Predicting Intermittent Running Performance: Critical Velocity versus Endurance Index

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Key words
- endurance capacity
- critical power
- time limit
- distance limit

Abstract

The aim of the present study was to examine the ability of the critical velocity (CV) and the endurance index (EI) to assess endurance performance during intermittent exercise. Thirteen subjects performed two intermittent runs: 15-s runs intersected with 15 s of passive recovery (15/15) and 30-s runs with 30-s rest (30/30). Runs were performed until exhaustion at three intensities (100, 95 and 90% of the speed reached at the end of the 30–15 intermittent fitness test, V_{IFT}) to calculate i) CV from the slope of the linear relationship between the total covered distance and exhaustion time (ET) (iCV); ii) anaerobic distance capacity from the *y*-intercept of the distance/duration relationship (iADC); and iii) EI from the relationship between the fraction of V_{IFT} at which the runs were performed and the log-transformed ET (iEI). Anaerobic capacity was indirectly assessed by the final velocity achieved during the Maximal Anaerobic Running Test (VMART). ET was longer for 15/15 than for 30/30 runs at similar intensities. $iCV_{15/15}$ and $iCV_{30/30}$ were not influenced by changes in ET and were highly dependent on V_{IFT}. Neither $iADC_{15/15}$ nor $iADC_{30/30}$ were related to VMART. In contrast, $iEI_{15/15}$ was higher than $iEI_{30/30}$, and corresponded with the higher ET. In conclusion, only iEI estimated endurance capacity during repeated intermittent running.

Introduction

The individualization of a training program is an important aspect of training program design. In addition to individualizing exercise intensity (i.e., percentage of maximal oxygen uptake or ventilatory threshold), the exercise exhaustion time (ET) at a given intensity can also be used to create an appropriate exercise stimulus [10]. Nevertheless, it is time-consuming and laborious to test ET over a wide range of exercise intensities. Thus, mathematical methods capable of predicting endurance running ability over a short number of field tests represent an attractive alternative. The critical power [28] and endurance index (EI) of Peronet and Thibault [32] are two models that can be simply computed from a series of endurance tests. The concept of critical power was originally proposed for use with small muscle groups [28], but was later adapted for whole body exercises, including running, cycling and swimming [37]. For running exercises where distance and velocity are used instead of work and time, the expression "critical velocity" (CV) is commonly used instead of critical power. CV, expressed as the slope of the regression line between the distance ran and the corresponding time over a series of maximal effort time-trials, has been used successfully to predict the highest speed that can be sustained for prolonged durations [37]. The *y*-intercept of this distance/time relationship has been interpreted as being equivalent to energy stores (oxygen bound to myoglobin and anaerobic capacity) [28] and to be an estimation of maximal anaerobic distance capacity (ADC, m) for running exercises [20]. The endurance index (EI) is defined as "the decrease in fractional utilization of maximal oxygen uptake ($\dot{V}O_{2max}$) when running duration exceeds seven minutes and when the natural logarithm of time is increased substantially" [13,32]. Thus, the higher the absolute EI score one achieves, the lower their endurance capacity is deemed to be. Although CV and EI index do not represent the same physiological entity (CV is a "power" whereas EI reflects aerobic "capacity"), we believe, when considering these indexes for training program design, that they can both assist

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with assessing one's ability to sustain a set amount of work over a given time. Thus, CV and EI may be used as practical field methods to assess endurance performance during intermittent running and to assist with the individualization of training programs. For example, knowledge of an "intermittent endurance capacity" together with the absolute maximal aerobic power level could assist to prescribe sports specific training content (i.e., emphasis on aerobic power vs. aerobic capacity development).

Although high-intensity interval training is common practice in athletes [8,25], and similar to the physiological demands of team sport events [4,19], only a small number of studies have attempted to examine predictors of the capacity to sustain short intermittent performance [21]. Ultimately, the simultaneous development of both aerobic and anaerobic capacity is of great importance [8]. Thus, mechanisms that improve oxygen availability and serve to spare anaerobic capacity, such as fast cardiorespiratory kinetics [27] or high muscle substrates repletion kinetics (i.e., reoxygenation of myoglobin and hemoglobin and phosphocreatine resynthesis), may influence the ability to repeat high-intensity intermittent exercise. As well, the characteristics of intermittent exercise itself, such as work interval intensity, work interval duration and rest interval intensity, will directly influence the exhaustion time during intermittent exercise [8, 29].

Kachouri et al. [24] and Berthoin et al. [6,17] have previously applied the CV concept to short intermittent high-intensity running exercise (15-s runs intersected with 15 s of passive recovery) and found linear relationships ($0.99 < r^2 < 1$; $p < 0.01$) between the distance covered and the exercise exhaustion time. Berthoin et al. argued that CV for intermittent exercise (iCV) was a good index of aerobic fitness and confirmed that it could be practically adapted to predict intermittent high-intensity running performance [6,24]. The *y*-intercept of the iCV relationship was thought to reflect anaerobic distance capacity (iADC) [6,17,24] as shown previously in continuous exercises. However, the remarkably high relationships between iCV and maximal aerobic velocity (MAV) reported in Berthoin's studies ($0.99 < r^2 < 1$; $p < 0.01$) leads one to question the validity of this relationship for predicting repeated intermittent running ability. As a result, we sought to reexamine the ability of the CV model to assess intermittent running performance. We also sought to examine this model alongside another endurance predictor method, namely the EI.

The purpose of the present study was to 1) apply the mathematical modelling methods of CV and EI to short intermittent runs and observe their respective ability to predict endurance performance; and 2) examine the use of the anaerobic distance capacity (iADC), calculated from the *y*-intercept of the distance/duration relationship, as a predictor of anaerobic capacity. To accurately reflect endurance during repeated short exercises, we hypothesized that the different methods (iCV and iEI) would provide indexes sensitive enough to detect differences in endurance capacity when i) exhaustion time was different between exercises with different bout durations, and ii) when subjects with similar reference running speeds displayed different exhaustion time at similar exercise intensities. Finally, we hypothesized that iADC would be similar irrespective of exercise bout duration and would be related to other objective indirect indices of anaerobic capacity (i.e., speed reached at the end of specific a maximal anaerobic running test).

