Title: Modeling intermittent running from a single-visit field test.

Abstract:

This study assessed whether the distance-time relationship could be modeled to predict time to exhaustion (TTE) during intermittent running. Thirteen male distance runners (age: 33±14yrs) completed a field test and three interval tests on an outdoor 400m athletics track. Field-tests involved trials over 3600m, 2400m and 1200m with a 30-minute rest between each run. Interval tests consisted of: 1000m at 107% of CS with 200m at 95% CS; 600m at 110% of CS with 200m at 90% CS; 200m at 150% of CS with 200m at 80% CS. Interval sessions were separated by 24hr recovery. Field-test CS and D′ were applied to linear and non-linear models to estimate the point of interval session termination. Actual and predicted TTE using the linear model were not significantly different in the 1000m and 600m trials. Actual TTE was significantly lower (*P*=0.01) than predicted TTE in the 200m trial. Typical error was high across the trials (range 334-1709s). The mean balance of D′ remaining at interval session termination was significantly lower when estimated from the non-linear model (-21.2 vs. 13.4m, *P*<0.01), however no closer to zero than the linear model. Neither the linear or non-linear model could closely predict TTE during intermittent running.

Keywords: Critical speed, interval training, modeling performance.

Introduction:

Interval training is a popular mode of conditioning in many sports and involves intermittent periods of work and relative recovery [19]. Interval training has the advantage of enabling a greater amount of high intensity work to be conducted in a single session than would be possible with continuous training [18]. High intensity running training, in terms of time spent above lactate threshold velocity, has previously been shown to be a contributing factor to longitudinal increases in performance [9]. Therefore designing interval training sessions that are individualized to athletes' specific needs is important. For aerobic training, parameters such as VO_{2max}, velocity at VO_{2max}, lactate/ventilatory thresholds and maximal heart rate have all been used to prescribe individualised training intensities [1].

The distance-time relationship can be used to calculate a two parameter model of critical speed (CS) and D′. A runner's CS has been suggested to reflect the highest sustainable running speed that can be maintained without a continual rise in $\dot{V}O_2$ to $\dot{V}O_{2\,max}$, whilst D′ is notionally the maximum amount of work (recorded as distance) that can be performed above CS [16]. Ferguson et al. [7] explain that an additional consideration when defining exercise intensity is that CS does not occur at a fixed percentage of maximal heart rate or VO_{2max} [22]. Furthermore between-subject differences in anaerobic capacity [5] result in the D' not representing the same volume of supra-CS exercise in all individuals [20]. The consequence of this is that the exercise intensity experienced during an interval training session will be variable between participants unless the distance-time relationship is accounted for [7]. The distance-time relationship is of considerable importance to sports performance because complete depletion of the D' prevents an athlete performing at an intensity above CS [23]. We recently validated a single-visit field test of the distance-time relationship in running which can be completed in ~90 minutes [11]. This raises the possibility that the single-visit field test could be used to design interval training; setting interval intensity at a percentage of CS and the number of interval repetitions in accordance with the depletion of D'. Thereby inducing the desired training load through the interplay between CS, D' and time to exhaustion (TTE).

Morton and Billat [19] applied the distance-time relationship to intermittent exercise, studying the speed and duration during the work and recovery phases (S_w, t_w, S_r, t_r). Morton and Billat suggest that the time to exhaustion (TTE) of an athlete during an interval session can be calculated from the following equation, where n is equal to the number of complete work-recovery cycles:

$$TTE = n(t_w+t_r) + \frac{D' - n[(S_w - CS)t_w - (CS - S_r)t_r]}{S_w - CS} \tag{1}$$

Chidnok et al. [3] utilized this linear model to investigate the effect of different recovery intensities during cycling exercise, whilst the data from Skiba et al [23] suggest a non-linear recovery model may be more appropriate. The application of these models to intermittent running exercise warrants further investigation. A model that can account for the depletion and restoration of D' during intermittent exercise, by accurately predicting the end point of exercise, could aid the design of interval training sessions and even have a performance application, allowing real-time monitoring of D' during competitions thereby informing race tactics. The aim of the current study therefore was to assess whether the distance-time relationship data from a single-visit field test could be accurately applied to linear and non-linear models to predict TTE during intermittent running exercise.

