



ORIGINAL ARTICLE

Reliability and validity of the 3-min all-out running test



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Abstract

Background/Aim: Determine critical speed (CS) and running distance above CS (D'), as estimated from the 3-min all-out running test (3MT) is reliable and predictive of CS and D' determined from time trials.

Methods: Seven males (26 ± 5 years, VO_{2max} : 56.6 ± 4.1 ml·kg⁻¹·min⁻¹) completed an incremental treadmill test, three separate time trials (T_{tim}) of 800, 1600, and 2400m to determine CS and D' , and two 3MTs to estimate CS and D' .

Results: Estimates of trial 1 ($CS = 3.90 \pm 0.41$ m·s⁻¹, $D' = 176 \pm 42$ m) and trial 2 ($CS = 3.89 \pm 0.48$ m·s⁻¹, $D' = 183 \pm 35$ m) of the 3MT did not differ. Estimates of CS (ICC=0.95, CV=2.97%) and D' (ICC=0.93, CV=5.12%) from the 3MT were reliable. The 3MT trials provided valid estimates of CS as determined using regression of the three time trials (ICCs ranged 0.88-0.93, TE ranged 0.13-0.15 m·s⁻¹, CV ranged 3.32-4.76%). The 3 MT underestimated D' by ~16%, a difference exceeding the test-retest variability.

Conclusions: Estimates of CS were valid and reliable; however, assessment of D' from the 3MT may not estimate anaerobic capacity accurately.

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PALAVRAS-CHAVE

Capacidade anaeróbia;
Velocidade crítica;
Potência crítica;
Fadiga

Confiabilidade e validade do teste de 3 minutos máximo**Resumo**

Antecedentes/Objetivo: Determinar se a velocidade crítica (CS) e a distância acima da CS (D'), estimadas pelo teste de três minutos máximo (3MT) é confiável e preditiva de CS e D' determinada a partir dos modelos lineares.

Métodos: Sete homens (26 ± 5 anos, $VO_{2max}: 56,6 \pm 4,1$ ml·kg⁻¹·min⁻¹) completaram um teste incremental em esteira, três tomadas de tempo separadamente para 800, 1.600 e 2.400 m, para determinar CS e D' e 2 3MTs para estimar CS e D'.

Resultados: O primeiro 3 MT (CS = $3,90 \pm 0,41$ m·s⁻¹, D' = 176 ± 42 m) e o segundo 3 MT (CS = $3,89 \pm 0,48$ m·s⁻¹, D' = 183 ± 35 m) não foram diferentes. Estimativas do CS (ICC = 0,95, CV = 2,97%) e D' (ICC = 0,93, CV = 5,12%) a partir de 3 MT eram confiáveis. Os 3 MTs forneceram estimativas válidas de CS (ICC variou de 0,88-0,93, variaram de 0,13 a 0,15 ms TE, CV variou de 3,32 a 4,76%); 3 MT subestimou D' em ~16%, uma diferença maior de variabilidade teste-reteste.

Conclusões: Estimativas CS são válidas e confiáveis. No entanto, a avaliação de D' a partir do 3MT não pode estimar com precisão a capacidade anaeróbica.

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PALABRAS CLAVE

Capacidad anaeróbica;
Velocidad crítica;
Potencia crítica;
Cansancio

Fiabilidad y validez de la prueba de 3 minutos máximos**Resumen**

Antecedentes/Objetivos: Determinar si la velocidad crítica (VC) y la distancia por encima de la VC (D'), según la estimación de la prueba de 3 minutos máximos (3MT) es fiable y predictiva de la VC y la D' determinada a partir de los mejores tiempos de carrera personales.

Métodos: Siete varones (26 ± 5 años, $VO_{2max}: 56,6 \pm 4,1$ ml·kg⁻¹·min⁻¹) completaron una prueba progresiva en la cinta de correr, con tres periodos de tiempo separados de 800, 1.600 y 2.400 m para determinar la VC y la D' y dos 3MT para estimar la VC y la D'.