Methods

Subjects

Participants were 13 male athletes (age 24.4 ± 3.9 y, weight 74.9 ± 7.3 kg, height 179.1 ± 16.1 cm) routinely involved in various intermittent activities (soccer, handball, basketball or tennis, 7.2 ± 2.1 $h \cdot wk^{-1}$). Subjects underwent medical screening and did not present contraindications for vigorous exercise. All subjects gave their written informed consent to participate in the study, which was approved by the local institutional ethics committee.

Overview

Subjects performed eight maximal field tests at the same time of day (± 1 h) over a 4- to 5-week period; each test was separated by at least 48 h. Field tests included one graded intermittent aerobic test, one short-term intermittent graded anaerobic test and six intermittent tests. All tests were performed on an indoor synthetic track where ambient temperature ranged from 18 to 22 °C. The two graded maximal aerobic and anaerobic tests were performed first, followed by the explosive strength tests and intermittent maximal tests in a random and balanced order for each subject. Subjects were familiarized with the exercise procedure prior to commencement of each test. Subjects were told to not perform exercise on the day prior to a test, and to consume their (usual) last meal at least 3 h before the scheduled test time. For all tests, subjects were verbally encouraged to run "to exhaustion" and were considered exhausted when 1) they could no longer maintain the required running speed, 2) their maximal heart rate (HR) was greater than 85 % of its maximal HR (HR_{max}), and 3) their rate of perceived exertion was greater than 8 on a 1 – 10 scale. Three subjects stopped running without presenting these criteria and were asked to perform the test again the following week. The repeated test scores of these subjects were included in the analysis.

Explosive power of lower limbs tests

After a supervised warm-up, lower limb explosive power was assessed by jumping and sprinting. Jump testing consisted of a vertical countermovement jump (CMJ; cm) on a Bosco jumping mat (Ergojump, Globus Italia, Codogne, Italy) that calculates the jump height. Since this method of assessment can present a methodological bias (notably landing with leg flexion), an experienced investigator validated each trial visually. Sprint abilities were evaluated by a 10-m standing-start run (10 m; s) recorded with photoelectric cells (Wireless Timing-Radio Controlled, Brower Timing System, Matsport, St. Ismier, France). Both tests were performed three times, separated by 45 s of passive recovery. Only the best performance was recorded.

Maximal graded intermittent aerobic test

Subjects performed the 30 – 15 intermittent fitness test ($30–15_{IFT}$), an intermittent and shuttle field test shown to be accurate for individualizing intermittent and shuttle running exercise [14]. The test has been shown to be reliable (intra-class correlation coefficient = 0.96 for the final running speed (V_{IFT}). The $30–15_{IFT}$ consists of 30-s shuttle runs interspersed with 15-s passive recovery periods. For this test, velocity was set at 8 $km \cdot h^{-1}$ for the first 30-s run, and speed was increased by 0.5 $km \cdot h^{-1}$ every 30-s stage thereafter. Subjects were required to run back and forth between two lines set 40 m apart at a pace which was governed by a prerecorded beep. The prerecorded beep allowed the subject to adjust their running speed when they entered a 3-m

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zone placed in the middle and at each extremity of the field. During the 15-s recovery period, subjects walked in the forward direction towards the closest line (at either the middle or end of the running area, depending on where their previous run had stopped); this line is where they would start the next run stage from. Subjects were instructed to complete as many stages as possible, and the test ended when the subject could no longer maintain the required running speed or when they were unable to reach a 3-m zone in time with the audio signal for three consecutive times. The velocity attained during the last completed stage, determined as the subject's V_{IFT}, although slightly higher than MAV, is highly correlated with most physiological variables predictive of performance during intermittent runs (i.e., explosive power of lower limbs and cardiovascular recovery abilities) [14]. Estimated $\dot{V}O_{2max}$ was obtained from the V_{IFT} according to the following formula:

$$\dot{V}O_{2max30-15IFT}\ (ml^{-1}\cdot min\cdot kg^{-1}) = 28.3 - 2.15\ G - 0.741\ A - 0.0357\ W + 0.0586\ A \times V_{IFT} + 1.03\ V_{IFT}$$

where G stands for gender (female = 2; male = 1), A for age, and W for weight [14].

Maximal graded intermittent anaerobic test

"Anaerobic capacity is the maximal amount of ATP resynthesized via anaerobic metabolism (by the whole organism) during a specific type of short-duration maximal exercise [22]". This definition means that a maximal effort is made such that the organism is exhausted at the end of the exercise, and that the exercise is of sufficient duration to evoke the largest anaerobic ATP yield. We thus used the track version of the maximal anaerobic running test (MART) [34], developed by Rusko and colleagues [30], as a way of evaluating the metabolic and neuromuscular components of anaerobic running performance. Since energy supply during each period of running is mainly derived from the lactic and alactic systems [34], we expected that maximal speed reached at the end of the test could be indirectly representative of the subjects' anaerobic capacity [26, 30, 31, 34]. Maxwell and Nimmo [26] have shown that maximal accumulated oxygen deficit (MAOD) is well correlated with the oxygen equivalent of MART, and that [La] measured after the MART and MAOD exercises are similar. It has also been recently been shown that, in sprint runners, the velocity of the seasonal best 400-m run time (accepted as a good index of anaerobic capacity [36]) correlates positively with final velocities in track MART protocols ($r = 0.92$, $p < 0.001$) [30]. Compared with the more commonly used Wingate anaerobic test, the MART is more appropriate for the present study since it is intermittent and can be performed while running on a track. Exhaustion in the MART was determined as the time when the subject could no longer run at the required speed. V_{MART} was determined as the velocity obtained during the last fully completed run prior to exhaustion, and $[La]_{MART}$, the peak blood lactate concentration measured 3 min after the end of the test.

