. Three-minute all-out test (3MT) parameter estimates of the speed- and power-duration relationships for trial 1 (3MT 1) and trial 2 (3MT 2).

	Speed-Time Model				**Power-Time Model**			
Participant	**3MT 1 CS (m/s)**	**3MT 2 CS (m/s)**	**3MT 1 *D´* (m)**	**3MT 2 *D´* (m)**	**3MT 1 CP (W)**	**3MT 2 CP (W)**	**3MT 1 *W´* (kJ)**	**3MT 2 *W´* (kJ)**
1	4.0	3.9	150	125	435	429	28	23
2	3.9	3.8	145	147	455	435	23	23
3	3.6	3.6	195	171	456	474	34	41
4	3.1	3.1	192	200	480	477	29	31
5	3.9	4.2	115	107	500	518	24	23
6	3.0	3.0	128	138	377	361	13	15
7	3.5	3.7	131	123	414	428	24	22
8	3.4	3.6	130	121	452	492	20	17
9	3.7	3.7	171	160	420	432	31	27
Mean	3.6	3.6	151	144	443	450	25	25
SD	0.4	0.4	29	29	37	46	6	8

Test re-test reliability of the 3MT

The test re-test reliability of the 3MT demonstrated no systematic differences for CS (3.6 ± 0.4 m/s vs. 3.6 ± 0.4 m/s, $P = 0.179$), *D´* (151 ± 29 vs. 144 ± 29 m, $P = 0.119$), CP (443 ± 37 vs. 450 ± 46 W, $P = 0.343$) and *W´* (25 ± 6 vs. 25 ± 8 kJ, $P = 0.749$). The CV (± 95 CI) for all variables were as follows: CS = 2.0 ± 0.9 %; *D´* = 5.6 ± 2.3 %; CP = 2.6 ± 1.0 %; *W´* = 8.1 ± 3.2 %.

Representative traces of speed and modelled power output during the multiple-visit tests (Figure 1) and the 3MT (Figure 2) are presented for a single participant.

****Insert Figure 1 here****

****Insert Figure 2 here****

Discussion

The current study evaluated the test re-test reliability of the 3MT to characterise both the over-ground running speed-duration and, for the first time, modelled power-duration relationships. These speed- and power-duration parameters were also compared to the traditional multi-visit derivation. There was a consistent performance of the 3MT between repeated visits, with all four parameters producing CV ranging from 2.0 to 8.1%, and no systematic differences between trials. The CS as derived from the 3MT compared closely to the multiple-visit testing (4.4% CV), yet *D´* had greater variation (12.5% CV). However, CP and *W´* were higher in the 3MT versus the traditional multiple-visit tests ($P < 0.05$) with a concomitant higher CV (5.1% and 20.8%, respectively) as compared to the speed-based parameters. Collectively, the results support the reliability of the over-ground 3MT for both power- and speed-related indices. Whilst the CS and *D´* also compare closely to the multiple-visit test, modelling over-ground power using the 3MT appears to produce larger parameter estimates of the power-duration relationship.

The close comparison of CS between multiple-visit testing and the 3MT (4.4% CV) is consistent with studies comparing laboratory and field-based single-visit methods comprising three maximal effort runs, with CV ranging between 0.4 to 3.8% (Galbraith, Hopker, Lelliot, Diddams, & Passfield, 2014; Triska et al., 2017). The *D´* error reported in this study for the multiple-visit testing and the 3MT (12.5% CV) also compares closely with the literature, with CV reported between 13.0 to 18.7% (Galbraith et al. 2014; Triska et al., 2017).

Modelled over-ground power parameters demonstrated less agreement between testing modes, despite being primarily based upon over-ground speed, with CV ranges of 5.1 to 20.8% *vs.* 4.4 to 12.5% for power and speed parameters, respectively. This was likely related to the computational framework of the adopted energetics model (Gray et al., 2020). During constant speed running, the model returns W_{hor} values of zero i.e. when acceleration is zero, no work is done by the CoM in the horizontal plane. As such, the work estimates produced by the model are attributable to W_{vert} (~ 55% at 4 m/s) and W_{limbs} (~ 40% at 4 m/s) (Gray et al., 2020); components that are modelled from the findings of prior experimental works on CoM motion (Ito, Komi, Sjödin, Bosco, & Karlsson, 1983; Lee & Farley 1998) and mechanical internal work during locomotion (Minetti, 1998; Nardello, Ardigò, & Minetti, 2010). However, despite substantial efforts to pace the participants during the fixed-speed trials, there is inevitable fluctuation in over-ground speed. The model correctly equates these accelerations to work done in the horizontal plane (W_{hor}). That is; minor unavoidable fluctuations in running speed translate to a heavier weighting in the work/power domain, thus application of the model might inherently lead to greater variation in estimated work done, even during 'intended' steady-state trials.