Resultados: Las estimaciones del ensayo 1 (VC = $3,90 \pm 0,41$ m·s⁻¹, D' = 176 ± 42 m) y del ensayo 2 (VC = $3,89 \pm 0,48$ m·s⁻¹, D' = 183 ± 35 m) de la prueba 3MT no fueron diferentes. Las estimaciones de la VC (ICC = 0,95; CV = 2,97%) y D' (ICC = 0,93; CV = 5,12%) a partir de la prueba 3MT fueron fiables. Las pruebas 3MT proporcionaron estimaciones válidas de la VC, como se determinó mediante regresión de las tres pruebas de tiempo (ICC se clasificaron desde 0,88 hasta 0,93 y la TE osciló entre 0,13 y 0,15 m·s⁻¹, la CV varió del 3,32 al 4,76%). La D' 3MT subestimó el ~16%, una diferencia superior a la variabilidad test-retest.

Conclusiones: Las estimaciones de VC fueron válidas y fiables; Sin embargo, la evaluación de D' desde la prueba de 3MT no puede estimar con precisión la capacidad anaeróbica.

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Introduction

Critical power (CP) represents, at least theoretically, the highest power output that can be sustained from an aerobic energy supply, and has been suggested to demarcate the heavy and severe intensity domains (Poole, Ward, Gardner, & Whipp, 1988). In this context, CP represents a good indicator of performance in long-duration events, and is a useful parameter for training prescription (Bosquet, Leger, & Legros, 2002; Vanhatalo, Jones, & Burnley, 2011). The concept of CP was proposed originally for use with small muscle groups (Monod & Scherrer, 1965) but was

later adapted for whole body exercises, including running, cycling, and swimming (Ettema, 1966; Hill, 1993).

Linear regression of total work performed during a series of exhaustive exercise bouts relative to time (Monod & Scherrer, 1965; Moritani, Nagata, deVries, & Muro, 1981) can be used to determine CP and the finite work capacity above CP (W'). Whipp et al. (1982) subsequently determined that the linear regression of power output relative to the inverse of time to exhaustion also could determine CP and W'. These linear models are known as the work-time limit (Linear W-T_{lim}) and power output-inverse time limit (P-T_{lim}) models, respectively (Gaesser, Carnevale, Garfinkel, Walter,

& Womack, 1995). CP is expressed as the slope the linear W - t_{lim} model, and theoretically, represents the maximum power output that can be maintained for an extended period without exhaustion (Wakayoshi et al., 1992). The parameter W' is given by the y -intercept of the W - T_{lim} model, and is defined as the finite energy reserve from the phosphagen pool, anaerobic glycolytic component, and O_2 stores (Poole et al., 1988). Additionally, W' also may relate to the attainment of a critical concentration of metabolites linked to muscle fatigue (Jones, Wilkerson, DiMenna, Fulford, & Poole, 2008). When applying the concept to running and swimming activities, power is replaced by speed, CP by critical speed (CS) and W' by maximal capacity to displace the body (D') (Jones, Vanhatalo, Burnley, Morton, & Poole, 2010).

Traditionally, use of the CP concept required a subject to exercise to exhaustion at several constant power outputs on separate days, and a early debate centered on the number of bouts that should be performed for valid modeling (Hill, 1993). Therefore, in order to reduce the bias in the research outcomes caused by the combination of different mathematical models and predictive trials (amount and duration), a single 3-min all-out test (3MT) was developed to determine CP (Burnley, Doust, & Vanhatalo, 2006) and W' (Vanhatalo, Doust, & Burnley, 2007). The 3 MT was based on the concept of CP , which implies that at the time point where W' becomes wholly depleted, the highest achievable power output is CP (Burnley et al., 2006; Coats et al., 2003; Vanhatalo et al., 2007). Namely, if there was a method to completely deplete W' (e.g. long all-out exercise bout), the remaining power output should equal CP . Indeed, Vanhatalo et al. (2007) observed that end-test power from 3 min of all-out exercise [i.e., average power output over final 30-s (EP)], and the work above EP (WEP) were not significantly different with CP and W' determined using repeated exhaustive exercise tests, respectively. Estimation of CP from EP was correlated positively and has a low standard error of estimation (SEE), whereas estimation of W' from WEP had a greater SEE.

The all-out concept has been adapted subsequently for isokinetic knee-extension exercise (Burnley, 2009), rowing (Cheng, Yang, Lin, Lee, & Wang, 2012), and running (Broxterman, Ade, Poole, Harms, & Barstow, 2013; Pettitt, Jamnick, & Clark, 2012). Pettitt et al. (2012) utilized the two-component model equations from the running 3 MT to predict performances of 800, 1600, and 5000 m outdoor races. Runners with higher D' values in that study ran at faster speeds relative to their CS . Subsequently, Broxterman et al. (2013) compared estimates of CS and D' from the 3 MT with the "traditional" model using exhaustive treadmill running bouts. The CS and D' estimates from the 3 MT and those modeled using the speed-inverse t_{lim} (S -inverse T_{lim}) model did not differ. When interpreting these results; however, it is worthy to note that estimations of CS between treadmill and track running performances can differ (Kranenburg & Smith, 1996).