Maximal intermittent tests to exhaustion

All tests were preceded by a supervised and standardized warm-up consisting of 5 min of running at 45% of V_{IFT} along with a few athletic drills and short bursts of progressive accelerations on the track [17]. Tests began two min after this warm-up. For the six intermittent shuttle exercise tests, subjects were asked to continually repeat as many intervals as possible. The tests consisted of 15-s (15/15) runs or 30-s (30/30) runs at 90%, 95% and 100% of V_{IFT} alternating with 15- or 30-s passive recovery periods. During the 15- or 30-s exercise period, athletes were required to run back and forth over the 40 m area so that they covered the distance determined according to their V_{IFT} (marked with cones; see **Fig. 1**). Run interval pace was provided by a digital timer that produced a sound every 15 (or 30) s from the start to the end of the exercise interval. After a 15- (or 30-) s rest, the subject ran again in the opposite direction. Effective exhaustion time (s) was measured for each intermittent exercise interval (not including the recovery period).

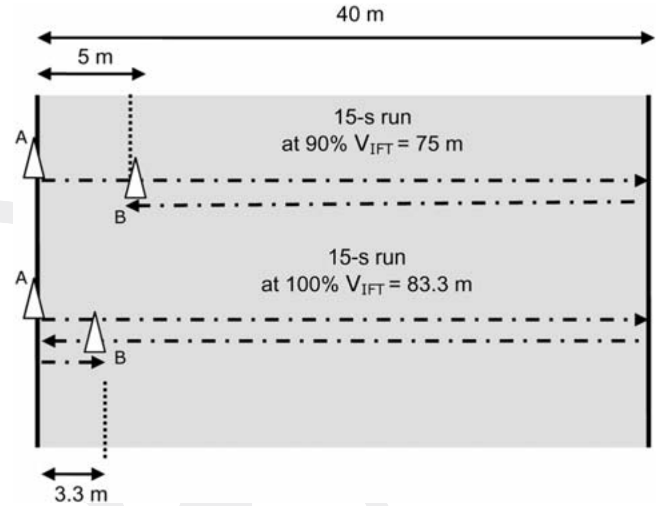

Fig. 1 Example of the organization for maximal shuttle intermittent runs for a subject with a maximal intermittent aerobic speed (V_{IFT}) of $20\ km\cdot h^{-1}$. The subject was required to run between cones (A→B) separated by either 75 m (upper way, 90% of V_{IFT}), 79.2 m (95% of V_{IFT}) or 83.3 m (lower way, 100% of V_{IFT}). After 15 or 30 s of passive recovery, the athlete ran in the opposite direction (B→A) for the next 15 or 30-s work interval.

Critical velocity for short intermittent runs

In accordance with the methods of Ettema [20], iCV was determined for each athlete using the plot of the covered distance (D) versus the exhaustion time (ET), with the iCV defined as the slope of the resulting linear relationship (**Fig. 2**, left panels) for 15/15 ($iCV_{15/15}$) and 30/30 ($iCV_{30/30}$) intermittent exercises. The intercept of the *y*-axis was defined as the anaerobic distance capacity (iACD) for 15/15 ($iADC_{15/15}$) and 30/30 ($iADC_{30/30}$) exercises. The mathematical relationship could be written as follow: D = iCV × ET + iACD.

Endurance index for short intermittent runs

iEI was determined while adapting the methods of Péronnet and Thibault [32] to field conditons. As direct oxygen uptake was not measured in the present study, iEI was fixed from the plot of the percentage of V_{IFT} (and not $\%\dot{V}O_{2peak}$ [32]) versus the logarithm of exhaustion time (Ln[ET]), with the slope of the resulting linear relationship being defined as iEI (**Fig. 2**, right panels) for 15/15 ($iEI_{15/15}$) and 30/30 ($iEI_{30/30}$) intermittent exercises.

Measurements

Heart rate

Following the application of conductive gel, an electrode transmitter belt (T61, Polar Electro, Kempele, Finland) was fitted to

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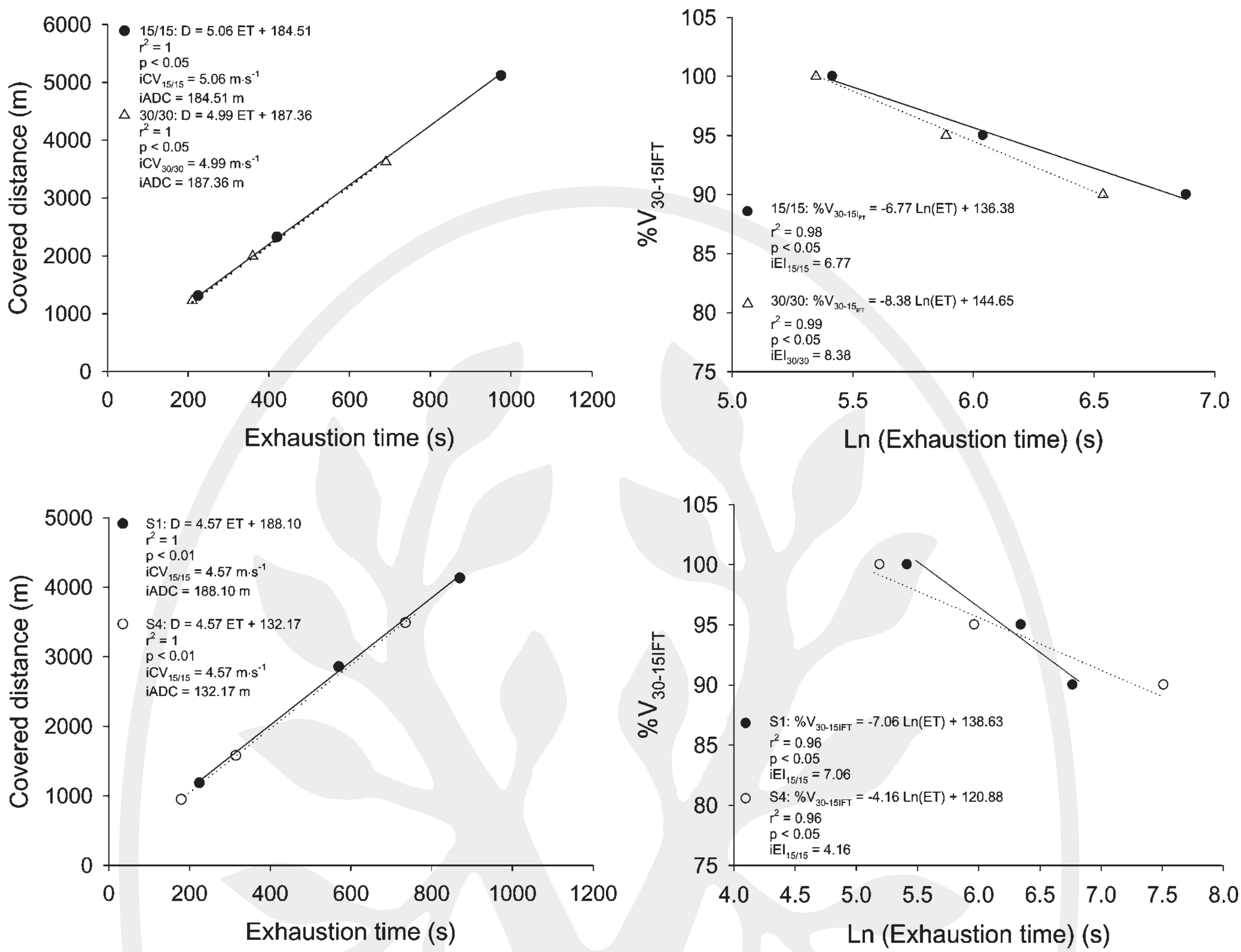

