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ORIGINAL ARTICLE

Determination of critical power in trained rowers using a three-minute all-out rowing test

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Abstract The purpose of this study was to determine whether the hyperbolic relationship between power output and time to exhaustion (work − time and power − [1/time] models) could be estimated from a modified version of a three-minute all-out rowing test (3-min RT), and to investigate the test–retest reliability of the 3-min RT. Eighteen male rowers volunteered to participate in this study and underwent an incremental exercise test (IRT), three constant-work rate tests to establish the critical power (CP) and the curvature constant (W'), and two 3-min RTs against a fixed resistance to estimate the end-test power (EP) and work-done-above-EP (WEP) on a rowing ergometer. Peak $\left(\dot{V}O_{2peak}\right)$ and maximal $\left(\dot{V}O_{2\,max}\right)$ oxygen uptakes were calculated as the highest 30 s average achieved during the 3-min RT and IRT tests. The results showed that EP and WEP determinations, based on the 3-min RT, have moderate reproducibility ($P = 0.002$). EP (269 ± 39 W) was significantly correlated with CP (work − time, 272 ± 30 W; power − [1/time], 276 ± 32 W) ($P = 0.000$), with no significant differences observed between the EP and CP values ($P = 0.474$). However, WEP did not significantly correlate with W' ($P = 0.254$), and was significantly higher than the W' values. There was a significant correlation between the $\dot{V}O_{2peak}$ (60 ± 3 ml kg^{-1} min^{-1}) and $\dot{V}O_{2\,max}$ (61 ± 4 ml kg^{-1} min^{-1}) ($P = 0.003$). These results indicate that the 3-min RT has moderate reliability, and is able to appropriately estimate the aerobic capacity in rowers, particularly for the CP and $\dot{V}O_{2\,max}$ parameters.

Keywords Exercise intensity · Exercise testing · Aerobic capacity · Indoor rowing

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Introduction

Traditionally, many approaches exist to identify or monitor the endurance capacity, training intensities, and training effects including the percentage of maximal oxygen uptake $\left(\dot{V}O_{2\,max}\right)$ and lactate threshold (LT). The critical power (CP) test, proposed by Monod and Scherrer (1965), uses simple mathematical models to identify a power output that an athlete is able to maintain at a physiological steady-state. One method to establish the CP is that the relationship between power output and time to exhaustion can be described using a hyperbolic function. Linear formulas that describe this relationship are obtainable by plotting total work done during a series of exhaustive exercise bouts, versus time (Monod and Scherrer 1965) or by plotting power output against the inverse of time (Moritani et al.

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1981; Poole et al. 1988). The linear power − [1/time] model is given by:

$$P = W' \times 1/t + \text{CP} \quad (1)$$

where W' is given by the slope of the graph of P versus $1/t$, and CP is represented by the y-intercept (Burnley et al. 2006; Dekerle et al. 2008; Poole et al. 1988; Vanhatalo et al. 2007). CP represents the work rate upper limit that can be maintained at physiologically steady states of pulmonary $\dot{V}O_2$, blood lactate concentration and pH value (Poole et al. 1988); and the W' term (curvature constant) is the maximum amount of work that can be performed above CP and is suggested to be related to the immediate energy stores available to the working muscles (Monod and Scherrer 1965), the O_2 deficit-related accumulation of metabolites, and the $\dot{V}O_2$ slow component and muscle fatigue during exercise at intensity above CP (Murgatroyd et al. 2011).

Compared to the approaches described above $\left(\dot{V}O_{2\,max}, \text{LT}\right)$, the CP test is a non-invasive and inexpensive method to determine the training intensity. However, the traditional CP test requires a participant to exercise to exhaustion under different constant workloads on separate days, and this is not convenient for practical use. Although previous studies (Gastin and Lawson 1994; Medbø et al. 1988) found that while the accumulated oxygen deficit and anaerobic capacity could be predicted from one exhausting bout of exercise, lasting 90 s or 2–3 min, the relationship between exercise intensity and $\dot{V}O_2$ should be established before conducting the supramaximal exercise test. Recently, a single test named the “3-minute all-out cycling test” was developed and was able to accurately determine the CP and $\dot{V}O_{2\,max}$ (Burnley et al. 2006; Dekerle et al. 2008; Vanhatalo et al. 2007) using a cycling ergometer.