The aforementioned studies demonstrated that the 3 MT can be used to determine CS and D' ; however, the validation was associated with laboratory tests and no study has reported on the reliability of these variables. In that regard, the objectives of the study were 1) to determine the test-retest reliability of the running 3 MT and 2) to examine if a

3MT could be used to accurately determine CS and D' derived from track performances.

Methods

Subjects

Seven college students (26 ± 5 years; 172.4 ± 0.05 cm; 75.5 ± 5.6 kg; VO_{2max} : 56.0 ± 4.2 ml $kg^{-1} \cdot min^{-1}$) volunteered to participate in the study. Subjects were informed of potential risks and discomforts of participation and provided written informed consent. All participants were apparently healthy, nonsmokers, free from injury, not taking any medication, practiced physical running activities at least twice a week and familiarized with track running performances. Furthermore, the subjects were required to rest the day before the test and to have his last light meal 2-h before the test. The study was approved by the local ethics committee and conformed to the Declaration of Helsinki.

Overview of procedures

Each subject visited the laboratory 7 times with at least 48-h separating each visit. All tests were completed within 4 weeks, at the same time of the day (± 2 h), to minimize the effects of biological variation. The tests consisted of: 1) an incremental treadmill exercise test for determination of VO_{2max} , 2) three track running performances of 800, 1600, and 2400 m to determine CS and D' , and 3) three running 3 MT bouts. The first 3 MT was used as familiarization and excluded from data analysis. The other two tests were used to evaluate the validity and test-retest reliability of CS and D' estimates from 3 MT. Running performances and 3MT were conducted on a level 200 m synthetic outdoor track, with minimal climate variations between conditions (wind and weather), and in counterbalanced order. All tests were preceded by a warm up consisting of 5 min of self-selected pace running followed by a 5 min rest.

Incremental treadmill exercise test

An incremental treadmill exercise test was performed to determine VO_{2max} and maximal aerobic speed (S_{max}). The initial treadmill speed was set at 2.22 ms^{-1} at a 1% grade and was increased by 0.14 ms^{-1} per minute until the participant terminated the test owing to volitional exhaustion. Exercising heart rates were monitored continuously using a telemetric heart rate monitor (model T41, Polar Electro Oy, Kempele, Finland), and each subject breathed through a facemask whereby cardiorespiratory data were measured continuously using an open circuit system with breath-by-breath analyzer (Cosmed Quark CPET, Rome, Italy). The gas-analysis system was calibrated before each test using the manufacturer's recommendations. Ear lobe capillary blood samples ($25 \mu l$) were taken immediately, 3 and 5 minutes postexercise. The blood samples were analyzed using an automated blood lactate analyzer (YSI 1500 Sport, Yellow Springs Instruments, Yellow Springs, OH, USA), which was calibrated with standards of 5 $mmol L^{-1}$ lactate

Table 1 Comparisons (Mean \pm SD) for critical speed (CS) and distance above CS (D') across measurements.

| Measurement | CS (m·s ⁻¹) | D' (m) |
|---------------------------------------|------------------------------|---------------------------|
| Linear D - T_{lim} Model | 3.69 \pm 0.50 ^a | 239 \pm 62 |
| Linear S -Inverse T_{lim} Model | 3.77 \pm 0.47 | 212 \pm 47 |
| 3-min all-out exercise test (Trial 1) | 3.90 \pm 0.41 | 176 \pm 42 ^b |
| 3-min all-out exercise test (Trial 2) | 3.89 \pm 0.48 | 183 \pm 35 ^c |

^a Significantly ($p < 0.05$) lower CS measure in comparison to the linear S - T_{lim} model.

^b Significantly ($p < 0.05$) lower D' measure in comparison to both the linear D - T_{lim} model and the linear speed-inverse T_{lim} model.