Methods:

Participants: Thirteen male middle/long-distance runners (age: 33 ± 14yrs; 5000m time: 1090 ± 86s) were recruited for the study. All participants were competitive club standard runners who had been competing for a minimum of 3 years. All participants provided written informed consent for this study that had been approved by the University of Kent School of Sport and Exercise Sciences Research Ethics Committee. Research was performed in accordance with the ethical standards of the IJSM [12].

Study design: The study involved two types of test; a single visit field test of the distance-time relationship, and an interval test, both completed on a standard outdoor 400m athletics track. A familiarisation session for each type of test was undertaken prior to commencing data collection.

Participants completed the same warm up and cool down routine, consisting of 5-10 minutes jogging at a self-selected pace, followed by the athlete's normal stretching routine [24]. Tests for each participant were completed at the same time of day (± 2hrs), with at least 48 hours recovery between test sessions. Participants were asked to arrive for testing in a well-hydrated and rested state, having avoided strenuous exercise in the preceding 24 hours.

Single visit field-test protocol: The single visit field test was conducted as previously described [11]. Each participant completed three runs over distances of 3600 m, 2400 m and 1200 m (9, 6 and 3 laps). Runs were conducted in this order for all sessions. These distances were chosen to result in completion times of approximately 12, 7 and 3 min [15]. Participants were instructed to complete each trial in the fastest time possible, and runs were hand-timed to the nearest second. All three runs were conducted on the same day with a 30-minute rest between each run. This single-visit field test protocol has previously been shown to be a reliable method of calculating CS and D′, with a coefficient of variation of <1% for CS [11]. Participants were not provided with feedback on the elapsed time during the track runs. Testing was not conducted if wind speed > 2.0 $m \cdot s^{-1}$ was recorded. Mean (±SD) environmental conditions during the field tests were: temperature 5.7°C (2.4˚C), humidity 74% (11%), barometric pressure 761 mmHg (2 mmHg) and wind speed 1.3 $m \cdot s^{-1}$ (0.3 $m \cdot s^{-1}$).

Interval test protocol: Three typical interval sessions were conducted, modeled using the CS from the field test. The interval sessions consisted of:

a) 1000m 'work intervals' at 107% of CS with 200m 'recovery intervals' at 95% CS.

b) 600m 'work intervals' at 110% of CS with 200m 'recovery intervals' at 90% CS.

c) 200m 'work intervals' at 150% of CS with 200m 'recovery intervals' at 80% CS.

Participants ran on the inside line of lane 1 of the running track and were provided with split times every 100m to ensure they maintained the required speed during the work and recovery intervals. Participants were instructed to continue the alternate work/recovery periods for as long as possible. The interval session was terminated if the participant was unable to continue, or if the participant was 0.5 sec slower than the designated split time for 3 consecutive 100m splits. Runs were hand timed with TTE recorded to the nearest second.

The three interval sessions were conducted on separate days with a minimum of 24 hours recovery between tests. Tests were only conducted if the wind speed was lower than 2.0 $m \cdot s^{-1}$. Mean (±SD) environmental conditions during the interval tests were: temperature 7.3 °C (4.2 ˚C), humidity 78 % (12 %), barometric pressure 760 mmHg (3 mmHg) and wind speed 1.2 $m \cdot s^{-1}$ (0.6 $m \cdot s^{-1}$).

Data analysis:

Calculation of CS and D′: A linear distance-time model was applied to the three runs from the single visit field test to calculate CS and D′ (r^2 range=0.997-1.000). The linear distance-time model is represented by:

$$d = (CS.t) + D' \quad (2)$$

Where: d = distance run and t = running time.

Linear recovery model: The depletion of D′ during the work (w) intervals and the restoration of D′ during the recovery (r) intervals was estimated as follows: where S = speed and t = time in seconds [19]

Depletion of D′ during work interval $= (S_w\text{-}CS)t_w$ (3)

Restoration of D′ during recovery interval $= (CS\text{-}S_r)t_r$ (4)

Actual TTE (total running time of combined work and rest intervals) and predicted TTE (total estimated running time calculated from equation 1 using CS and D′ from the field test protocol and S_w, S_r, t_w and t_r from the interval session) were calculated.

