Iso-duration determination of *D´* and CS under laboratory and field conditions

Abstract

Whilst Critical Speed (CS) has been successfully translated from the laboratory into the field, this translation is still outstanding for the related maximum running distance (*D´*). Using iso-duration exhaustive laboratory and field runs, this study investigated the potential interchangeable use of both parameters, *D´* and CS. After an incremental exercise test, ten male participants (age: 24.9±2.1 yrs; height: 180.8±5.8 cm; body mass: 75.3±8.6 kg; $\dot{V}O_{2peak}$ 52.9±3.1 $mL \cdot min^{-1} \cdot kg^{-1}$) performed three time-to-exhaustion runs on a treadmill followed by three exhaustive time-trial runs on a 400 m athletics outdoor track. Field time-trial durations were matched to their respective laboratory time-to-exhaustion runs. *D´* and CS were calculated using the inverse-time model (speed=*D´*/t+CS). Laboratory and field values of *D´* and CS were not significantly different (221±7 m vs. 225±72 m; $P = 0.73$ and 3.75±0.36 $m \cdot s^{-1}$ vs. 3.77±0.35 $m \cdot s^{-1}$, $P = 0.68$), and they were significantly correlated ($r = 0.86$ and 0.94). The 95% LoA were ±75.5m and ±0.24 $m \cdot s^{-1}$ for *D´* and CS, respectively. Applying iso-durations provides non-significant differences for *D´* and CS and a significant correlation between conditions. This novel translation method can consequently be recommended to coaches and practitioners, however a questionable level of agreement indicates to use *D´* with caution.

Introduction

The translation of standardized laboratory performance tests into the field arguably presents a challenge to applied sport science research. An example of such can be found in the translation of the power-duration relationship of Critical Power (CP) and Critical Speed (CS). A high level of research attention has been focused on the utility of these parameters in the laboratory and in the field [14,23,39], as CS and its related maximum running distance above CS (*D´*) are important for performance assessments [20,22,29], training prescription [13,25], and performance predictions [13,25,32].

D´ represent a finite distance that can be performed when exercise intensity is above CS [30]. At speeds marginally above CS, *D´* is depleted slowly whilst speeds considerably higher lead to a faster discharge of *D´* [34]. When *D´* is depleted, exercise either terminates if speed is to be maintained at or above CS or speed has to drop below CS where *D´* starts to reconstitute [5,36,41]. Furthermore at speeds above CS, *D´* accurately predicts tolerable exercise duration in the severe domain [12]. Knowledge of *D´* is essential to understand the limits of high intensity exercise as there is for example a large contribution of *D´* for running distances between 400 and 10.000 m [e.g. 6,7,9]. Modelling the depletion and repletion of *D´* could help coaches and practitioners to predict the termination of exercise more accurately [15] whilst also be useful for pacing strategies [37]. Today's technology is furthermore able to estimate depletion and reconstitution of *D´* during exercise in real time (e.g. Garmin, Colorado, USA.)

Originally, *D´* was considered to represent a finite energy source consisting mainly of anaerobic sources such as intramuscular ATP, PCr, stored oxygen and glycogen [28] but later deemed to represent an accumulation of metabolites (e.g. [La], P_i, H^+, and K^+) inducing fatigue [42]. The mechanistic base of *D´* however still remains equivocal.

Until recently, the determination of CS/CP and *D´* (*W´* in cycling) was exclusively performed under laboratory conditions. However, practical and ecological reasons lean coaches and practitioners closer towards field testing [14,23,39]. Moreover, performance data obtained during field testing such as power or speed is more applicable for coaches and practitioners than common physiological variables obtained from the laboratory determined using stationary cycling or treadmill running [25].