^c Significantly ($p < 0.05$) lower D' measure in comparison to the linear distance- T_{lim} model.

concentrations immediately before each test. VO_{2max} corresponded to the highest VO_2 average obtained in 15 s, and S_{max} was calculated as the speed of the last stage fully completed, plus, if necessary, the fraction of time spent multiplied by 0.14 m s⁻¹ in the stage at which exhaustion occurred. VO_{2max} was considered to be reached when a leveling off of VO_2 was observed despite increasing running speed (change in VO_2 at $VO_{2max} < 100$ ml min⁻¹) or when two or more of the following criteria were observed: (1) a final respiratory exchange ratio higher than 1:1; (2) visible exhaustion; (3) a heart rate at the end of exercise within 10 bpm of the predicted maximum (220 – age); and (4) a maximal blood lactate concentration higher than 8 mmol L⁻¹ (Howley, Bassett, & Welch, 1995).

Linear models for estimating CS and D'

To determine the CS and D' from linear models, subjects performed separate day, randomized time-trials running over three distances of 800, 1600, and 2400 m. The subjects were instructed to give their best effort during trials and were encouraged verbally throughout the test. Two different linear relationships for determining the CS and D' were used, and are described as follows:

$$D = (CS \times T_{lim}) + D' \text{ (Linear } D\text{-}T_{lim} \text{ model)} \quad (1)$$

where CS is the slope of the relationship and D' is the y-intercept of the relationship, and

$$S = (D' / T_{lim}) + CS \text{ (Linear } S\text{-inverse } T_{lim} \text{ model)} \quad (2)$$

where CS is the y-intercept and D' is the slope of the relationship (Fukuba & Whipp, 1999).

3-min all-out running test

In the 3MT the subjects were instructed to maintain their velocity as fast as possible at all times throughout the test. Verbal encouragement was provided as motivation; however, the subjects were neither informed of the elapsed time nor remaining time to discourage pacing. Split times were acquired manually by two researchers positioned strategically in the center of the track field to provide a full vision and minimize the parallax error of the cones placed at 20-m intervals along the inside lane of the track. Thus, an elapsed time was obtained every 20-m averaging the time recorded by the two researchers. CS and D' estimated from 3 MT were obtained according to Pettitt et al. (2012), which assumes that a runner expends their finite energy reserve within

2.5-min of all-out effort, whereby the speed between 150-s and 180-s would be performed in a steady-state. Thus, CS was determined by averaging the speed between 150 and 180 s (m·s⁻¹), and D' (m) was derived using the follow equation:

$$D' = 150 \text{ s} \times (S_{150s} - CS) \quad (3)$$

where S_{150s} is the mean speed for the initial 150 s of the 3 MT.

Statistical analyses

All data are expressed as mean \pm standard deviation (SD) and rejection of the null hypothesis was accepted at a level of $p < 0.05$. All parameters were tested for normal distribution by the Shapiro-Wilks test for normality before further analysis. The differences between mean values (Linear D - T_{lim} model, Linear S -inverse T_{lim} model, and the 3 MTs) were tested using a repeated-measure, one-way analysis of variance (ANOVA) completed with post hoc Bonferroni-adjusted t tests. package Intraclass correlation coefficient were used to determine the relative consistency of the 3 MT. Typical error, coefficient of variation were calculated to evaluate absolute variations between estimated parameters from 3 MT and the linear models. Data analysis was performed using the Statistical Package (version 18.0 for Windows, SPSS Inc., Chicago, IL, USA) and a modified statistical Excel spreadsheet (Hopkins, 2000).

Results

Mean values of S_{max} and VO_{2max} obtained from incremental test were 4.36 \pm 0.22 m·s⁻¹ and 56.6 \pm 4.1 ml kg⁻¹·min⁻¹, respectively. Performance times for the 800, 1600, and 2400 m distances were 158 \pm 12 s, 364 \pm 34 s and 599 \pm 75 s. Summary statistics of the estimated parameters from the 3 MT trials and the linear models are presented in Table 1. For all subjects, the data obtained from the two linear models displayed with a high goodness of fit (R^2 of 0.955 \pm 0.045). The standard errors as a percentage of the parameter estimates of CS and D' were 1.0 \pm 0.7% and 20.7 \pm 9.9%, for the linear D - T_{lim} model and 3.3 \pm 2.4% and 13.9 \pm 7.4% for the S -inverse T_{lim} model, respectively.

Figure 1 depicts the determination of CS and D' from two trials of the 3 MT (left panel) along with linear D - T_{lim} model (top right panel), and the speed-inverse T_{lim} model (bottom right panel) for representative subject. Test retest reliability of the CS and D' estimates were strong (Table 2).