The effects of minor speed fluctuations on the modelled over-ground power are observable in Figure 1 for a representative participant, where variation in the intended flat pacing profile leads to increased corresponding power values, relative to the change in speed. To demonstrate this, applying the over-ground model to this participant, a minor acceleration of 0.2 m/s^2 during 0.1-s segment of a steady state trial, was equivalent to a combined W_{vert} and W_{hor} of 26.3 J (~ 50% of W_{tot}). Thus, the multiple components of modelled work result in a relatively greater magnitude of variation as compared to speed. The magnitude of these values is, perhaps, best understood by normalising them to their maxima during the 3MT. In the same participant, their maximal combined W_{vert} and W_{hor} across 0.1-s was ~141 J, while their corresponding maximal acceleration was 8.8 m/s^2. Our example values therefore represent 18.6% and 2.3% of the maximal W_{vert} + W_{hor} and acceleration, respectively, which highlights the potential for unequal variation in these measures. Interestingly, as the 8.8 m/s^2 acceleration also elicited the highest W_{vert} + W_{hor} value, this highlights the important point that all elements of the model will contribute to the overall work done and that during periods of presumed 'steady state' running the instantaneous work estimations will be more sensitive to speed changes. The cumulative effect of this across the constant work bouts translates to higher relative change values of work compared to speed. Therefore, speed and distance might compare well between methods but power and work might not. Notably, variations in speed are more frequent during the 3MT, characterised by the rapid acceleration phase, progressive deceleration phase and the presumed constant-speed period thereafter. The overall consequence of this is that running bouts with more speed variation will lead to larger discrepancies between parameters of power, rather than speed, which is consistent with our findings. As a result, the CP (~ 25 W) and *W´* (~ 7 kJ) are overestimated by the 3MT, and the 20.8% variation in *W´* could lead to a seemingly inaccurate quantification of this parameter. While estimated work done is accurately captured by the model, this disturbs the direct assessment of the two testing methods – particularly where steady states are assumed. Thus, this study highlights the potential incompatibility of physiological assessments when using the speed-time or power-time relationship. This might be important to potential users if gold standard measures of CP, and particularly *W´*, are necessary.

The test re-test reliability values of all variables compared closely to laboratory-based reports, where the 3MT conducted on a cycling ergometer demonstrated CV values of 1.2% and 5.4% and SEE of 6.4 W and 2.7 kJ for CP and *W´*, respectively (Vanhatalo, Doust, & Burnley, 2007; Wright, Bruce-Low, & Jobson, 2017). Furthermore, estimation of the speed-duration relationship during over-ground running using the 3MT has previously demonstrated CV values of 3.0% and 5.1% for CS and *D´*, respectively (de Aguiar et al., 2018). Thus, errors measured herein for the CS (2.0% CV) and *D´* (5.6% CV) in the 3MT are consistent with those reported previously. However, for the first time, the current study extends these findings to over-ground running CP (2.6% CV), which compared closely to CS (2.0% CV), as measured by the 3MT. In contrast, *W´* and *D´* error measured at 8.1% and 5.6% CV, respectively, in the 3MT. The poorer test re-test reliability of *D´* and *W´* parameters has been reported previously (Gaesser & Wilson, 1988; Johnson, Sexton, Placek, Murray, & Pettitt, 2011), wherein *D´* and *W´* consistently produced greater variability in comparison to the CS or CP.

The greater variation in CP and *W´* might be further explained by nuances of the over-ground energetics model, where variance in total work done can be sensitive to fluctuations in horizontal speed (i.e. accelerating and decelerating). It is feasible that slightly poorer reliability of the power-duration model is related to the sensitivity of the energetics model in estimating work done across stages of the 3MT involving acceleration and deceleration. This is particularly noteworthy during the initial acceleration phase, which is demonstrated effectively in Figure 2. Here, the integral of the power-time relationship above CP during initial acceleration (i.e. *W´*) in this representative participant is descriptively larger in test 1 compared to test 2. During acceleration, approximately 25% of the variance in work done is explained by W_{hor}, where large amounts of total work are achieved (peak values of ~ 31 W/kg) (Gray et al., 2020). Thus, minor alterations in the initial acceleration profile of participants between visits would lead to increased estimations of total work done (*W´*), thereby affecting the reliability of the test above that demonstrated by *D´*.