In the laboratory, time-to-exhaustion trials (TTE) at fixed work-rates are regularly employed to determine CP or CS [e.g. 14,20,33]. However, these tests do not reflect real-life exercise, as constant intensities are rarely observed in a sporting context nor are athletes required to perform at such fixed intensity until exhaustion. A lower reliability of TTE compared to time trials (TT) (using fixed durations or fixed distances) has also been criticised [27]. However, to determine *D´* and CS in the laboratory TTE testing trials are still seen as the 'Golden Standard' and generally serve as criterion variable in research [14,24]. TT efforts do reflect real-life exercise better and typically also represent competitive performance [19].Compared to fixed work rates, Thomas et al. [38] importantly stipulated that TTs which involve a fast-start strategy can result in a higher mean power output and due to the altered $\dot{V}O_2$ response at exercise onset, can consequently lead to similar *W´* but higher CP values [3]. Applying TTs for the determination of CP and *W´* however carries a higher level of ecological validity as athletes are familiar with fixed-distance or timed effort performances [31]. A number of researchers recently demonstrated the successful translation of CP between conditions and effort types [23,24,39]. Even though comparing TTE with TT efforts, results demonstrated similar conditional CP values but in cycling these works also revealed significant differences for *W´*. Karsten et al. [23] for example suggested that the methodological dissimilarities, i.e. the start from a standing position involving a different muscle fibre recruitment pattern under field conditions might have caused the differences for *W´*. To clarify this, Triska et al. [39] consequently equalised the testing conditions by using a rolling start in the laboratory and in the field. Together with a low agreement and a high prediction error results demonstrated the starting condition not to be at the cause of the differences for *W´* values. In contrast to these findings, Black et al. [3] identified significantly greater CP values but no differences in *W´*, when comparing self-selected cadence TT with conventional resistance step increases TTE efforts in the laboratory. Matching total work performed during the TTE efforts, athletes had to perform as much work as possible in respective TT efforts using the linear-mode of the ergometer which allows time trials to be performed against a fixed resistance. The methodological differences between fixed resistances versus adjustable resistance TTs might explain these findings and the aforementioned cycling studies highlight the need to equalise not just starting but also test mode conditions in future research.

The successful translation of CS between treadmill and field running performances was recently reported by Galbraith et al. [14]. Results indicate a significant correlation for CS between the conditions, a small bias and acceptable levels of agreement [14]. Equally to *W´* in cycling, *D´* also revealed significant differences with a large bias and an unacceptable level of agreement [14]. Galbraith et al. [14] initially suspected differences in exhaustive durations to have caused these findings for *D´*. However, their further analysis revealed a non-significant difference in the combined duration of exhaustive runs [14].

With pertinent research providing a sufficient insight into the interchangeable use of CP and CS under laboratory and field conditions, much less is known about the interchangeable use of *W´* and *D´*. The purpose of the current work therefore was to further investigate this issue by applying not combined but individual iso-duration predictive trial tests (IDT) between conditions. We hypothesised non-significant differences, a small bias, a close level of agreement and significant correlation for both, *D´* and CS.

Materials & Methods

Participants

Ten male moderately trained participants (age: 24.9 ± 2.1 yrs; height: 180.8 ± 5.8 cm; body mass: 75.3 ± 8.6 kg; $\dot{V}O_{2max}$ 52.9 ± 3.1 $mL \cdot min^{-1} \cdot kg^{-1}$) with about 4 hours of weekly running training volunteered to participate in this study. After all experimental procedures were explained, participants completed a health questionnaire and provided written informed consent. Prior to each visit, participants were asked to refrain from alcohol the preceding 24 hours and from food and caffeine intake the preceding 3 hours. Participants were furthermore asked to arrive in a fully hydrated state, and they were instructed not to perform strenuous exercise the previous 24 h and to wear the same running shoes for all tests. The study was conducted in accordance with the *Declaration of Helsinki* and met the ethical standards of the International Journal of Sports Medicine [16]. The Ethics Committee of the host institution approved all procedures (Reference Number: 00155).