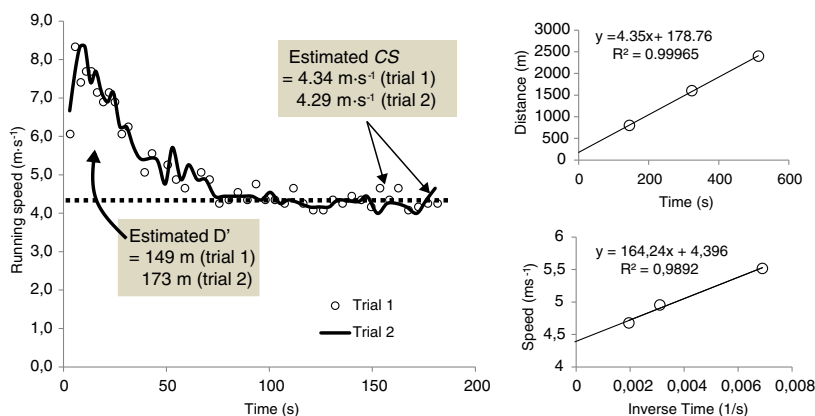


Figure 1 Parameter estimations for a representative subject. A) Data points are 20 m average speeds of the first (o) and (-) second 3-min all-out test (3 MT). The dotted line represents the critical speed (CS) of first and second 3MT, respectively. Distance performed above CS (D') was determined by the equation: $D' = 150 \times (\text{mean speed of the first 150-s} - \text{CS})$, where mean speed of the first 150-s and CS are expressed in $\text{m}\cdot\text{s}^{-1}$ and D' are expressed in m. B) linear D - T_{lim} model and C) linear S -inverse T_{lim} model determined from 800, 1600 and 2400 m running performances. In B) D' is the y -intercept and CS is the slope of linear regression, whereas in C) D' and CS is the slope and y -intercept, respectively.

Table 2 Consistency statistics between the 3-min all-out running test (3 MT) trials and comparison with the linear speed-inverse T_{lim} and linear distance- T_{lim} models.

| Comparisons | Intraclass Correlation Coefficient (α) | Typical Error | Coefficient of Variation |
|---|---|---|---------------------------------|
| 3 MT trial 1 vs. 3 MT trial 2 | $CS = 0.95$ $D' = 0.96$ | $CS = 0.10 \text{ m}\cdot\text{s}^{-1}$ $D' = 7.99 \text{ m}$ | $CS = 2.97\%$ $D' = 5.12\%$ |
| 3 MT trial 1 vs. speed-inverse T_{lim} model | $CS = 0.92$ $D' = 0.93$ | $CS = 0.13 \text{ m}\cdot\text{s}^{-1}$ $D' = 12.08 \text{ m}$ | $CS = 3.65\%$ $D' = 7.18\%$ |
| 3 MT trial 2 vs. speed-inverse T_{lim} model | $CS = 0.93$ $D' = 0.83$ | $CS = 0.13 \text{ m}\cdot\text{s}^{-1}$ $D' = 17.07 \text{ m}$ | $CS = 3.32\%$ $D' = 9.77\%$ |
| 3 MT trial 1 vs. linear distance-time model | $CS = 0.88$ $D' = 0.93$ | $CS = 0.16 \text{ m}\cdot\text{s}^{-1}$ $D' = 26.91 \text{ m}$ | $CS = 4.76\%$ $D' = 11.39\%$ |
| 3 MT trial 2 vs. linear distance-time model | $CS = 0.92$ $D' = 0.71$ | $CS = 0.14 \text{ m}\cdot\text{s}^{-1}$ $D' = 7.99 \text{ m}$ | $CS = 3.79\%$ $D' = 5.12\%$ |

Analysis of CS and D' revealed a significant main effect ($F = 6.925$, $P=0.045$ and $F = 10.48$, $P=0.023$, respectively). CS differed between the linear D - T_{lim} and S -inverse T_{lim} models ($P=0.031$), but no differences for CS were observed between the 3 MT trials, or between 3 MTs and the linear models ($P>0.2$) (Table 1). D' for the linear models did not differ ($P=0.058$), but they were significantly higher than D' estimates from the 3 MT ($P<0.05$). Small and moderate variations were observed for CS and D' , respectively, between the 3 MT and linear models (Table 2). Moreover, CS and D' presented high and significant ($P<0.01$) intraclass correlation coefficients between 3MT and linear methods.