The current data provide the first evidence that a field-based 3MT can produce reliable parameter estimates of the power- and speed-duration relationship. However, to appropriately evaluate measurement error (reliability), the CV of the derived parameters should be considered relative to a signal change of practical relevance (Atkinson & Nevill, 1998). For example, CS can increase by between 6.0% and 8.6 % in soccer players following four-week (Clark et al., 2013) and six-week (Karsten et al., 2016) training interventions, respectively. Based on the current study, the reliability of the test would permit detection of these changes, since the noise (error of 2.0%) is less than the signal change. Owing to the paucity of current data relating to over-ground CP and *W´*, it is more challenging to understand the acceptability of our reliability values. However, unpublished data produced from our laboratory indicates that the measurement error would be sufficiently small to allow detection of changes in these variables as a result of a field-based training intervention, which are of a similar magnitude to speed-based metrics.

There are a number of potential error sources during the current testing procedure, such as the type of micro-technology used. In the current study, we used a GPS device, sampling at 10 Hz. Others have used wrist-mounted accelerometers for similar purposes, without reporting the technical specification or reliability of the device (Broxterman et al., 2013). Owing to the reported reliability of the current GPS devices during this type of locomotion (CV = 2%; Wilmott et al., 2019), this technology would be the more preferable option for measurement of outdoor over-ground speed. It is also possible that both of these devices do not provide a valid measure of over-ground speed; however, GPS devices typically underestimate criterion measures of velocity at higher movement speeds and during directional changes (Duffield, Reid, Baker, & Spratford, 2010), which is not the case during the fixed-speed trials or the final 30 s of the 3MT. The variability of GPS devices at higher speeds could, however, explain some of the increased error between visits for the *D´* and *W´*. As discussed above, in this instance, the accumulation of seemingly minor horizontal speed fluctuations will accrue error in the W_{hor} portion of the over-ground model. Ongoing improvements in micro-technology and filtering processes will facilitate more robust characterisation of the speed-duration and, thus, power-duration relationship. Furthermore, variability on behalf of the participants (i.e. biological error; Hopkins, 2000) is expected during test re-test study designs, which contributed to the observed testing error. The reliability values reported herein, therefore, support the conduct of the current study, which included a familiarisation trial to assist with the participants' understanding of the necessary all-out effort. Accordingly, we would advise that a familiarisation trial is performed by potential users of the over-ground running 3MT.

Practical considerations

There are several assumptions upon which our modelling of over-ground power was based. The vertical displacement of the CoM, stride frequency and duty factor were predicted from knowledge of forward velocity. The effects of fatigue (Brueckner et al., 1991), size (Saibene & Minetti, 2003), running surface (Lejeune, Willems, & Heglund, 1998), running ability (Paradisis et al., 2019) and other contextual factors on these kinematic variables were unaccounted. Nonetheless, this serves as a first approximation until direct field-based measurement of these variables is possible. Additionally, oscillation of the CoM is quantified by changes in potential energy with movement in the coronal plane assumed to be negligible (Gray et al. 2020). The mechanical demand of air resistance encountered from headwinds is also not considered. However, at submaximal speeds (3 m/s) against a 5 m/s headwind the difference has been shown to be negligible (0.15 W/kg) (Gray et al., 2020). Moreover, the mechanical demand of swinging the limbs is based on a prediction equation that assumes four limbs are straight segments with fixed inertial properties across all running speeds, which does not account for interindividual differences in limb kinematics (Minetti, 1998). Nonetheless, the prediction equation provides values within 1 W/kg of gold standard measures (Pavei et al., 2019), thus offering a robust alternative to direct measurement.

The current study has important implications for the application of both the over-ground running energetics model and its coupling with the critical power concept. We have recently argued for the utilisation of the current energetics model to derive mechanical work done during team sports performance (Gray et al., 2018). This permits the sports practitioner to monitor external load during low-speed, yet high-intensity movements, which are typical of field-based training and competition. However, using modelled over-ground power to characterise the power-duration relationship enables the practitioner, for the first time, to establish a well-known threshold of endurance performance (i.e. CP) and continuously monitor the utilisation and reconstitution of internal energetic indices, such as *W´* using non-invasive methods. This has been previously achieved in cycling to predict performance (Skiba, Chidnok, Vanhatalo, & Jones, 2012; Townsend, Nichols, Skiba, Racinais, & Périard, 2017) and during intermittent running (Vassallo, Gray, Cummins, Murphy, & Waldron, 2020). The CP and *W´* can also be used to profile athletes, prescribe training intensities, predict performance and monitor responses to training programmes (Jones et al., 2010; Jones & Vanhatalo, 2017; Vanhatalo, Jones, & Burnley, 2011), which we encourage team sports practitioners to do by performing 3MT and modelling over-ground power (Gray et al., 2020; Vassallo et al., 2020). The 3MT produced reliable results, which would support its use to detect typical changes in the power-duration relationship; however using the multiple-visit test or use of the speed-based parameters would be preferable if the higher estimations of CP (~ 25 W) and *W´* (~ 7 kJ) are unacceptable. Of course, sports practitioners may also need to consider the time constraints of their environment when choosing between the 3MT and multiple-visit tests.