Fig. 2 *Left panels:* example of the determination of critical velocity (iCV) and anaerobic distance capacity (iADC) from total covered distance (D) vs. exhaustion time (ET) for intermittent runs 1) in S10 for 15/15 and 30/30 exercises (upper panel), and 2) in two subjects (S1 and S4) with similar maximal intermittent aerobic speeds (V_{IFT}) for 15/15 intermittent exercise (lower panel). *Right panels:* example of the determination of endurance index (iEI), which was obtained from the percentage of the reference speed used to prescribe intermittent shuttle run velocity (%V_{IFT}) vs. ET expressed logarithmically (Ln[TE]), 1) during 15/15 and 30/30 runs in subject 10 (upper panel), and 2) during 15/15 runs for S1 and S4 (lower panel).

the chest of each subject as prescribed by the manufacturer. During all the exercise tests, HR was recorded at 5-s intervals using an S610 HR monitor (Polar Electro, Kempele, Finland). In case of artifacts, HR was corrected by interpolation from adjacent values. Final HR reached at the end of the 30–15_{IFT} was considered as the maximal HR.

Blood lactate measurement

Three min after the end of each exercise set, a fingertip blood sample (5 µL) was collected and blood lactate concentration $[La]_b$ was determined (Lactate Pro, Arkray Inc., Kyoto, Japan) [35]. The accuracy of the analyzer was checked before each test using standards.

Statistical analyses

Statistical analyses were carried out using Minitab 13.2 Software (Minitab Inc., Paris, France) and data is presented as means and standard deviations (SD). As data were normally distributed, paired *t*-tests were used to compare iCV, iACD and iEI between 15/15 and 30/30 runs. A one-way ANOVA with Tukey's post hoc tests were used to determine differences in exhaustion time, HR and $[La]_b$ between each run. Pearson's correlation coefficients were also determined to assess relationships between variables. Significance was set at $p < 0.05$.

Results

Lower limb explosive power tests

Lower limb explosive power performances were 41.7 ± 5.2 cm and 1.95 ± 0.10 s for the countermovement jump and 10-m sprint time, respectively.

Maximal intermittent graded aerobic test

The mean V_{IFT} was 5.47 ± 0.22 $m \cdot s^{-1}$ (19.7 ± 0.8 $km \cdot h^{-1}$), which corresponded to an estimated $\dot{V}O_{2max}$ of 54.3 ± 2.6 $ml \cdot min^{-1} \cdot kg^{-1}$. Maximal HR and $[La]_b$ at the end of the 30–15_{IFT} were 192 ± 8 $beats \cdot min^{-1}$ and 11.8 ± 2.4 $mmol \cdot l^{-1}$, respectively.

Maximal intermittent graded anaerobic test

The mean V_{MART} was 6.98 ± 0.31 $m \cdot s^{-1}$ (25.1 ± 1.1 $km \cdot h^{-1}$). Maximal $[La]_{MART}$ was 13.0 ± 2.1 $mmol \cdot l^{-1}$.

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Time-to-exhaustion during intermittent running

Exhaustion time at 100, 95 and 90% of V_{IFT} during 15/15 and 30/30 is presented in ▶ **Table 1**. Exhaustion time was significantly higher for the 15/15 runs compared with the 30/30 runs at all exercise intensities ($p < 0.001$). As well, exhaustion time was significantly longer with lower compared with higher intermittent exercise intensities ($p < 0.001$; ▶ **Table 1**).

Heart rate and blood lactate concentration during intermittent exercise

▶ **Table 1** presents mean values of $\%HR_{max}$ and $[La]_b$ measured following each intermittent run sequence. HR was near 90% of HR_{max} for all trials and was not significantly different between the various exercise tests. In contrast, at a similar percentage of V_{IFT}, $[La]_b$ was significantly higher for all 30/30 tests compared with the corresponding 15/15 tests. Compared with 90% V_{IFT}, $[La]_b$ was higher for 100% and 95% V_{IFT}, but 100% V_{IFT} was not significantly different from 95% V_{IFT} ($p = 0.09$ and $p = 0.08$ for 15/15 and 30/30 runs, respectively).