Discussion

To our knowledge, this is the first study that determined the reliability of the running 3 MT, as well its validity for estimating the parameters of linear relationships from track running performances. The high test-retest reliability observed in the present study demonstrates that the parameters estimated from the running 3MT have minimal variability. Furthermore, our results also indicate that the

3 MT is able to estimate CS , however, underestimates D' . Taken together, our results suggest that 3 MT might be useful tool to assess and monitor training-induced changes in aerobic power, but caution is warranted when using 3 MT for measuring anaerobic capacity through the estimate of D' .

The 3 MT for cycling has been reported to have good predictive validity and reliability for CP , and moderate reliability for W' (Burnley et al., 2006; Johnson, Sexton, Placek, Murray, & Pettitt, 2011; Vanhatalo et al., 2007; Simpson et al., 2015) when performed under linear factor resistance applied. Nonetheless, the validity is doubtful, when the resistance model was changed (e.g. isokinetic mode) (Karsten B et al., 2014). For rowing, Cheng et al. (2012) reported that the 3 MT provided moderate test-retest reliability for assessing CP ($ICC = 0.788$) and W' ($ICC = 0.628$). In running, our results also demonstrate that 3 MT is sufficiently robust and not significantly affected by biological and technical variations of the test, since CS and D' estimated from running 3 MT was reliable. These results are impactful because good reliability implies good precision of single measurements, and better tracking of changes in measurements in research or practical settings.

The CS metric has been described as a good indicator of performance in long-duration events, and a useful parameter for training prescription (Bosquet et al., 2002; Vanhatalo et al., 2011); however, the traditional linear models were time-consuming, and might therefore be a problem for experimental studies and training programs. The 3MT has emerged as a solution to this problem (Broxterman et al., 2013; Cheng et al., 2012; Vanhatalo et al., 2007). For running, Broxterman et al. (2013) reported that the CS determined from the 3 MT was positively correlated ($r = 0.92$) and not significantly different from the CS determined from three exhaustive treadmill running bouts using the S -inverse T_{lim} model. Further, they observed steady state VO_2 during a subsequent square-wave bout below CS, whereas VO_2 was driven to VO_{2max} with exhaustion occurring prior to 15 min in a square-wave bout exceeding CS, as determined from the 3 MT. We used track running performances to determine CS and our results are similar to those of Broxterman, et al. (2013). Moreover, we observed lower typical errors and coefficient of variations between CS estimated from 3 MT and linear models. Collectively, these studies indicated that the running 3 MT may reduce the bias in the research outcomes caused by different mathematical models, and can be applied successfully to determine the CS in both laboratory and field settings.

A finite energy reserve from anaerobic sources and myoglobin O_2 stores (Miura, Sato, Whipp, & Fukuba, 2000; Monod & Scherrer, 1965; Moritani et al., 1981), and/or the attainment of a critical concentration of one or more metabolites linked to muscle fatigue (Jones et al., 2008), are suggested as mediating factors for W' and D' . In cycling exercise, Vanhatalo et al. (2007) reported that the W' from 3 MT was predictive of W' from the linear models; where others have reported lower reliability for W' (Johnson et al., 2011) and lower predictive validity W' and D' (Broxterman et al., 2013; Cheng et al., 2012). In our study, D' from the 3 MT correlated positively with D' estimated from the linear models, yet yielded lower estimates. Similarly, Broxterman et al. (2013) reported that the 3 MT underestimated D' for five of the seven subjects measured, despite not being statistically different. In addition, Galbraith A. et al., 2014 found higher D' value in the treadmill protocol compared to the field protocols. Differences in energetic demand between methods may account for the discrepancy between parameters. The high speeds sustained in sprint running, cost of acceleration and aerodynamic resistance are important components of the total energy demand during all-out bouts, which is reduced during middle and long performances relying on the linear models, though still higher than treadmill running (di Prampero, Atchou, Bruckner, & Moia, 1986; di Prampero et al., 1993). In this context, Arsac and Locatelli (2002) reported that the energy required to overcome aerodynamic resistance and changes in kinetic energy were 13% and 24% of the total energy demand of 100 m running performance, respectively. Therefore, D' might have been lower due to the higher energy required by non-locomotor elements during the 3 MT.