According to the concept of CP and Eq. 1, if W' is fully utilized (reduced to zero), the maximum power output would be the CP (Burnley et al. 2006; Coats et al. 2003; Dekerle et al. 2008; Vanhatalo et al. 2007). In other words, if there was a method to completely deplete W', the remaining power output should equal to CP, i.e., if $W' = 0$, then the $P = \text{CP}$. Coats and colleagues (2003) noted that the CP was the greatest power output that could be maintained after fatiguing exercise (i.e., with W' depleted). In the 3-minute all-out cycling test, participants perform an all-out effort to deplete W' after which the power developed is equal to CP; this has been termed the end-test power (EP) by previous researchers (Burnley et al. 2006; Dekerle et al. 2008; Vanhatalo et al. 2007).

Vanhatalo et al. (2007) found that the EP determined by the 3-min all-out cycling test highly correlated with CP as calculated by either the work − time or power − [1/time] models, and that the standard error between the estimation of CP and EP was approximately 6 W ($\sim$2% of the mean EP value). Francis et al. (2010) noted that EP also correlated with the power outputs at LT ($r = 0.79$) and ventilatory threshold ($r = 0.87$) on a cycling ergometer. Therefore, CP could be simply established using a 3-minute all-out cycling test. Shimoda and Kawakami (2005) found that a value for CP, as calculated from traditional CP test methods strongly correlated with 2,000 m indoor rowing performance, and was a useful indicator for monitoring the training effect for rowing athletes. However, there is currently no evidence as to whether or not such a 3-minute all-out test could be successfully applied to rowing exercise.

Barfield et al. (2003) showed that physiological responses, such as oxygen uptake $\left(\dot{V}O_2\right)$, heart rate, and blood lactate concentration, during indoor rowing exercise for recreactionally active adults were similar to those seen during the cycling exercise. Although both activities are considered as non-weight-bearing exercise, the working muscle groups differ. That is, cycling involves the lower body, while rowing involves both upper and lower body. We hypothesized that the 3-minute all-out cycling test could be modified for a rowing ergometer and that the modified 3-minute all-out test could be used to evaluate CP or W' estimates derived from the traditional CP test. Therefore, our purpose for this study, was to determine the test–retest reliability of the 3-minute all-out rowing test (3-min RT), and the differences between the 3-min RT and traditional CP tests. Additionally, we wished to clarify if the 3-min RT would elicit a comparable peak $\dot{V}O_2$ value, to that measured during an incremental rowing exercise test.

Methods

Participants

Eighteen male rowers (age 17.7 ± 1.9 years; height 178.0 ± 4.3 cm; weight 70.7 ± 5.0 kg; 2,000 m time 418.7 ± 11.7 s) volunteered to participate in this study. In attempt to minimise the influence of rowing technique on the results of the study, participants were required to have a minimum 2 years rowing experience. The study was conducted in the off-season period of the athletes’ annual training plan. All participants completed a medical history and health questionnaire, and signed written informed consent forms before participating in the experiment. Prior to testing, parents and guardians of participants under 18 years of age read and signed written informed consent forms and parental/guardian consent forms. Participants refrained from drinking alcohol or caffeine containing beverages for 24 h before the experiments began, and to fast at least 4 h prior to visiting the laboratory, to reduce any interference from food on the experiment.

The Institutional Review Board of the National Taiwan Normal University reviewed and approved the protocol used in this study to protect the human rights of the participants.