Table 1 Mean (± SD) values of exhaustion times (ET), heart rate (HR) expressed as a percentage of maximal HR and blood lactate concentration ($[La]_b$) for 15/15 or 30/30 maximal intermittent shuttle runs performed at 90, 95 and 100% of the maximal intermittent aerobic speed (V_{IFT}). At equivalent exercise intensities, ET and $[La]_b$ were all significantly different between 15/15 and 30/30 runs

Measures	Exercise	% V_{IFT}		
		100%	95%	90%
ET (s)	15/15	218 ± 40*†	495 ± 124*	1190 ± 431
	30/30	175 ± 42*†	321 ± 71*	739 ± 295
HR ($\%HR_{max}$)	15/15	91.6 ± 2.6	91.6 ± 4.1	89.6 ± 4.2
	30/30	92.7 ± 2.5	94.0 ± 2.7	93.0 ± 3.5
$[La]_b$ (mmol·l^{-1})	15/15	10.3 ± 1.8*	9.5 ± 2.6*	6.1 ± 3.6
	30/30	12.2 ± 3.7*	11.7 ± 2.9*	9.7 ± 4.8

*: significant difference vs. 90%. †: significant difference vs. 95%

Critical velocity for short intermittent runs

Individual iCV values for 15/15 and 30/30 runs are presented in ▶ **Table 2**. As illustrated in ▶ **Fig. 2** (left panels), the relationship between covered distance and exhaustion time for each subject was strong ($r^2 = 1$; $p < 0.01$). ▶ **Table 2** shows that mean iCV was comparable for 15/15 and 30/30 runs (4.76 ± 0.2 m·s^{-1} [87.0 ± 0.1% V_{IFT}] vs. 4.75 ± 0.2 m·s^{-1} [86.8 ± 0.1% V_{IFT}]) and the relationship was strong ($r^2 = 0.89$, $p < 0.001$, ▶ **Fig. 3**). $iCV_{15/15}$ and $iCV_{30/30}$ showed strong relationships with V_{IFT} ($r^2 = 0.97$ and $r^2 = 0.96$, $p < 0.001$ for 15/15 and 30/30 runs, respectively) (▶ **Fig. 4**).

Anaerobic distance capacity for short intermittent runs

iADC was significantly different between 15/15 and 30/30 runs (▶ **Table 2**). No significant relationship was shown between $iADC_{15/15}$ and $iADC_{30/30}$, nor between V_{MART} and $iADC_{15/15}$ ($r^2 = 0.06$, $p = 0.41$) or $iADC_{30/30}$ ($r^2 = 0.07$, $p = 0.37$).

Endurance index for short intermittent runs

Individual iEI values for 15/15 and 30/30 runs are presented in ▶ **Table 2**. The relationship between $\%V_{IFT}$ and Ln(ET) during the three exercise sets was strong for each individual subject ($0.95 < r^2 < 1$; $p < 0.01$), as also demonstrated in ▶ **Fig. 2** (right panels). ▶ **Table 2** shows that mean iEI was significantly lower for 15/15 than for 30/30 runs (6.12 ± 1.21. vs. 7.36 ± 1.41, $p < 0.001$) and were not significantly related ($r^2 = 0.22$, $p = 0.09$, ▶ **Fig. 5**). Finally, there was no significant relationship between both iEIs and V_{IFT} ($r^2 = 0.01$, $p = 0.74$ and 0.02, $p = 0.62$ for 15/15 and 30/30 runs, respectively) (▶ **Fig. 6**).

Relationship between iCV and iEI

For both the 15/15 and 30/30 runs, the iCV and iEI were not significantly related to one another ($r^2 = 0.01$, $p = 0.74$ and $r^2 = 0.01$, $p = 0.65$, respectively).

Table 2 Individual values of maximal reference running velocity (V_{IFT}, msec·s^{-1}), critical velocity (iCV, msec·s^{-1}), anaerobic distance capacity (iADC, m), correlation coefficient (r^2) of linear regression used for the iCV method (distance covered vs. exhaustion time), endurance index (iEI) calculated for intermittent runs and r^2 of linear regression used for the iEI method ($\%V_{IFT}$ vs. Ln[ET]) for 15/15 and 30/30 exercises

		iCV method						iEI method			
		15/15			30/30			15/15		30/30	
	V_{IFT}	$iCV_{15/15}$	$iADC_{15/15}$	r^2	$iCV_{30/30}$	$iADC_{30/30}$	r^2	$iEI_{15/15}$	r^2	$iEI_{30/30}$	r^2
S1	5.28	4.57	188.10	1.00	4.53	114.49	1.00	7.06	0.96	8.03	0.98
S2	5.56	4.89	156.95	1.00	4.86	136.00	1.00	5.18	0.97	6.44	1.00
S3	5.14	4.46	182.68	1.00	4.38	148.37	1.00	6.30	0.99	8.64	0.99
S4	5.28	4.57	132.17	1.00	4.69	116.10	1.00	4.16	0.96	7.01	0.99
S5	5.28	4.58	210.28	1.00	4.53	157.87	1.00	6.90	0.96	7.93	0.98
S6	5.56	4.77	159.52	1.00	4.78	149.59	1.00	7.90	0.99	7.69	1.00
S7	5.56	4.87	199.24	1.00	4.74	138.71	1.00	5.85	0.99	9.07	1.00
S8	5.69	5.01	165.70	1.00	4.97	195.06	1.00	5.26	0.97	8.22	0.97
S9	5.28	4.68	177.81	1.00	4.71	74.48	1.00	4.22	0.99	3.50	1.00
S10	5.83	5.06	184.51	1.00	4.99	187.36	1.00	6.77	0.99	8.38	1.00
S11	5.69	4.86	197.03	1.00	4.97	100.92	1.00	7.28	1.00	6.74	1.00
S12	5.28	4.56	149.89	1.00	4.56	83.70	1.00	7.29	1.00	7.21	0.95
S13	5.69	5.02	167.55	1.00	5.00	155.87	1.00	5.45	0.98	6.81	0.99
Mean	5.47	4.76	174.76	1.00	4.75	135.17	1.00	6.12	0.98	7.36	0.99
(SD)	(0.22)	(0.2)	(22.06)	(0.00)	(0.2)	(36.45)*	(0.00)	(1.21)	(0.01)	(1.41)*	(0.01)