A few studies have shown correlations between W' and D' with metabolic measures of anaerobic capacity (i.e. maximally accumulated oxygen deficit and work performed in a 30-s all-out cycle ergometer test (Chatagnon, Pouilly, Thomas, & Busso, 2005; Hill & Smith, 1993; Jenkins &

Quigley, 1991). However, poor test-retest reliability of W' and D' has been observed (Gaesser & Wilson, 1988; Johnson et al., 2011; Taylor & Batterham, 2002) which may complicate its validity to determine anaerobic capacity. Conversely, D' estimates in our study had good reliability, probably due to the lack of influence of the high variability of time to exhaustion at a given intensity or performance time inherent in the traditional CS model (Whipp & Ward, 2009). Additional studies are needed to analyze the relationships between D' estimated from different methods and measures of anaerobic capacities to determine the validity and physiological meaning of D' from 3 MT.

Our study was unique to prior studies in that we determined time and speed of the 3 MT manually every 20-m, whereas Broxterman et al. (2013) and Pettitt et al. (2012) utilized accelerometer strapped to the right foot and GPS systems to record their data, respectively. Manual time-keeping appears to represent an inexpensive and reliable alternative for estimating CS and D' from the 3 MT.

In summary, the results our study indicates that estimated parameters from 3 MT have good test-retest reliability. Furthermore, despite that 3 MT underestimated D' , CS was similar between estimates from the 3 MT and traditional linear models. Therefore, we conclude a running 3 MT utilizing manual timekeeping is inexpensive and noninvasive method to evaluate aerobic fitness in running; however, further studies are needed for analyze the validity of D' from 3 MT as a measure of anaerobic capacity.

Practical applications

Based on the present study, we suggest that the CS from 3 MT is a valid and reliable means to determine aerobic capacity in running. Therefore, a running 3 MT utilizing manual timekeeping can be used as an inexpensive, noninvasive and suitable method for prescribing aerobic training and monitoring training-induced performance changes in aerobic capacity; however, we recommend caution when using D' from 3 MT as a measure of anaerobic capacity.

Conflicts of interest

The authors have no conflicts of interest to declare.

References

- Arsac LM, Locatelli E. Modeling the energetics of 100-m running by using speed curves of world champions. *Journal of Applied Physiology* 2002;92:1781–8.
- Bosquet L, Leger L, Legros P. Methods to determine aerobic endurance. *Sports Medicine* 2002;32:675–700.
- Broxterman RM, Ade CJ, Poole DC, Harms CA, Barstow TJ. A single test for the determination of parameters of the speed-time relationship for running. *Respiratory Physiology & Neurobiology* 2013;185(2):380–5.
- Burnley M. Estimation of critical torque using intermittent isometric maximal voluntary contractions of the quadriceps in humans. *Journal of Applied Physiology* 2009;106(3):975–83.
- Burnley M, Doust JH, Vanhatalo A. A 3-min all-out test to determine peak oxygen uptake and the maximal steady state. *Medicine Science Sports Exercise* 2006;38(11):1995–2003.