Non-linear recovery model: To assess the effect of non-linear recovery of D′, equation 5 from Skiba et al [23] was used to estimate the balance of D′ (D'_{bal}) remaining at the point the interval session was terminated. The time constant of D′ repletion ($\tau_{D'}$) was set at 578s. This was based on the mean $\tau_{W'}$ reported by Skiba et al [23] for recovery in the heavy exercise intensity domain (the same intensity domain used for recovery in the current study).

$$D'_{bal} = D' - \int_0^t (D'_{exp}) \left(e^{-(t-u)/\tau_{D'}}\right) \quad (5)$$

$\tau_{D'}$: To investigate $\tau_{D'}$, the time constant for each participant for each trial was varied by an iterative process until modeled D'_{bal} equaled zero at the point of interval session termination [23]. The intensity of the recovery interval for each participant across each trial was also recorded by calculating the difference between recovery speed and critical speed (D_{CS}).

Statistical analysis: Data were checked for normality of distribution using the Shapiro-Wilk statistic. Paired samples *t*-tests were used to identify differences in actual and predicted TTE. Pearson correlation coefficients were used to assess the relationship between these parameters. The 95% limits of agreement and Bland Altman plots [2] along with the typical error were calculated to assess agreement between methods. A Repeated measures ANVOA was used to identify differences between linear and non-linear models across the interval sessions.

Analysis was conducted using the SPSS statistical software package (IBM SPSS statistics, Rel. 20.0, 2011. SPSS Inc. Chicago, USA). Statistical significance was accepted at $P < 0.05$ for all tests.

Results:

Participants' mean CS and D′ calculated from the field-test protocol were 4.41 ± 0.48 $m.s^{-1}$ and 121 ± 52m respectively.

Linear model:

****INSERT TABLE 1 HERE****

Table 1 shows the actual and predicted TTE, which were not significantly different in the 1000m ($P = 0.59$) and 600m ($P = 0.09$) trials. The actual TTE was significantly lower ($P = 0.01$) than predicted TTE in the 200m trial.

INSERT Fig. 1 HERE

There were no significant relationships between actual and predicted TTE across the different interval trials (Fig. 1). The typical error between actual and predicted TTE was 334s, 350s and 1709s for the 1000, 600 and 200m trials, respectively.

INSERT Fig. 2 HERE

Fig. 2 shows the closest agreement between actual and predicted TTE was in the 1000m and 600m trials (95% limits of agreement = 926 and 969s respectively). Agreement between actual and predicted TTE became considerably worse in the 200m trial (95% limits of agreement = 4734s). The 200m trial (c) showed evidence of heteroscedastic errors. Therefore, ratio limits of agreement were calculated [21]. The ratio limits of agreement were 0.17 and 115.51. Therefore, if a subject's actual TTE in the 200m trial was 310s, it is possible the predicted TTE (worst case scenario) could be as low as 54s (310 x 0.17) or as high as 35808s (310 x 115.51).

Linear vs. non-linear model:

INSERT TABLE 2 HERE

Table 2 shows the D'_{bal} at interval session termination estimated from the linear model of Morton and Billat [19] and the non-linear model of Skiba et al [23].

A 3x2 (trial x model) repeated measures ANOVA showed a significant effect for 'model' ($P<0.01$). The mean D'_{bal} at interval session termination was significantly lower when estimated from the non-linear model (-21.2 and 13.4m, respectively). There was a significant effect of 'trial' on D'_{bal} at interval session termination, with differences observed between the 1000 and 200m trials ($P=0.03$). There was a significant interaction effect (trial x model) for D'_{bal} at interval session termination ($P<0.01$). This effect was seen between the linear and non-linear models in the 200m trial. The non-linear modeled D'_{bal} at interval session termination was significantly lower than that of the linear model (-24.4 and 47.0m, respectively) in the 200m trial.

Non-linear model $\tau_{D'}$*:*

INSERT TABLE 3 HERE

Table 3 shows the Mean $\tau_{D'}$ and D_{CS} for each trial using the non-linear model. There was no significant difference in $\tau_{D'}$ across trials ($P>0.05$). D_{CS} was significantly different across trials ($P<0.01$), with all trials being significantly different from each other.