*: significant difference vs. 15/15 exercise

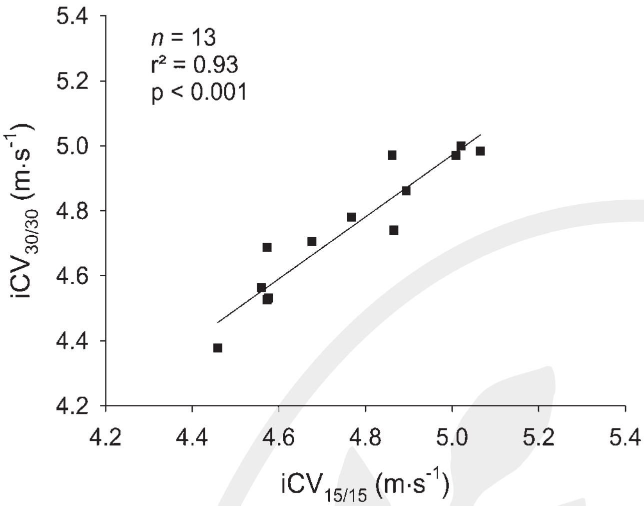
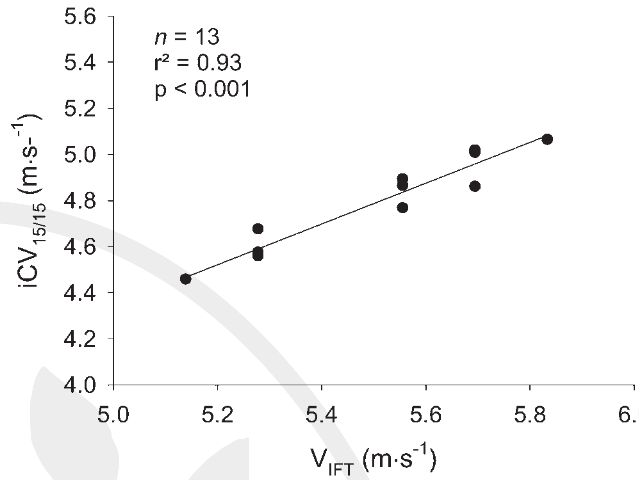


Fig. 3 Relationship between critical velocity (iCV) calculated for 15/15 ($iCV_{15/15}$) and 30/30 ($iCV_{30/30}$) intermittent exercises.



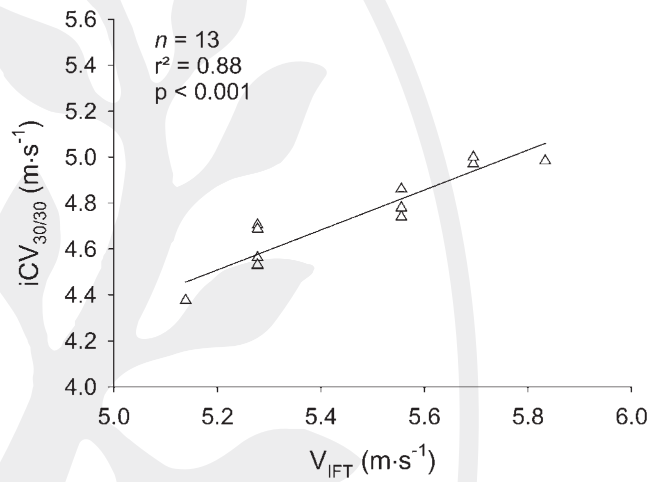


Fig. 4 Relationships between critical velocity (iCV) determined for 15/15 ($iCV_{15/15}$) and 30/30 ($iCV_{30/30}$) exercises and the reference speed used to prescribe the running distance during the maximal intermittent tests (V_{IFT}).

Discussion

To our knowledge, the present study is the first to simultaneously use the critical velocity [28] and endurance index [32] as methods to assess repeated intermittent exercise performance in the field. Our results show that both iCV and iEI can be simply calculated from three sets of intermittent runs performed to exhaustion at different exercise intensities. The fact that iCV was similar for the two different intermittent run combinations (i.e., 15/15 and 30/30) with distinct exhaustion times and that iCV was highly dependent on V_{IFT}, leads one to question the validity of iCV as an index of endurance during repeated runs. Moreover, the *y*-intercept of the distance/duration relationship, which has been considered as an indicator of anaerobic distance capacity [6,17], was not related to V_{MART}, a validated index of anaerobic capacity [26,30,31,34]. On the contrary, iEI appeared to be a more valid method for assessing endurance during intermittent runs, since it reflected differences in exhaustion time over the repeated 15/15 and 30/30 shuttle exercises, even in athletes with similar V_{IFT} scores (**Table 2**).

Intermittent shuttle running performance at high exercise intensities

Intermittent running times to exhaustion in the present study were similar to those shown in others that have used similar exercise intensities (i.e., 100 and 130% of MAV [9,17]). However, due to the reference speed used in the present study (V_{IFT}), running intensities were not exactly identical to those used previously [9,17] and thus precise comparisons remain difficult. Moreover, the present study is also the first to use shuttle runs (including turns), which may be a more specific testing procedure to use with team sport athletes compared with straight runs. The present investigation shows, that even at a similar intensity and with identical work/rest ratios, exhaustion time is significantly longer for 15/15 than for 30/30 runs. This finding is in accordance with the earlier work of Åstrand et al. [2], who showed that the duration of the work period, rather than recovery or total work output, was of primary importance in determining the metabolic response and resultant endurance time for repeated high-intensity exercise. Indeed, the higher lactate concentration shown with the 30/30 tests demonstrates the greater anaerobic energy release needed to complete 30/30 compared with 15/15 work : rest intervals [2,15]. Thus, a larger discrepancy occurs between energy demand and aerobic energy contribution during the 30/30 interval format, leading to a greater accumulated oxygen deficit, a higher transient lactate production, possible muscle function disturbance and a reduced exhaustion time.