Study design

Each participant attended two laboratory tests and one field test. During the initial laboratory visit the first ventilatory threshold (VT), maximal aerobic running speed (MAS) and peak oxygen uptake ($\dot{V}O_{2peak}$) were determined using an incremental treadmill exercise test. Participants also completed one familiarization TTE run. To determine *D´* and CS, this was followed by the laboratory and the field runs in that order. The durations of each exhaustive trial under field conditions was matched with their laboratory counterparts (IDT). Participants were given a 30-min passive rest period between exhaustive runs during which they were allowed to drink water ad libitum. During all tests participants were strongly verbally encouraged throughout exhaustive efforts. Testing was performed at the same time of the day

(± 2 h). At least 48 h separated each testing session and all tests were completed within a 3-week period. Laboratory conditions were controlled using an air condition system. The temperature was within 22-23°C and humidity between 45 and 55%. To compensate for air resistance, the treadmill grade was set to 1% during all tests [21].

Incremental exercise test & familiarization trial

The incremental treadmill test (Saturn, h/p cosmos Sport and Medical, Traunstein, Germany) commenced with 3 min baseline walking at 1.39 $m \cdot s^{-1}$. After that, the treadmill speed was set to 1.67 $m \cdot s^{-1}$ and was increased by 0.14 $m \cdot s^{-1}$ every minute until volitional exhaustion. MAS was estimated according to the equation of Kuipers et al. [26] if the last stage could not be completed:

$$MAS = sL + (\frac{t}{60}\ x\ 0.14) \qquad (1)$$

where MAS is the maximum aerobic speed, sL is the speed of the last completed stage ($m \cdot s^{-1}$) and t is the duration of the incomplete stage (s).

Respiratory gases were measured on a breath-by-breath basis throughout the test (MetaMax3B, Cortex Biophysik GmbH, Leipzig, Germany). Participants wore a face mask covering nose and mouth, and they breathed through a low-resistance impeller turbine. Before each test the gas analyser was calibrated according to the manufacturer's guidelines using gases with known concentrations (5 Vol% CO_2, 16% Vol% O_2, Cortex, Biophysik GmbH, Leipzig, Germany), and the flow volume was calibrated using a 3-L syringe (Type M 9474-C, Cortex Biophysik GmbH, Leipzig, Germany). VT was determined following the criteria of a) an increase of the ventilatory equivalent of oxygen ($\dot{V}E/\dot{V}O_2$) without a concomitant increase in the ventilatory equivalent of carbon dioxide ($\dot{V}E/\dot{V}CO_2$) and b) the first loss of linearity in minute ventilation ($\dot{V}E$) and $\dot{V}CO_2$ [2]. The highest 30-s $\dot{V}O_2$ interval during the incremental test was taken as $\dot{V}O_{2peak}$.

This was followed by a familiarization TTE trial after a 30 min passive recovery period at a chosen speed that approximated 100% MAS (range: 95 to 110% MAS).

Laboratory test to estimate D´ and CS

Participants had to complete three TTE trials at individualised fixed speeds. Intensities for TTE trials were estimated to be at 75%Δ (75% of the difference between VT and MAS), 98% of MAS and 108% of MAS. These intensities were chosen to elicit exhaustion within 3 and 15 min [17,24,25,35]. Consistent with literature the sequence of the TTE trials was from the longest to the shortest efforts using a 30-min passive recovery period between runs to ensure a fully reconstituted D' [11,14,23,39]. A 10-min standardized warm-up at a speed corresponding to 80% VT was performed prior all exhaustive runs [32]. After 3-min of baseline walking at ~1.39 $m \cdot s^{-1}$, participants' respective trial speeds were set where the transition between walking and running first had to be completed [32]. Timing started when participants released both handrails (range: 1 to 3 s) and stopped when participants grasped at least one handrail to signal exhaustions. Timing was measured to the nearest second using a stop watch. Prior, during and post runs, no feedback about elapsed time, speed, or expected duration was provided. However, participants were informed about the order of the trials, i.e. from the longest to the shortest.