Discussion:

The main finding of this study is that the Morton and Billat [19] model of intermittent running based upon CS and D′ does not closely predict TTE. No significant differences in actual and predicted TTE were seen in the 1000m and 600m trials. However, there was a trend (P = 0.09) in the 600m trial for actual TTE to be lower than predicted TTE. Actual TTE was significantly lower (P = 0.01) than predicted TTE in the 200m trial. Using a progressive statistics approach [14] the standardised mean difference between actual TTE and predicted TTE for the 600m trial produces a small effect. Furthermore, the lack of significant correlation (range r = -0.21 to -0.04, P>0.05) and the relatively high typical error (range 334-1709s) support the conclusion that the intermittent critical speed model cannot be used to accurately predict TTE in intermittent running exercise. When modeled in this way, the CS and D′ from the field test tend to predict a greater TTE than could be achieved, resulting in an interval session with an unrealistic number of work and recovery intervals. The findings of the current study support the earlier work of Kachouri et al [17], who report that it is not possible to predict the maximum number of repetitions of an intermittent exercise session from the continuous distance-time relationship.

The agreement between actual and predicted TTE in the 200m interval trial was considerably worse than in the other two trials. Vandewalle at al [25] suggest that the distance-time relationship should not be extrapolated for time durations that are very short or very long. The 200m trial was the shortest bout with a mean work interval ~27-40 sec. Therefore, this trial may have fallen outside of the *'window'* for which predictions from the distance-time relationship are valid [25]. This is further supported by Chidnok et al [4], who report that the ability to predict TTE may be less accurate at higher, compared to lower, severe-intensity work-rates. This suggests that the ability to model intermittent exercise may be specific to the percentages of CS used during the work and recovery intervals, with percentages set closer to CS allowing a more accurate prediction.

The effect of errors in the estimation of D′.

The variability in D′ has been reported to be very high [10, 11, 13]. This variability may explain the inability of the model to predict TTE. Consequently, the actual and predicted D′ were considered in the current study. The predicted D′ was calculated from the linear distance-time relationship of three runs in the field test. The actual D′ was calculated post-hoc as the starting D′ that would allow full depletion at interval session termination. Although actual and predicted TTE from the combined trials were significantly different (P = 0.01), there were no significant mean group differences between actual (111 $\pm$ 67m) and predicted (120 $\pm$ 52m) D′ (P = 0.23; typical error = 33m). Therefore, it seems plausible to attribute some of the differences seen in actual and predicted TTE to relatively small errors in the estimation of D′ for each participant. These errors could be due to the relatively high variability in D′ between repeat trials.

Linear vs. non-linear recovery of D′

NB: CS and D′ are assumed to be synonymous with their cycling equivalents (CP and W’). For clarity CS and D′ alone will be used.

It has been suggested that D′ is depleted in a linear fashion during exercise above CS, resulting in a predictable TTE [3, 4, 6]. What is less clear is whether the reconstitution of D′ (once exercise drops below CS) also occurs in a linear fashion, or if recovery kinetics are different. Morton and Billat [19] and Chidnok et al. [3] assumed a linear reconstitution of D′

during the recovery intervals. Ferguson et al. [6] cast doubt on this theory and suggest that the recovery kinetics of D′ may in fact be curvilinear. Skiba et al. [23] more recently modeled recovery of D′ using an exponential model. Results of their work demonstrated the model provided a better 'fit' than the traditional linear approach in describing the dynamic state of D′ during intermittent cycling exercise. If the recovery of D′ is curvilinear, athletes in the current study may be expected to replenish less of their D′ during the recovery intervals than a linear model would predict. Therefore, with a slower replenishment of D′ during the recovery intervals, athletes would be predicted to fatigue quicker and have a shorter TTE in the overall interval session. Consequently, TTE predicted from a curvilinear model may be brought closer to the actual TTE.

To assess the effect of the recovery model, the linear model of Morton and Billat [19] and the non-linear model of Skiba et al [23] were compared (Table 2). Although there was a significant effect for model on the D'_{bal} at interval session termination, the non-linear model only resulted in a D'_{bal} closer to zero at interval session termination in the 200m trial. Overall (regardless of trial), the non-linear model did not produce at D'_{bal} at interval session termination that was closer to zero than the linear model (-21.2 and 13.4m, respectively).