Experimental design

The experimental protocol involved eight visits to the laboratory by each participant. Visits were separated by at least 24 h, and all tests were completed within 2 weeks to minimise any influence of fitness variation. All tests were performed on the same rowing ergometer (Concept II, Model E, Morrisville, VT, USA), and the manufacturers software (Concept II Venue Race Application) was used to record rowing data. First, participants performed an incremental rowing exercise test (IRT) for determination of $\dot{V}O_{2\,max}$. During the second visit, participants performed a test to determine maximal power (P_{max}), which was required to determine the target power outputs used for the critical power test. P_{max} was defined as the highest power output measured during three sets of ten maximal strokes on the rowing ergometer (Shimoda and Kawakami 2005). During the following visits, participants performed three predicting trials, to exhaustion under constant workloads, to determine CP and W', following a randomised design. During their sixth visit, participants practiced a 3-min RT familiarization trial, which was unused in the subsequent data analysis. In visits 7 and 8, participants performed two 3-min RT trials with or without oxygen uptake measurement in a crossover design to determine EP and WEP, and to evaluate the test–retest reliability. Prior to each trial, all participants performed a brief warm-up on a rowing ergometer (approx. 5 min, self-selected damper setting and stroke rate).

Incremental rowing exercise test

After warming up, each participant performed the IRT to volitional exhaustion to determine $\dot{V}O_{2\,max}$. Oxygen uptake was analyzed simultaneously by the portable Cortex metabolic analysis system (Metamax 3B; Cortex Biophysik GmgH, Germany). The IRT, modified from a previous study (Beneke et al. 2001), began with an initial workload of 180 W for 3 min, followed by 35-W increments every 3 min until exhaustion. Maximal effort was confirmed by attainment of at least three criteria: (1) a respiratory exchange ratio (RER) >1.2; (2) heart rate >90% of age-predicted maximum; (3) a plateau of $\dot{V}O_2$ defined as no expected increases (<150 ml min^{-1}) in $\dot{V}O_2$ from the previous test stage; or (4) rating of perceived exertion > 17 on Borg's 6–20 scale (Riechman et al. 2002). The greatest $\dot{V}O_2$ value (averaged every 30 s) measured during the IRT was recorded as $\dot{V}O_{2\,max}$.

Critical power test

The CP test, modified from a previous study (Shimoda and Kawakami 2005), included a maximal power test, and three exhaustive trials at three different power levels determined from the maximal power test. In the maximal power test, each participant underwent three sets of ten strokes on the rowing ergometer, with maximal effort. During the maximal power test, the power output of each stroke displayed on the rowing ergometer's monitor was recorded by a video camera for further analysis. P_{max} was recorded as the highest value displayed on the rowing ergometer's monitor during the 30 maximal strokes. The 50, 60, and 70% P_{max} values were used as target powers for the exhaustive trials during CP testing. All participants performed the three different target intensities on separate days, and in randomised order.

In each trial, participants were instructed to maintain their target power output for as long as possible. Each participant was regarded as exhausted and the test terminated, when power output fell by more than 10% below the target intensity for more than 5 s. Strong verbal encouragement was provided throughout the test, and time to exhaustion was recorded to the nearest second. The time to exhaustion was defined as the period commencing when target power output was first attained, and ending when the participant was unable to maintain the required power output (Shimoda and Kawakami 2005). Linear regression was used to provide two sets of CP and W' estimates from the results of these trials, using the work − time ($W = \text{CP} \times t + W'$) and the power − [1/time] ($P = W' \times 1/t + \text{CP}$) models.

Three-minute all-out rowing test

After the brief warm-up, participants' rested for 5 minutes on the rowing ergometer. The 3-min RT, modified from previous studies (Burnley et al. 2006; Vanhatalo et al. 2007), began with 3 min of unloaded baseline rowing at each participant's preferred stroke rate, followed by an all-out 3-min maximal effort. During the 3-min RT, the ergometer was programmed for a 6 min trial at its maximum damper setting (ten on the resistance control dial). A large plastic bag was used to cover the rowing ergometer's flywheel to create an unloaded baseline. Participants were asked to stop in a preparatory position on the rowing ergometer during the final 5 s of the baseline period. The plastic bag was then removed, and participants performed the all-out 3-min effort with strong verbal encouragement. To prevent pacing during the test, participants were not informed of the rowing ergometer's monitor information, or the elapsed time. To ensure an all-out effort, participants were instructed to maintain their stroke rates as high as possible at all times throughout the test.