Field test to determine D´ and CS

Under field conditions participants completed three TTs on a 400 m athletics track. The durations for each of these TTs equalled the corresponding TTE trial (i.e. a predictive trial in laboratory with a duration of 12 min equalled a 12 min TT under field conditions). In order to pace efforts, each participant was equipped with a stopwatch and instructed to cover the greatest distance possible within given times. Around the track, cones were set at 20 m intervals beneath the first lane to measure running distances to the closest ± 5 m. The number of completed laps and number of cones past that final lap were counted. Added to this distance was the distance covered past the final cone which was measured to the nearest meter using a distance measuring wheel. The final positions at the end of each TT were recorded as close as possible and total distance was calculated subsequently. Tests were only performed under dry conditions with a wind speed <3 $m \cdot s^{-1}$. The warm-up and walk-to-run procedures were similar to laboratory testing. Timing started when participants crossed the starting line on the 400-m athletics track. Temperature and humidity were between 19 and 24°C and between 40 and 60%, respectively.

Estimation of D´ and CS

D' and CS were determined using mean running speeds and inverse durations of each run. Parameter estimates were calculated using a linear regression where running speed is plotted against the inverse of time using the following equation:

$$speed = D' \, x \, 1/t + CS \qquad (2)$$

where speed is in $m \cdot s^{-1}$, D' is the maximum running distance above CS (m), t represents time (s), and CS is critical speed ($m \cdot s^{-1}$). The y-intercept of the linear regression is CS and the slope

D´. For both conditions, the standard error (SE) of *D´* and CS were calculated from the linear regression for all participants.

Statistical analyses

The normal distribution of each variable was examined using the Shapiro-Wilk-statistic. This was followed by a paired sample t-test to detect any significant differences between laboratory and field conditions of *D´* and CS. Validity was assessed using the typical error of the estimate [18], where laboratory retrieved *D´* and CS estimates were used as criterion and field derived *D´* and CS estimates were used as a practical variables [14]. Limits of agreement (LoA) were used to assess the agreement between laboratory and field derived estimates [4]. Pearson product-moment correlation coefficient was used to provide an indication of the strength of any relationship between laboratory and field derived *D´* and CS values. Furthermore, the standard error of the estimate (SEE) for *D´* and CS was calculated to describe the error between the conditions. For all measurements, the significance level was accepted at $P < 0.05$ and data is reported as mean ± SD. The number of participants was calculated using G*Power 3.1.9.2. [10]. In line with unpublished findings from our laboratory *D´* and CS were expected to result in 220 m and 3.80 $m \cdot s^{-1}$ respectively. The smallest worthwhile effect was assumed to be 15 m and 0.15 $m \cdot s^{-1}$ for *D´* and CS respectively. A difference of that magnitude would result in 5-km running times of 1258 s vs. 1214 s (<5%), which is within day-to-day variation [18]. Ten participants were required to detect a difference at an alpha-level of $P < 0.05$ with a statistical power of 80%.

Results

D´ and CS results are presented in Table 1 and Table 2. Figure 1 illustrates CS and *D´* estimates of a representative participant. *D´* and CS were not significantly different ($t_9 = 0.357$; $P = 0.729$ and $t_9 = 0.432$; $P = 0.676$ for *D´* and CS, respectively) and strongly correlated between conditions ($r = 0.855$; $P = 0.016$ and $r = 0.938$; $P < 0.001$ for *D´* and CS, respectively) (Figure 2a and 2c).

For *D´* the mean SE was 29.5 ± 16.0 m (14.0 ± 7.9%) under laboratory conditions and 48.8 ± 40.8 m (24.6 ± 21.4%) under field conditions ($t_9 = -1.360$; $P = 0.207$). The mean SE for CS was 0.10 ± 0.05 $m \cdot s^{-1}$ (2.6 ± 1.3%) vs. 0.14 ± 0.12 $m \cdot s^{-1}$ (3.7 ± 3.6%) under laboratory and field conditions, respectively ($t_9 = -0.866$; $P = 0.409$). In addition, the coefficients of determination (R^2) of the linear regressions were 0.976 ± 0.021 and 0.934 ± 0.093 under laboratory and field conditions, respectively ($t_9 = 1.390$; $P = 0.198$).