The results of the present investigation suggest that the linear model of Morton and Billat [19] and the model developed for cycling by Skiba et al [23] cannot accurately model intermittent running exercise. These models, therefore, appear to have limited application in the design of interval training sessions, where the number of work:recovery periods an athlete can perform at given intensity cannot be accurately predicted. It could be argued, however, that predicting the exact number of repetitions is not important; as long as the athlete performs enough repetitions to cause fatigue (and therefore send a signal for adaptation), the purpose of the workout has been met. However the inability to accurately model intermittent exercise within a controlled interval session reduces the likelihood that the models, in their present form, have any further real-time performance monitoring application during competition.

When comparing the linear model of Morton and Billat [19] and the non-linear model of Skiba et al [23], it should be noted that the model of Skiba et al (equation 5) was derived for cycling exercise and suggests a time constant of W' repletion ($\tau_{W'}$) of 578s. It is possible that recovery of W' and D′ may differ and therefore a specific time constant of D′ repletion ($\tau_{D'}$) may be required for running research. To further investigate $\tau_{D'}$, the time constant for each participant for each trial was varied by an iterative process until modeled D'_{bal} equaled zero at the point of interval session termination [23]. The intensity of the recovery interval for each participant across each trial was also recorded by calculating the difference between recovery speed and critical speed (D_{CS}). Mean $\tau_{D'}$ and D_{CS} for each trial are shown in table 3.

D_{CS} was significantly different across trials (P<0.01), with all trials being significantly different from each other. However, it can be estimated that the recovery speed during all trials fell within the heavy exercise domain (between gas exchange threshold and CS), as recovery speed during trials was 95, 90 and 80% of CS for the 1000m, 600m and 200m trials, respectively. There was no significant difference in $\tau_{D'}$ across trials (P>0.05). Skiba et al [23] reported differences in $\tau_{W'}$ across all trials in their study. However, trials in the Skiba et al study spanned the exercise intensity domains, whereas recovery intensity in the present study fell in the heavy domain for all trials. Therefore, differences in $\tau_{D'}$ within this domain were not expected. Furthermore, there was no significant correlation between $\tau_{D'}$ and CS across any of the trials (r = -0.20, P=0.23; combined trial data). Using the magnitude scale proposed by Hopkins et al [14] this level of correlation would be described as small. This is in contrast to the findings of Skiba et al [23], who report a trend (P=0.08) for an inverse relationship between these parameters within the heavy intensity domain. There was a small non-significant correlation between $\tau_{D'}$ and D_{CS} across the trials (r = -0.04, P=0.81; combined trial data). This is also in contrast to the findings of Skiba et al [23], who report a large inverse relationship between these parameters (r = -0.67, P < 0.01). Mean $\tau_{D'}$ across the three trials was 377 ± 129s. This is in contrast to the reported $\tau_{W'}$ of 578 ± 105s during the heavy intensity recovery condition of Skiba et al [23].

It would appear from the above results that there might be differences in the time constants for W' and D′ repletion. Further research to develop a running specific D'_{bal} model and $\tau_{D'}$ is needed before the true potential of the non-linear model during intermittent running exercise can be assessed.

Whilst the ability to perform continuous and intermittent exercise are somewhat different abilities, the underpinning rationale governing the distance-time relationship suggests it may be possible to predict intermittent exercise performance from the results of a continuous-running field test. The results of the present investigation suggest that CS and D′ estimated from a continuous-running field test cannot accurately quantify TTE during intermittent running. This may be due to the variability in the measurement of D′ [10, 11] and differing recovery kinetics between running and cycling exercise.

Conclusion:

The results of this study demonstrate that neither the current linear nor nonlinear recovery models accurately predict TTE in intermittent exercise. This suggests that models based upon CS and D′ do not presently appear applicable to intermittent running exercise. Furthermore intermittent TTE predictions are less accurate for shorter high intensity intervals, whilst the manner in which recovery is modelled during intermittent exercise also alters the estimated TTE. Coaches therefore need to be wary of prescribing intervals based on these methods. This has implications for the practical application of the distance-time relationship to prescribe intermittent exercise and monitor real-time performance. Future research should determine whether a distance-time model is appropriate for intermittent exercise and what recovery kinetics should be assumed.