Critical velocity model for intermittent running to exhaustion

In continuous running, the relationship between completed distance and time-to-exhaustion has consistently been reported to be linear between three and five exercise bouts ranging from 3 to 35 min [10,13]. For 15/15 intermittent exercise, Dupont et al. [17] and Berthoin et al. [6] also have reported the distance vs. time relationship (obtained from 3 and 4 points, respectively) to be linear ($0.99 < r^2 < 1$). In both of these studies, iCV was very near to the reference speed used for intermittent running (104.1 ± 4.3 [6] and 108.0 ± 6.1 [17] %MAV). In the present investigation, the correlation coefficients of the relationship between covered distance and exhaustion time ($r^2 = 1$) were similar to those re-

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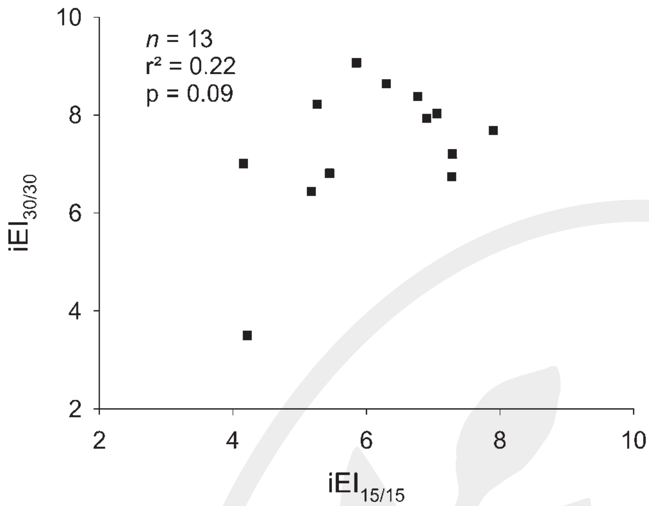

Fig. 5 Relationship between endurance index (iEI) calculated for 15/15 ($iEI_{15/15}$) and 30/30 ($iEI_{30/30}$) exercises.

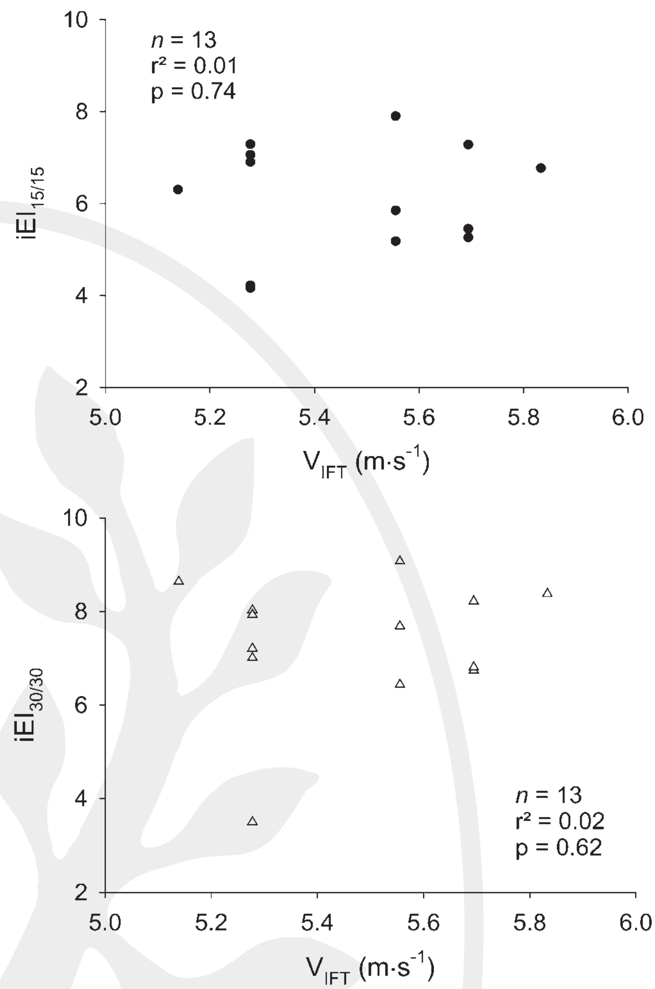

Fig. 6 Relationships between endurance index (iEI) determined for 15/15 ($iEI_{15/15}$) or for 30/30 ($iEI_{30/30}$) exercises and the reference speed used to set running distance during maximal intermittent tests (V_{IFT}).

ported from previous studies on intermittent exercise [6,17] and on continuous swimming, running or cycling exercise [11,16,20, 37]. iCV for both 15/15 and 30/30 running was also highly related to the chosen reference speed (V_{IFT}) ($r^2 = 0.97$ and $r^2 = 0.96$, $p < 0.001$ for $iCV_{15/15}$ and $iCV_{30/30}$, respectively) and corresponded to 87.0 ± 0.1 and 86.8 ± 0.1 of $\%V_{IFT}$; values nearly identical to MAV, which has been reported to be 88% of V_{IFT} [14]. It is also worth noting that even when the exhaustion time at 90% of V_{IFT} was longer than 30 min in some subjects, correlation coefficients of the distance vs. time relationship remained strong. However, the nearly linear relationship shown between iCV and V_{IFT} suggests that the predetermined reference speed largely influences the calculated iCV. This may lead one to question the value of the iCV described in previous studies [6,17].

Is iCV a good index of endurance during repeated high intensity runs?

When CV was applied to the 15/15 and 30/30 runs, a methodological limitation to CV was observed. Although exhaustion time was consistently longer in the 15/15 runs (**Table 1**), we could not detect differences between $iCV_{15/15}$ and $iCV_{30/30}$ (4.76 ± 0.2 vs. 4.75 ± 0.2 $m \cdot s^{-1}$, **Table 2**). As shown in **Fig. 2** (upper left panel), the distance vs. time relationship for both 15/15 and 30/30 runs appear to be superimposed on one another for subject 10. In two subjects with similar V_{IFT} but distinct absolutes exhaustion times, the $iCV_{15/15}$ was similar (**Fig. 2**, lower left panel). **Fig. 3** further illustrates the strong correlation between $iCV_{15/15}$ and $iCV_{30/30}$. Thus, iCV does not appear to be relevant for assessing changes in repeated intermittent exhaustion time.
As highlighted by the strong relationship between iCV and V_{IFT} ($r^2 = 0.97$ and $r^2 = 0.96$, $p < 0.001$ for 15/15 and 30/30 runs, respectively, **Fig. 4**), iCV is highly dependant on the reference speed used and does not represent a valid indicator of endurance during repeated high-intensity runs. When CV is determined with several continuous trials, athletes are asked to perform to the best of their ability on each CV trial by adjusting their speed over a given distance, or by running the longest distance for a given time [10,13]. With this continuous exercise protocol, no reference speed (i.e., MAV) is directly implicated in the distance/time relationship. The moderate relationships between CV and MAV reported in continuous exercise studies [10,13] confirm that endurance capacity is independent of MAV and maximal oxygen uptake [32]. During intermittent runs, the distance vs. time relationship is fixed, and as we have demonstrated, the iCV becomes mathematically dependant on the reference speed used (i.e., MAV [6,17] or V_{IFT} in the present study).