Conclusion

The results of the current study demonstrate the reliability of the over-ground running 3MT for both power- and speed-related indices. While the 3MT can be used to produce reliable speed-based parameters, characterisation of the power-duration relationship will overestimate CP and *W´* compared to traditional multiple-visit tests and produce more variable results. Therefore, we provide evidence that the current over-ground energetics model can reliably estimate CP and *W´* from GPS speed data during the 3MT, which supports its use for athletic training and monitoring purposes. However, the overestimation of traditional methods means that there will be some unsuitable applications, depending on the importance of this to the user and their tolerance of error.

Disclosure statement

Authors report no potential conflict of interest.

References

Atkinson, G., & Nevill, A. M. (1998). Statistical methods for assessing measurement error (reliability) in variables relevant to sports medicine. *Sports Medicine*, *26*(4), 217–238. doi:10.2165/00007256-199826040-00002

Beaver, W. L., Wasserman, K., & Whipp, B. J. (1986). A new method for detecting anaerobic threshold by gas exchange. *Journal of Applied Physiology, 60*(6), 2020–2027. doi:10.1152/jappl.1986.60.6.2020

Broxterman, R. M., Ade, C. J., Poole, D. C., Harms, C. A., & Barstow, T. J. (2013). A single test for the determination of parameters of the speed-time relationship for running. *Respiratory Physiology & Neurobiology*, *185*(2), 380–385. doi:10.1016/j.resp.2012.08.024

Brueckner, J. C., Atchou, G., Capelli, C., Duvallet, A., Barrault, D., Jousselin, E., Rieu, M., & di Prampero, P. E. (1991). The energy cost of running increases with the distance covered. *European Journal of Applied Physiology and Occupational Physiology*, *62*(6), 385–389. doi:10.1007/BF00626607

Buglione, A., & di Prampero, P. E. (2013). The energy cost of shuttle running. *European Journal of Applied Physiology*, *113*(6), 1535–1543. doi:10.1007/s00421-012-2580-9

Caiozzo, V. J., Davis, J. A., Ellis, J. F., Azus, J. L., Vandagriff, R., Prietto, C. A., & McMaster, W. C. (1982). A comparison of gas exchange indices used to detect the anaerobic threshold. *Journal of Applied Physiology: Respiratory, Environmental and Exercise Physiology*, *53*(5), 1184–1189. doi:10.1152/jappl.1982.53.5.1184

Cavagna, G. A., Saibene, F., & Margaria, R. (1964). Mechanical work in running. *Journal of Applied Physiology, 19*, 249-256. doi:10.1152/jappl.1964.19.2.249

Clark, I. E., West, B. M., Reynolds, S. K., Murray, S. R., & Pettitt, R. W. (2013). Applying the critical velocity model for an off-season interval training program. *Journal of Strength and Conditioning Research*, *27*(12), 3335–3341. doi:10.1519/JSC.0b013e31828f9d87

Cummins, C., Gray, A., Shorter, K., Halaki, M., & Orr, R. (2016). Energetic and metabolic power demands of national rugby league match-play. *International Journal of Sports Medicine*, *37*(7), 552–558. doi:10.1055/s-0042-101795

de Aguiar, R. A., Salvador, A. F., Penteado, R., Faraco, H. C., Pettitt, R. W., & Caputo, F. (2018). Reliability and validity of the 3-min all-out running test.

Revista Brasileira Ciências do Esporte, 40(3), 288-294. doi:10.1016/j.rbce.2018.02.003

di Prampero, P. E. (1986). The energy cost of human locomotion on land and in water. *International Journal of Sports Medicine, 7*(1), 55-72. doi:10.1055/s-2008-1025736

Duffield, R., Reid, M., Baker, J., & Spratford, W. (2010). Accuracy and reliability of GPS devices for measurement of movement patterns in confined spaces for court-based sports. *Journal of Science and Medicine in Sport*, *13*(5), 523–525. doi:10.1016/j.jsams.2009.07.003

Furlan, N., Waldron, M., Shorter, K., Gabbett, T. J., Mitchell, J., Fitzgerald, E., Osborne, M. A., & Gray, A. J. (2015). Running-Intensity Fluctuations in Elite Rugby Sevens Performance. *International Journal of Sports Physiology and Performance*, *10*(6), 802–807. doi:10.1123/ijspp.2014-0315