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Figures

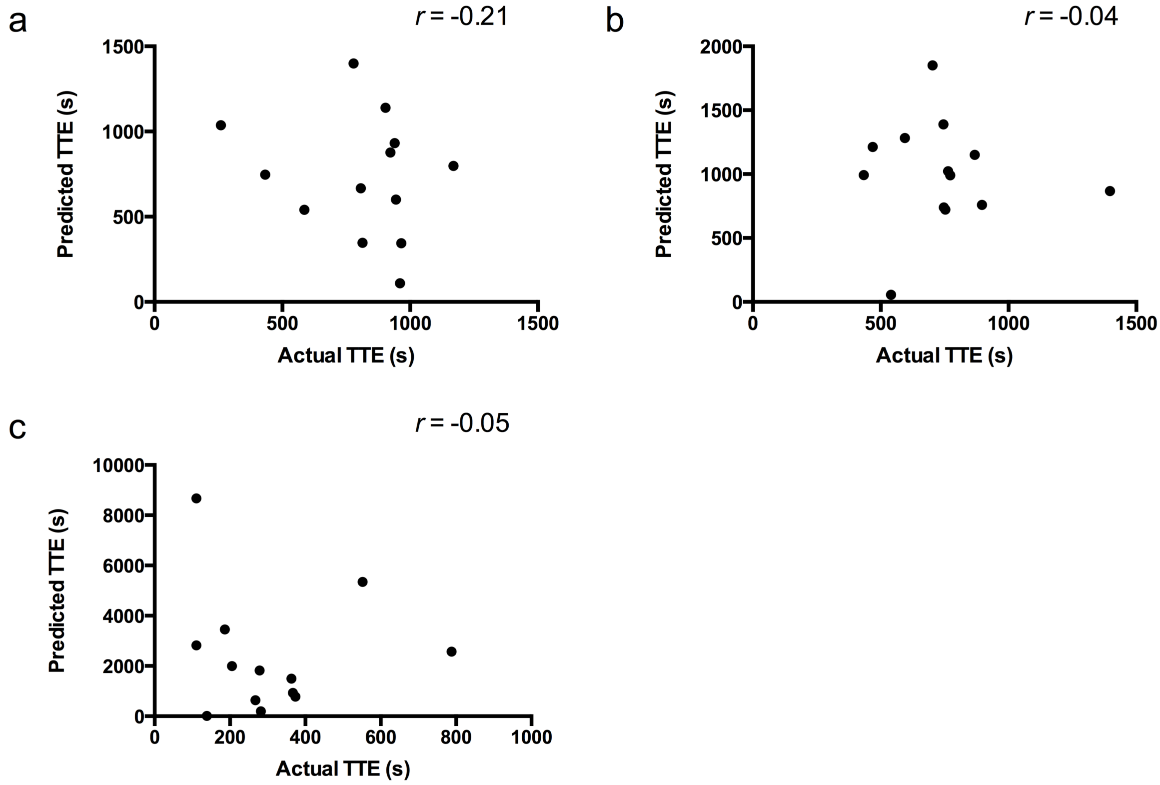

Fig. 1: Relationship between the actual and predicted time to exhaustion (TTE) for the 1000m trial (a), the 600m trial (b) and the 200m trial (c). Predicted TTE is estimated from the linear model.