Power output was recorded for every stroke and transferred via LogCard (Concept II Inc., USA) to a personal computer. The 3-min RT EP value was calculated as the average power output for the final 30 s of the test, and the WEP was calculated as the power − time integral above the EP value (Burnley et al. 2006; Vanhatalo et al. 2007).

The Cortex metabolic analysis system and a Polar heart rate monitor (Polar S810i™; Polar Electro Inc., Oy, Finland) were used continuously to measure oxygen uptake and heart rate, respectively, during the 3-min RT. Peak oxygen uptake $\left(\dot{V}O_{2peak}\right)$ and peak heart rate (HR_{peak}) were calculated as the highest 30-s average achieved during the test. Capillary blood samples (∼5 μL) were obtained by finger puncture at rest prior to the 3-min RT and 5 min following its completion. Blood lactate concentrations were assessed using a Lactate Pro™ chemistry analyzer (KDK Corporation, Japan). The Lactate Pro™ chemistry analyzer, which displayed good reliability and accuracy (Tanner et al. 2010), was calibrated using check and calibration strips provided by the manufacturer, to assure the correct operation and precision of the analyzer 30-min before testing capillary blood samples. In addition, all participants were asked to perform a second 3-min RT at least 48 h after the first 3-min all-out trial, to assess the test–retest reliability of the 3-min RT. For reasons of practicality, and to reduce equipment interference, the oxygen uptake measurement was performed only during one of the two 3-min RT trials.

Statistical analysis

All data are expressed as mean ± standard deviation (SD). The intraclass correlation coefficient (ICC), typical error of measurement, and coefficient of variation (CV) were used to assess the test–retest reliability of the 3-min RT. Student's paired-samples *t* tests and 95% paired-samples confidence intervals of the mean differences were used to compare the responses (EP, WEP, average power, stroke rate etc.) between the two 3-min RT trials. The Pearson product-moment correlation was used to assess the relationships between EP and CP, and between WEP and W'. Bland–Altman analyses were performed to establish limits of agreement between EP and CP estimates, and between $\dot{V}O_{2peak}$ and $\dot{V}O_{2\,max}$ values. The differences between mean values (work − time model, power − [1/time] model, and the 3-min RT) were tested by repeated measures one-way analysis of variance (ANOVA). In the presence of a significant *F* value, post hoc comparisons of means were provided by Bonferroni-adjusted *t* tests. Paired-samples *t* tests were used to compare the physiological parameters ($\dot{V}O_{2peak}$ and $\dot{V}O_{2\,max}$, HR_{peak} and HR_{max}, and blood lactate concentration) between 3-min RT and IRT. The SPSS software package was used for statistical analysis (SPSS for Windows 17.0, SPSS, Inc., Chicago, IL, USA). Statistical significance was denoted by a P value ≤ 0.05.

Results

Test–retest reliability of 3-min RT

There were significant test–retest reliabilities in the EP and WEP values between the two 3-min RT trials (Table 1). Table 1 shows that other parameters also have significantly moderate to high reliabilities (ICC = 0.60–0.98, $P < 0.05$). There were no significant differences on the EP (95% confidence limits −11 to 14 W) or WEP (95% confidence limits −3 to 1 W) between trails. The average coefficient of variation between the two trials in EP was 13.7%; however, the WEP CV value was large (30.1%). Figure 1 shows the results of correlation and Bland–Altman analyses for the comparison of EP between the two trials. The typical error of the EP estimates between the two trials was ± 25 W or 9% of the mean value in trial 2.

Table 1 The test–retest reliability of the 3-min all-out rowing test

	First trial (CV%)	Second trial (CV%)	ICC	95% Confidence limits
EP (W)	217 ± 35 (12.8)	269 ± 39 (14.6)	0.788*	−11 to 14
WEP (kJ)	15.98 ± 5.74 (35.9)	16.63 ± 4.03 (24.2)	0.628*	−3 to 1
Average power (W)	355 ± 44 (12.3)	356 ± 42 (11.7)	0.979*	−6 to 3
Distance (m)	893 ± 38 (4.3)	888 ± 43 (4.8)	0.903*	−4 to 14
Stroke rate (1 min^{-1})	36 ± 3 (6.9)	36 ± 3 (8.0)	0.681*	−1 to 1
HR_{peak} (bpm)	180 ± 9 (4.8)	181 ± 9 (4.7)	0.929*	−3 to 0
Blood lactate (mmol L^{-1})	11.52 ± 2.44 (21.1)	10.70 ± 2.38 (22.2)	0.602*	−0.21 to 1.86