Gaesser, G. A., & Wilson, L. A. (1988). Effects of continuous and interval training on the parameters of the power-endurance time relationship for high-intensity exercise. *International Journal of Sports Medicine, 9*(6), 417–421. doi:10.1055/s-2007-1025043

Galbraith, A., Hopker, J., Lelliott, S., Diddams, L., & Passfield, L. (2014). A single-visit field test of critical speed. *International Journal of Sports Physiology and Performance, 9*(6), 931–935. doi:10.1123/ijspp.2013-0507

Galbraith, A., Hopker, J., Cardinale, M., Cunniffe, B., & Passfield, L. (2014). A 1-year study of endurance runners: training, laboratory tests, and field tests. *International Journal of Sports Physiology and Performance*, *9*(6), 1019–1025. doi:10.1123/ijspp.2013-0508

Galbraith, A., Hopker, J., & Passfield, L. (2015). Modeling intermittent running from a single-visit field test. *International Journal of Sports Medicine*, *36*(5), 365–370. doi:10.1055/s-0034-1394465

Gray, A. J., Shorter, K., Cummins, C., Murphy, A., & Waldron, M. (2018). Modelling movement energetics using global positioning system devices in contact team sports: Limitations and solutions. *Sports Medicine, 48*(6), 1357–1368. doi:10.1007/s40279-018-0899-z

Gray, A., Andrews, M., Waldron, M., & Jenkins, D. (2020). A model for calculating the mechanical demands of overground running. *Sports Biomechanics*. doi:10.1080/14763141.2020.1795238

Hopkins, W. G. (2000). Measures of reliability in sports medicine and science. *Sports Medicine, 30*(1), 1–15. doi:10.2165/00007256-200030010-00001

Hughson, R. L., Orok, C. J., & Staudt, L. E. (1984). A high velocity treadmill running test to assess endurance running potential. *International Journal of Sports Medicine, 5*(1), 23–25. doi:10.1055/s-2008-1025875

Ito, A., Komi, P. V., Sjödin, B., Bosco, C., & Karlsson, J. (1983). Mechanical efficiency of positive work in running at different speeds. *Medicine & Science in Sports & Exercise*, *15*(4), 299–308. doi:10.1249/00005768-198315040-00009

Johnson, T. M., Sexton, P. J., Placek, A. M., Murray, S. R., & Pettitt, R. W. (2011). Reliability analysis of the 3-min all-out exercise test for cycle ergometry. *Medicine and Science in Sports and Exercise*, *43*(12), 2375–2380. doi:10.1249/MSS.0b013e318224cb0f

Jones, A. M., & Doust, J. H. (1996). A 1% treadmill grade most accurately reflects the energetic cost of outdoor running. *Journal of Sports Sciences*, *14*(4), 321–327. doi:10.1080/02640419608727717

Jones, A. M., Vanhatalo, A., Burnley, M., Morton, R. H., & Poole, D. C. (2010). Critical power: Implications for determination of V̇O2max and exercise tolerance. *Medicine & Science in Sports & Exercise, 42*(10), 1876–1890. doi:10.1249/mss.0b013e3181d9cf7f

Jones, A. M., & Vanhatalo, A. (2017). The 'critical power' concept: Applications to sports performance with a focus on intermittent high-intensity exercise. *Sports Medicine, 47*(1), 65–78. doi:10.1007/s40279-017-0688-0

Karsten, B., Larumbe-Zabala, E., Kandemir, G., Hazir, T., Klose, A., & Naclerio, F. (2016). The effects of a 6-week strength training on critical velocity, anaerobic running distance, 30-m sprint and yo-yo intermittent running test performances in male soccer players. *PLoS ONE*, *11*(3), e0151448. doi:10.1371/journal.pone.0151448

Kramer, M., Clark, I. E., Jamnick, N., Strom, C., & Pettitt, R. W. (2018). Normative data for critical speed and *D'* for high-level male rugby players. *Journal of Strength and Conditioning Research*, *32*(3), 783–789. doi:10.1519/JSC.0000000000001880

Kramer, M., Watson, M., Du Randt, R., & Pettitt, R. W. (2019). Critical speed as a measure of aerobic fitness for male rugby union players. *International Journal* *of Sports Physiology and Performance*, *14*(4), 518–524. doi:10.1123/ijspp.2018-0411

Lee, C. R., & Farley, C. T. (1998). Determinants of the center of mass trajectory in human walking and running. *The Journal of Experimental Biology*, *201*(Pt 21), 2935–2944.

Lejeune, T. M., Willems, P. A., & Heglund, N. C. (1998). Mechanics and energetics of human locomotion on sand. *The Journal of Experimental Biology*, *201*(13), 2071–2080.