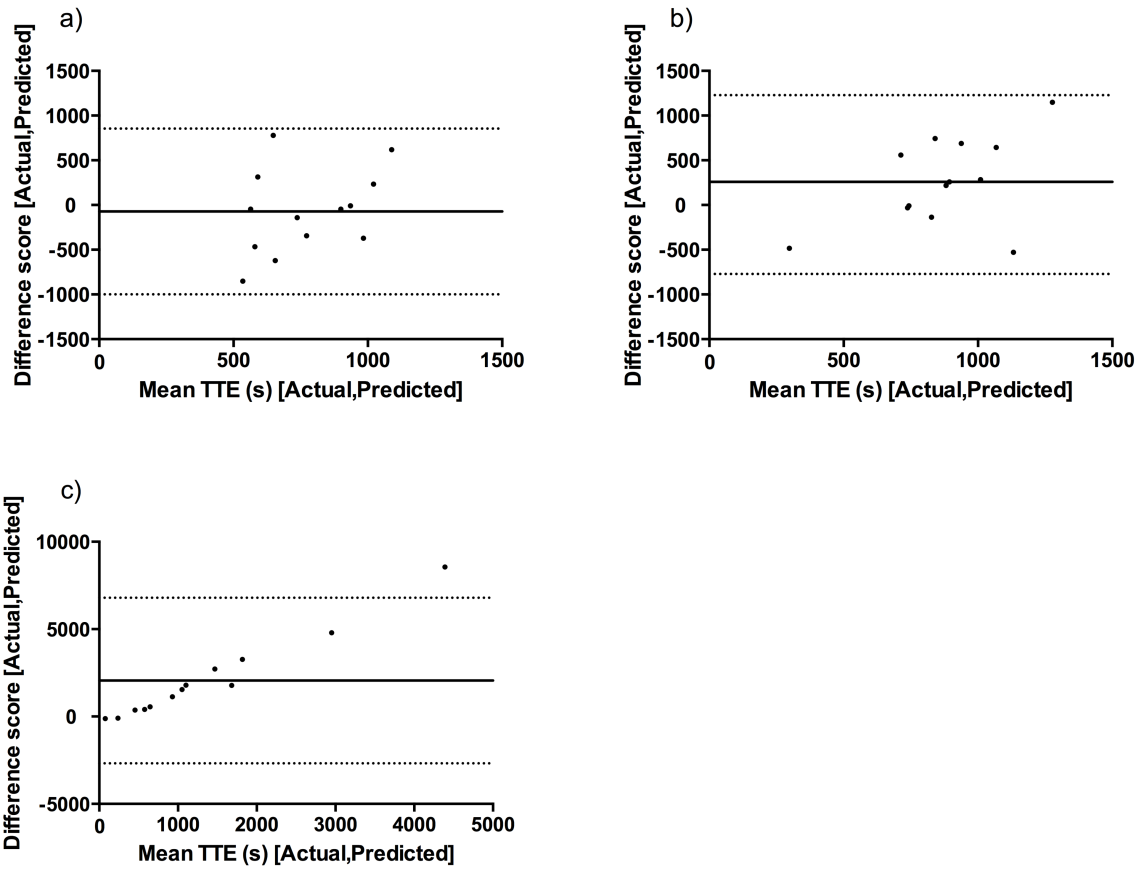

Fig. 2: Bland-Altman plots of differences in time to exhaustion (TTE) between the actual and predicted methods for the 1000m trial (a), the 600m trial (b) and the 200m trial (c). The solid horizontal lines show the mean bias, whilst the dashed lines represent the 95% limits of agreement. Predicted TTE is estimated from the linear model.

Tables

Table 1: Comparison of actual and predicted TTE

	Actual TTE (s)	**Predicted TTE (s)**
1000m trial	806 ± 246	734 ± 355
600m trial	745 ± 242	1003 ± 422
200m trial	310 ± 191 *	2364 ± 2399

TTE = time to exhaustion.
Data are presented as mean ±SD. Predicted TTE is estimated from the linear model.
* Significantly lower than predicted TTE (*P* = 0.01)

Table 2: D'_{bal} (m) at interval session termination estimated from linear and non-linear models

1000m Trial		**600m Trial**		**200m Trial ***	
Linear	**Non-linear**	**Linear**	**Non-linear**	**Linear**	**Non-linear ****
-16.9 ±46.7	-19.8 ±34.4	10.2 ±37.4	-19.5 ±26.3	47.0 ±39.2	-24.4 ±33.3

D'_{bal} = balance of D′ remaining
Values are displayed as mean ± SD. Non-linear model $\tau_{D'}$ = 578s.
* 200m trial D'_{bal} significantly higher than 1000m trial (*P*=0.03).
** Non-linear 200m trial D'_{bal} significantly lower than linear 200m trial D'_{bal} (*P*<0.01).

Table 3: Calculated $\tau_{D'}$ (s) and D_{CS} ($m.s^{-1}$) for each trial

1000m Trial		**600m Trial**		**200m Trial**	
$\tau_{D'}$	D_{CS} *	$\tau_{D'}$	D_{CS}	$\tau_{D'}$	D_{CS} ◆
353 ± 118	0.35 ± 0.09	378 ± 100	0.51 ± 0.08	397 ± 167	0.82 ± 0.16

$\tau_{D'}$ = time constant of D′ repletion; D_{CS} = difference between recovery speed and critical speed
values are displayed as mean ± SD
* Significantly lower than 600m and 200m trial D_{CS} (*P*<0.01).
◆ Significantly higher than 1000m and 600m trial D_{CS} (*P*<0.01).