- Chatagnon M, Pouilly JP, Thomas V, Busso T. Comparison between maximal power in the power-endurance relationship and maximal instantaneous power. *European Journal Applied Physiology* 2005;94:711–7.
- Cheng CF, Yang YS, Lin HM, Lee CL, Wang CY. Determination of critical power in trained rowers using a three-minute all-out rowing test. *European Journal Applied Physiology* 2012;112:1251–60.
- Coats EM, Rossiter HB, Day JR, Miura A, Fukuba Y, Whipp BJ. Intensity-dependent tolerance to exercise after attaining $V(O_2)$ max in humans. *Journal of Applied Physiology* 2003;95(2):483–90.
- di Prampero PE, Atchou G, Bruckner JC, Moia C. The energetics of endurance running. *European Journal Applied Physiology Occupational Physiology* 1986;55:266–9.
- di Prampero PE, Capelli C, Pagliaro P, Antonutto G, Girardis M, Zamparo P, et al. Energetics of best performances in middle-distance running. *Journal of Applied Physiology* 1993;74:2318–24.
- Ettema JH. Limits of human performance and energy-production. *European Journal Applied Physiology Occupational Physiology* 1966;22:45–54.
- Fukuba Y, Whipp BJ. A metabolic limit on the ability to make up for lost time in endurance events. *Journal of Applied Physiology* 1999;87(2):853–61.
- Gaesser GA, Carnevale TJ, Garfinkel A, Walter DO, Womack CJ. Estimation of critical power with nonlinear and linear models. *Medicine Science Sports Exercise* 1995;27(10):1430–8.
- Gaesser GA, Wilson LA. Effects of continuous and interval training on the parameters of the power-endurance time relationship for high-intensity exercise. *International Journal Sports Medicine* 1988;9(6):417–21.
- Galbraith A, Hopker J, Lelliott S, Diddams L, Passfield L. A Single-Visit Field Test of Critical Speed. *Int J Sports Physiol Perform* [Internet] 2014;9(6):931–5.
- Hill DW. The critical power concept. A review. *Sports Medicine* 1993;16:237–54.
- Hill DW, Smith JC. A comparison of methods of estimating anaerobic work capacity. *Ergonomics* 1993;36(12):1495–500.
- Hopkins WG. Measures of reliability in sports medicine and science. *Sports Med* 2000;30(1):1–15, PMID:10907753.
- Howley ET, Bassett DR Jr, Welch HG. Criteria for maximal oxygen uptake: review and commentary. *Medicine Science Sports Exercise* 1995;27(9):1292–301.
- Jenkins DG, Quigley BM. The y-intercept of the critical power function as a measure of anaerobic work capacity. *Ergonomics* 1991;34:13–22.
- Johnson TM, Sexton PJ, Placek AM, Murray SR, Pettitt RW. Reliability analysis of the 3-min all-out exercise test for cycle ergometry. *Med Science Sports Exercise* 2011;43(12):2375–80.
- Jones AM, Vanhatalo A, Burnley M, Morton RH, Poole DC. Critical power: implications for the determination of VO_2 max and exercise tolerance. *Medicine Science Sports Exercise* 2010;42:1876–90.
- Jones AM, Wilkerson DP, DiMenna F, Fulford J, Poole DC. Muscle metabolic responses to exercise above and below the “critical power” assessed using 31P-MRS. *American journal of physiology. Regulatory, integrative and comparative physiology* 2008;294(2):R585–93.
- Karsten B, Jobson S, Hopker J, Jimenez A, Beedie C. High Agreement between Laboratory and Field Estimates of Critical Power in Cycling. *Int J Sports Med* [Internet] 2014;35(4):298–303.
- Kranenburg KJ, Smith DJ. Comparison of critical speed determined from track running and treadmill tests in elite runners. *Medicine Science Sports Exercise* 1996;28:614–8.
- Miura A, Sato H, Whipp BJ, Fukuba Y. The effect of glycogen depletion on the curvature constant parameter of the power-duration curve for cycle ergometry. *Ergonomics* 2000;43(1):133–41.
- Monod H, Scherrer J. The work capacity of a synergistic muscle group. *Ergonomics* 1965;8:329–38.
- Moritani T, Nagata A, deVries HA, Muro M. Critical power as a measure of physical work capacity and anaerobic threshold. *Ergonomics* 1981;24(5):339–50.
- Pettitt RW, Jamnick N, Clark IE. 3-min all-out exercise test for running. *International Journal Sports Medicine* 2012;33:426–31.
- Poole DC, Ward SA, Gardner GW, Whipp BJ. Metabolic and respiratory profile of the upper limit for prolonged exercise in man. *Ergonomics* 1988;31(9):1265–79.
- Simpson LP, Jones AM, Skiba PF, Vanhatalo A, Wilkerson D. Influence of hypoxia on the power-duration relationship during high-intensity exercise. *Int J Sports Med* 2015;36(2):113–9.
- Taylor SA, Batterham AM. The reproducibility of estimates of critical power and anaerobic work capacity in upper-body exercise. *European Journal Applied Physiology* 2002;87(1):43–9.
- Vanhatalo A, Doust JH, Burnley M. Determination of critical power using a 3-min all-out cycling test. *Medicine Science Sports Exercise* 2007;39(3):548–55.
- Vanhatalo A, Jones AM, Burnley M. Application of critical power in sport. *International Journal Sports Physiology Perform* 2011;6:128–36.
- Wakayoshi K, Ikuta K, Yoshida T, Udo M, Moritani T, Mutoh Y, et al. Determination and validity of the critical velocity as an index of swimming performance in the competitive swimmer. *European Journal Applied Physiology Occupational Physiology* 1992;64:153–7.
- Whipp BJ, Huntsman DJ, Stoner N, Lamarra N, Wasserman KA. A constant which determines the duration of tolerance to high-intensity work. *Federation Proceedings* 1982;41:1591.
- Whipp BJ, Ward SA. Quantifying intervention-related improvements in exercise tolerance. *European Respiratory Journal* 2009;33(6):1254–60.