Minetti, A. E. (1998). A model equation for the prediction of mechanical internal work of terrestrial locomotion. *Journal of Biomechanics*, *31*(5), 463–468. doi:10.1016/s0021-9290(98)00038-4

Monod, H., & Scherrer, J. (1965). The work capacity of a synergic muscular group. *Ergonomics, 8*(3), 329–338. doi:10.1080/00140136508930810

Osgnach, C., Poser, S., Bernardini, R., Rinaldo, R., & di Prampero, P. E. (2010). Energy cost and metabolic power in elite soccer: A new match analysis approach. *Medicine & Science in Sports & Exercise*, *42*(1), 170–178. doi: 10.1249/MSS.0b013e3181ae5cfd

Paradisis, G. P., Bissas, A., Pappas, P., Zacharogiannis, E., Theodorou, A., & Girard, O. (2019). Sprint mechanical differences at maximal running speed: Effects of performance level. *Journal of Sports Sciences*, *37*(17), 2026–2036. doi:10.1080/02640414.2019.1616958

Pavei, G., Zamparo, P., Fujii, N., Otsu, T., Numazu, N., Minetti, A. E., & Monte, A. (2019). Comprehensive mechanical power analysis in sprint running acceleration. *Scandinavian Journal of Medicine & Science in Sports*, *29*(12), 1892–1900. doi:10.1111/sms.13520

Pettitt, R. W., Jamnick, N., & Clark, I. E. (2012). 3-min all-out exercise test for running. *International Journal of Sports Medicine*, *33*(6), 426–431. doi:10.1055/s-0031-1299749

Pettitt, R. W. (2016). Applying the critical speed concept to racing strategy and interval training prescription. *International Journal of Sports Physiology and Performance*, *11*(7), 842–847. doi:10.1123/ijspp.2016-0001

Polglaze, T., Hogan, C., Dawson, B., Buttfield, A., Osgnach, C., Lester, L., & Peeling, P. (2018). Classification of intensity in team-sport activity. *Medicine &*

Science in Sports & Exercise, 50(7), 1487-1494. doi:10.1249/MSS.0000000000001575

Poole, D. C., Burnley, M., Vanhatalo, A., Rossiter, H. B., & Jones, A. M. (2016) Critical power: An important fatigue threshold in exercise physiology. *Medicine & Science in Sports & Exercise, 48*(11), 2320–2334. doi:10.1249/mss.0000000000000939

Saari, A., Dicks, N. D., Hartman, M. E., & Pettitt, R. W. (2019). Validation of the 3-minute all-out exercise test for shuttle running prescription. *Journal of Strength and Conditioning Research, 33*(6), 1678–1684. doi:10.1519/JSC.0000000000002120

Saibene, F., & Minetti, A. E. (2003). Biomechanical and physiological aspects of legged locomotion in humans. *European Journal of Applied Physiology*, *88*(4-5), 297–316. doi:10.1007/s00421-002-0654-9

Skiba, P. F., Chidnok, W., Vanhatalo, A., & Jones, A. M. (2012). Modeling the expenditure and reconstitution of work capacity above critical power. *Medicine & Science in Sports and Exercise*, *44*(8), 1526–1532. doi:10.1249/MSS.0b013e3182517a80

Townsend, N. E., Nichols, D. S., Skiba, P. F., Racinais, S., & Périard, J. D. (2017). Prediction of critical power and *W′* in hypoxia: Application to work-balance modelling. *Frontiers in Physiology*, *8*, 180. doi:10.3389/fphys.2017.00180

Triska, C., Karsten, B., Nimmerichter, A., & Tschan, H. (2017). Iso-duration determination of D′ and CS under laboratory and field conditions. *International Journal of Sports Medicine*, *38*(7), 527-533. doi:10.1055/s-0043-102943

Vanhatalo, A., Doust, J. H., & Burnley, M. (2007). Determination of critical power using a 3-min all-out cycling test. *Medicine & Science in Sports and Exercise*, *39*(3), 548–555. doi:10.1249/mss.0b013e31802dd3e6

Vanhatalo, A., Jones, A. M., & Burnley, M. (2011). Application of critical power in sport. *International Journal of Sports Physiology and Performance*, *6*(1), 128-136. doi:10.1123/ijspp.6.1.128

Varley, M. C., Fairweather, I. H., & Aughey, R. J. (2012). Validity and reliability of GPS for measuring instantaneous velocity during acceleration, deceleration, and constant motion. *Journal of Sports Sciences*, *30*(2), 121–127. doi:10.1080/02640414.2011.627941