Anaerobic distance capacity

For 15/15 intermittent exercise in adults, Dupont et al. [17] reported *y*-intercepts similar to those shown in the present study (186.9 ± 9 vs. 174.8 ± 22.1 m). Since $iADC_{30/30}$ (135.2 ± 36.5 m) was significantly lower than $iADC_{15/15}$, and $iCV_{15/15}$ was similar to $iCV_{30/30}$, our study is in line with previous results [11,16] which confirmed the original finding of Vandewalle et al. (1987) [36] in that iADC determination is protocol dependant, and that the range of exercise bout durations and exhaustion time used in the calculation influence the iADC more than the iCV [23]. Since the *y*-intercept has been assumed to be an estimation of maximal anaerobic capacity for general exercises [20, 28], we expected that $iADC_{15/15}$ or $iADC_{30/30}$ would be linked to a validated indirect index representative or associated with anaerobic capacity (i.e., V_{MART} [26,30,31,34]). However, no significant correlation was found with either $iADC_{15/15}$ or $iADC_{30/30}$.

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Even if the present results are in agreement with previous studies that have questioned the validity of the *y*-intercept to estimate anaerobic capacity [5,16], they should be interpreted with care, since V_{MART} may not be the ideal way to estimate anaerobic capacity. Even though V_{MART} is well correlated to 400-m performance [30] and MAOD [26], similar comparisons of iADC with directly measured MOAD or all-out constant-load tests to exhaustion may be a more appropriate method [36]. As well, Hill [23] has noted that ADC generally presents low correlations with indirect indicators of anaerobic capacity. Due to the numerous flaws and limitations we have shown with the iCV method, the use of another method, such as the endurance index, may be desired by coaches and Sport Scientists.

Adapting EI to maximal intermittent exercise

To our knowledge, the present study is the first to adapt the endurance index developed by Péronnet and Thibault [32] to intermittent exercise. For application in the field, we replaced $\%\dot{V}O_{2max}$ with $\%V_{IFT}$ from the *y*-axis. Our results show that, as for continuous exercise, the relationship between the decrease in the fractional maintenance of V_{IFT} and exhaustion time expressed logarithmically is linear. Correlation coefficients were strong ($r^2 = 0.99 \pm 0.01$) and similar to those reported in studies using continuous exercise [10,13]. These results suggest, that even if the physiological background underlying maximal intermittent performance is more complex than for continuous exercise [8], the relationship between time and exercise intensity remains linear. The practicality of determining EI is important, as it would appear to be a method capable of detecting differences in exhaustion time.

The iEI – a good index to assess endurance capacity during maximal intermittent exercise

The present results have shown that the iEI was sensitive enough to detect differences in exhaustion time, while iCV was not (**Table 2**). iEI would appear, therefore, to be a better assessor of endurance capacity during intermittent runs. Indeed, the improved endurance shown during the 15/15 runs (inferred by a lower $iEI_{15/15}$ compared to $iEI_{30/30}$) is consistent with the longer exhaustion time observed during 15/15 runs for all intensities (**Table 1**). $iEI_{15/15}$ was often different from $iEI_{30/30}$, as shown for subject 10 (**Fig. 2**, upper right panel). **Fig. 2** also illustrates that subject 4, who had a longer exhaustion time than subject 1 at all exercise intensities, displayed lower $iEI_{15/15}$ (right lower panel), whereas $iCV_{15/15}$ was similar (left lower panel). Furthermore, iEI was not related to V_{IFT} (**Fig. 6**) or estimated $\dot{V}O_{2max}$, and appears, therefore, less protocol dependent. These combined observations confirm that the iEI index, in addition to its ease of assessment, provides accurate assessment of one's endurance capacity during intermittent exercise.

Several factors may influence endurance (and thus IE index) during intermittent exercise. Although oxygen uptake is near maximal for such exercise [8,18,27], anaerobic contribution is also critical [8]. Thus, mechanisms that assist to spare anaerobic capacity, such as myoglobin content [3], muscle capillarity and oxidative capacity [33], muscle substrates repletion kinetics (i.e., reoxygenation of myoglobin and hemoglobin [15] and phosphorylcreatine resynthesis [21]) and cardiorespiratory kinetics [27], may also influence intermittent exercise performance. Finally, the ability to tolerate acidosis through increases in muscle buffering capacity [12] and lactate transport [7] may also be important. Recently, it has been demonstrated [18], notwithstanding the fact that active recovery enhances lactate removal [1], that passive recovery assists with the obtainment of a longer exhaustion time because it capitalizes on increases in myoglobin reoxygenation and phosphorylcreatine resynthesis.

Limitations

It is possible that the method of V_{IFT} determination may have introduced some bias into the protocol and may have slightly influenced exhaustion times. As mentioned, only the speed at the last completed stage was recorded, even if a subject had performed more than half of the next stage. It would have been easy to calculate the exact V_{IFT} while taking into account the precise distance covered during last stage. Nevertheless, we believe that differences of less than $0.5\ km \cdot h^{-1}$ (corresponding to less than 2 m per 15-s runs) would not have significantly influenced exhaustion time. We can also not discount the potential for a training effect to have occurred, as subjects performed two tests per week during a four- to five-week period. However, randomization of the test order and the fact that most athletes substituted the tests into their usual training program should have minimized this potential confounding effect.

In conclusion, the present study has shown that although both the iCV and the iEI could easily be determined from three sets of intermittent runs performed to exhaustion, only the iEI was able to detect corresponding differences in intermittent endurance times. The present results therefore challenge the validity of the critical velocity method to assess endurance during high-intensity intermittent exercise. Moreover, the *y*-intercept of the distance/duration relationship was not shown to provide a reliable estimation of anaerobic capacity. In light of these findings, we suggest that iEI should be used as an index of endurance capacity for short intermittent runs. Further research is required to assess the validity of iEI for assessing longer work-interval durations (> 1 min).

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