No significant differences were identified for the distance covered during the lowest ($t_9 = 0.639$; $P = 0.538$) and highest intensity run ($t_9 = -0.159$; $P = 0.877$), but significant differences were found for the distance covered during the medium intensity run ($t_9 = -3.468$; $P = 0.007$) (Table 1).

Discussion

Our novel findings demonstrate a non-significant difference for both parameters, *D´* and CS. Moreover, results show a significant correlation and a low bias between the conditions. Although a higher level of agreement between criterion (i.e. laboratory) and practical (i.e. field) values and a smaller typical error compared to earlier studies were demonstrated (Figure 2; Table 2) results for *D´* are still debatable [14,23,39]. However, the reduction in differences between *D´* estimates can be attributed to the implementation of the iso-duration test methodology and results provide further insights into the translation of laboratory tests into the field.

D´

The present findings are consistent with Black et al. [3] who utilised a similar method by matching work performed (i.e. iso-work) between TTE and TT efforts in cycling. Their results demonstrated a non-significant difference for *W´* and similar to our work found a significant correlation for *W´* ($r = 0.67$). It can consequently be suggested that only matched-work or match-duration trials result in an improved agreement between laboratory and field estimates of *D´*/*W´* and between TTE and TT efforts. As TTs have shown to provide a higher reliability and a higher ecological validity [27,39], we therefore suggest to employ this type of effort under both conditions with either fixed-durations or fixed-distances.

Compared to Galbraith et al. [14], the mean bias for *D´* in the present study was markedly lower (4.4 m vs -143.3 m), 95% LoA showed a markedly higher level of agreement (± 75.5 m vs. ± 186.9 m) (see Figure 2b) and the typical error was notably smaller (39.2 m vs 88.4 m). This typical error in the present study can be interpreted as *small*, whilst in the work of Galbraith et al. [14] the typical error is interpreted as *moderate* [18]. Whilst no significant correlation between conditions was found previously for *D´* ($r = 0.13$ in [14]), the present study identified such significant correlation ($r = 0.855$; $P = 0.016$). These enhancements in the conditional translation appear to be based in the use of IDT, which to-date was not investigated for running or between conditions.

Although the durations for the corresponding trials was the same, mean covered distance for the medium intensity run in the field was 2.1% greater (*P* = 0.007), whereas non-significant differences of <1% were found for the lowest and highest intensity run. However, all trials provided significant correlations for all respective runs (*r* = 0.989-0.995), which demonstrates a high reproducibility between treadmill running and over-ground running.

However, the differences in the medium distance runs might be responsible for the higher predictive error (18.7%) and the lower LoA. Even a small difference in trial durations can result in a different estimate of $D´$ [40]. Transferring this to covered distance, this might have had a vast impact on the estimate of $D´$ under field conditions. This is furthermore supported by unpublished observations from our laboratory, which indicate that different durations together with different distances of the corresponding trials result in a large typical error (34.3%) and an unacceptable level of agreement (± 161.4 m). Using IDT can consequently lower the typical error for $D´$.

Previous works have demonstrated that fast TT-starts result in a faster $\dot{V}O_2$ on-kinetics and thus a smaller O_2 deficit and smaller breakdown of anaerobic sources which together also result in a higher mean power output [1,3]. As a fast-start is usually performed in TTs [8], the rate of anaerobic source usage can therefore be suggested to be different between TTE and TT efforts when testing conditions are not standardized (i.e. similar acceleration patterns). Black et al. [3] speculated that a fast-start neither precipitates fatigue nor results in a premature depletion of $D´$, though faster $\dot{V}O_2$ on-kinetics during a fast-start could have altered usage of $D´$ in the present study.