Vassallo, C., Gray, A., Cummins, C., Murphy, A., & Waldron, M. (2020). Exercise tolerance during flat over-ground intermittent running: Modelling the expenditure and reconstitution kinetics of work done above critical power. *European Journal of Applied Physiology*, *120*(1), 219–230. doi:10.1007/s00421-019-04266-8

Whipp B.J., Davis, J. A., Torres, F., & Wasserman, K. (1981). A test to determine parameters of aerobic function during exercise. *Journal of Applied Physiology*, *50*(1), 217–221. doi:10.1152/jappl.1981.50.1.217

Willmott, A., James, C. A., Bliss, A., Leftwich, R. A., & Maxwell, N. S. (2019). A comparison of two global positioning system devices for team-sport running protocols. *Journal of Biomechanics, 83*, 324–328. doi:10.1016/j.jbiomech.2018.11.044

Wright, J., Bruce-Low, S., & Jobson, S. A. (2017). The reliability and validity of the 3-min all-out cycling critical power test. *International Journal of Sports Medicine*, *38*(6), 462–467. doi:10.1055/s-0043-102944

Zamparo, P., Pavei, G., Monte, A., Nardello, F., Otsu, T., Numazu, N., Fujii, N., & Minetti, A. E. (2019). Mechanical work in shuttle running as a function of speed and distance: Implications for power and efficiency. *Human Movement Science*, *66*, 487–496. doi:10.1016/j.humov.2019.06.005

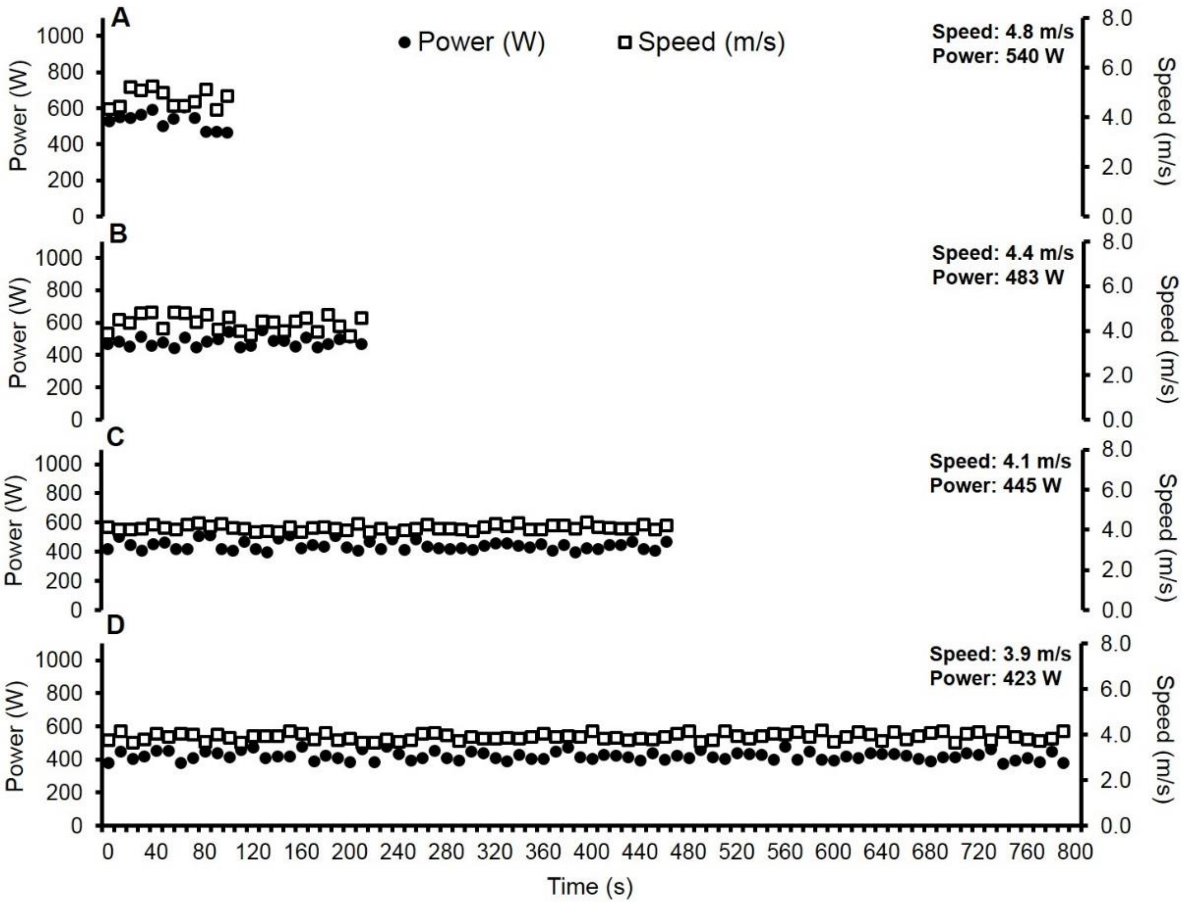
Table and figure captions

Table 1. Multiple-visit testing parameters derived from the linear distance- and work-time models to characterise the speed- and power-duration relationships. SEE = Standard error of the estimate for *D´* (m) and *W´* (kJ), respectively.