Usage of $D´$ ($D´_{\text{used}}$) during the exhaustive runs under field conditions was calculated using

$$D´used = speed - CS\ x\ t \tag{3}$$

Figure 1 represents one participant (parameter estimate ± SE: 3.54 ± 0.03 $m \cdot s^{-1}$ and 188.6 ± 14.5 m for CS and $D´$, respectively). Interestingly, the predictive trials resulted in 170.9 m, 200.6 m and 186.3 m of $D´_{\text{used}}$ for the lowest, medium and highest intensity run, respectively. This results in a $D´$ balance of 17.7 m, -12.3 m and 2.3 m for the lowest, medium and highest intensity run, respectively. Even though the SE for this representative participant was < 10% which is within acceptable limits [12], $D´_{\text{used}}$ does not equal estimated $D´$ for all predictive runs, demonstrating a difference of ~10%. Moreover, a SE within the acceptable limit may not truly represent the 'physiological' $D´$ and estimates $D´$ with some error. Thus $D´$ shows a higher typical error and a lower level of agreement compared to CS. We consequently suggest that a mean SE >10% is largely responsible for the predictive error of ~19% in the present study. A lowering of the SE <10% could further reduce the predictive error and consequently increase the transferability of *D´*. Given the above we therefore have to reject our hypothesis for *D´* to provide interchangeable values when applying IDT.

Critical Speed

Compared to Galbraith et al. [14] the mean bias, 95% LoA, and the typical error are in close agreement (Figure 2d). The typical error of the estimate can be interpreted as *small* across both studies [18]. Compared to earlier studies the correlation coefficient in the present study (r = 0.94) is higher (r = 0.89-0.90 [14,25]) even though we assessed a cohort of runners with lower aerobic fitness levels.

Interestingly, significantly increased CP estimates were found when using a fast-start TT strategy compared to step increase constant load TTE tests [3]. Arguing this, Black et al. [3] stated that during the fast-start a smaller oxygen deficit and a smaller $\dot{V}O_2$ slow component could have increased mean power and delayed fatigue. As TT are usually performed with a fast start and a following decline in speed/power [8], a fast-start had no negative effects on the estimate of *D´* in the present study.

IDT do not seem to be considerably superior over non-matched durations when estimating CS. However, as participants in the present study had notably lower aerobic capacity levels, compared to recent work for CS [14] applying IDT in a cohort of well-trained athletes would probably decrease the predictive error and mean bias further.

Limitations of the study:

No continuous measure of speed was conducted to assess pacing and speed characteristics during the TT runs. Furthermore, un-accustomed durations and distances (e.g. 3 min 27 s and 987 m) were used for the TTs which somewhat lowered the ecological validity of the tests as our participants were familiar with running typical race distances of e.g. 5-km. Finally, the measurement of distance was limited to the closest metre which might have had some impact on the calculation of *D´*.

Conclusions:

Compared to previous works, using IDT has improved the transfer of laboratory results into the field when investigating *D´* and CS. When employing this novel testing method, CS shows less error, a better agreement and a stronger correlation. However, despite a notably lower error some caution should be practiced when using *D´* in a field training prescription context as the typical error might still be unacceptably high as *D´* cannot be used interchangeably between conditions.

Above all, it still remains unclear if *D´* estimated from three exhaustive runs truly represents the 'physiological' *D´*. Therefore, it can be recommended that future works include a performance trial (e.g. a depleting *D´* run) to investigate possible differences between predicted and actual sustainable severe intensity exercise durations. Moreover, to further raise the ecological validity, common race distances or durations should be used for the determination of *D´* and CS.

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Figure captions:

Figure 1: Example of a representative participant, where the inverse of time ($1 \cdot t^{-1}$) is on the x-axis and mean speed ($m \cdot s^{-1}$) is on the y-axis. The slope of the linear regression represents *D´* and the y-intercept CS.

Figure 2: Relationship between *D´* and CS between the conditions (panels *a* and *c*). The solid line represents the linear regression and the grey-dotted line represents the line of identity. Bland-Altman plots of the differences between laboratory and field estimated of *D´* and CS (panels *b* and *d*)