Table 2. Three-minute all-out test (3MT) parameter estimates of the speed- and power-duration relationships for trial 1 (3MT 1) and trial 2 (3MT 2).

Figure 1. Power output (y-axis) and over-ground speed (yy-axis) during the multi-visit testing at: 110%V_{max} (A), V_{max} (B), Δ85% (C), Δ70% (D) in a representative participant. Note: Data are presented as 10-s averages; stated speeds and power outputs are means from that trial.

Figure 2. Modelled over-ground power output (A) and raw speed (B) from a 10 Hz Global Positioning System device during the three-minute all-out test in a representative participant.



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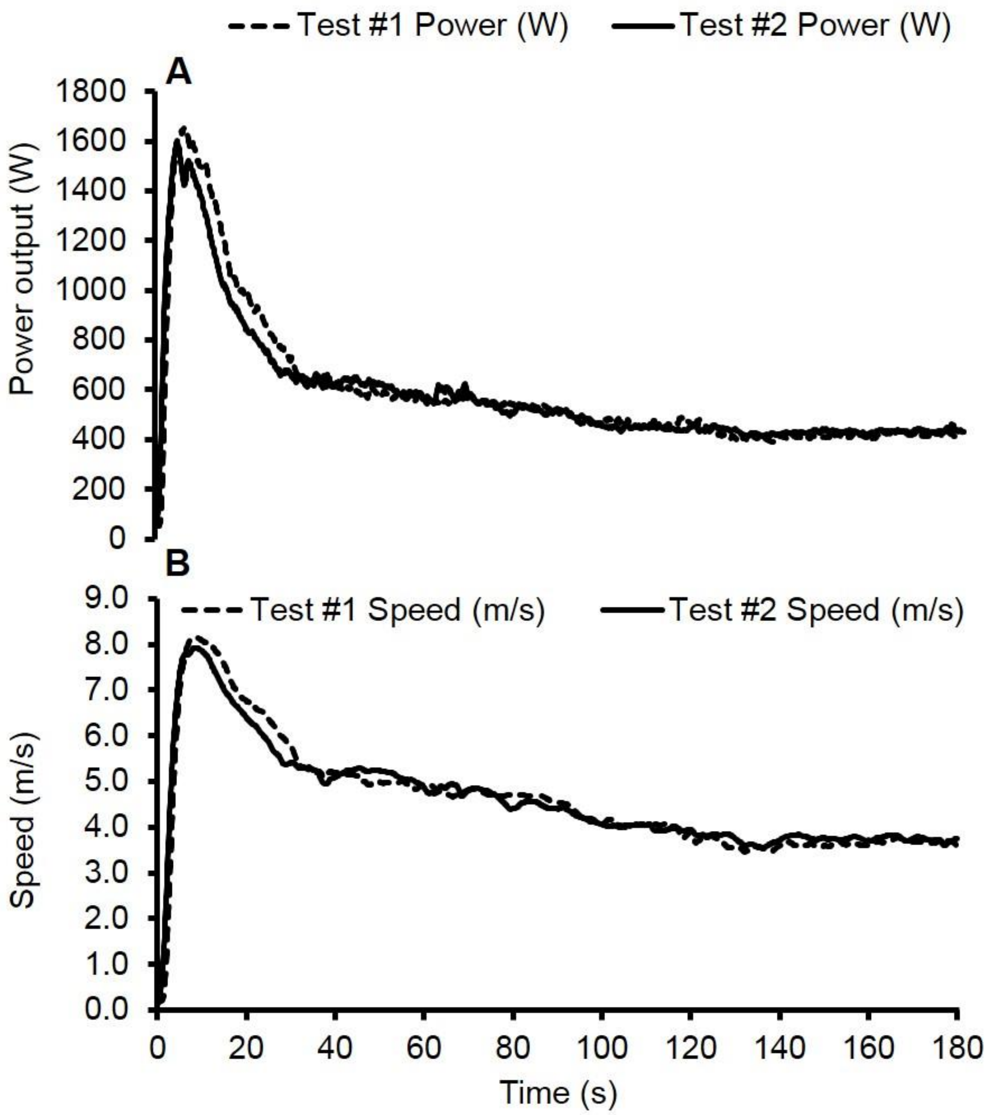

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