Values are presented as mean ± SD

CV coefficient of variation, *EP* end-test power output, *WEP* work done above end-test power output, HR_{peak} peak heart rates

* $P < 0.05$

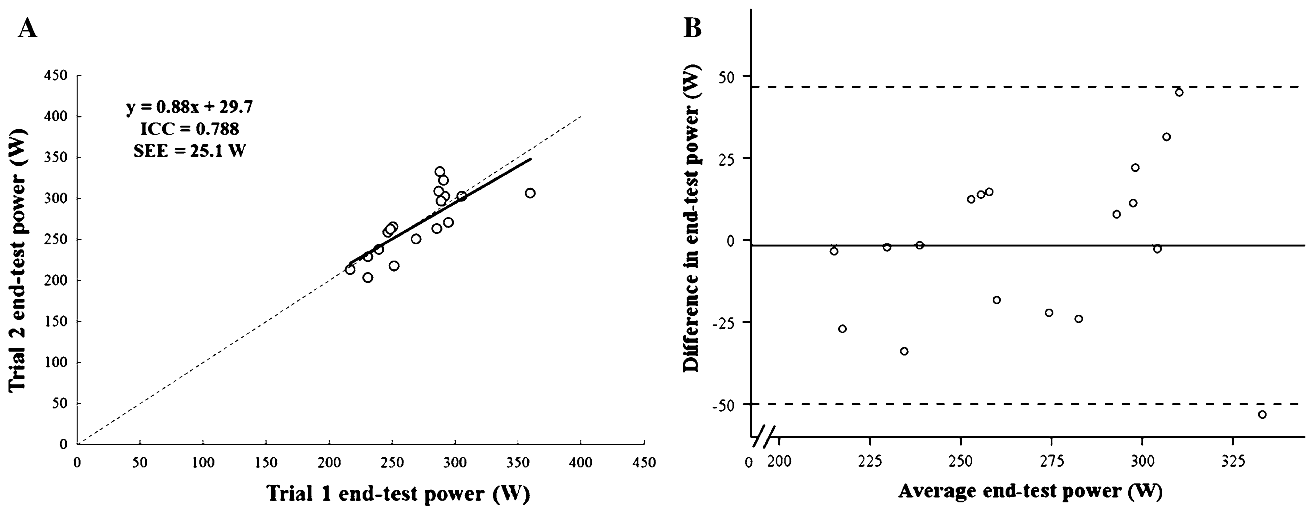

Fig. 1 Bland–Altman plots of the relationship (**a**) and limits of agreement (**b**) for the end-test power between the two 3-min RT trials. In panel **a**, the *solid line* is the best-fit linear regression, and the *dashed line* is the line of identity. In **b**, the *solid line* represents the mean difference between the two trials, and the *dashed line* represents the 95% limits of agreement

Correlation between 3-min RT and CP test

The group mean power output profile during the 3-min RT is shown in Fig. 2a. The group mean power averaged over every 30-s interval are compared in Fig. 2b. All time points differed significantly from the previous 30-s period ($F = 118.84$, $P < 0.05$), with the exception of 120–150 and 150–180 s values, which differed by just 5 W. The power output gradually declined over the first 90 s and reached a plateau during approximately the last 30 s. Figure 3 shows the derivation of CP and W' estimates from the work − time and power − [1/time] models, and the power output profile during a representative participant's 3-min RT. The linear regressions of the work − time ($r^2 \geq 0.99$) and power − [1/time] ($r^2 \geq 0.98$) models correlated well in this study.

EP significantly correlated with the CP values derived from the work − time ($r = 0.745$, $P < 0.05$) and power − [1/time] ($r = 0.801$, $P < 0.05$) models. However, WEP did not significantly correlate with the W' values as calculated from the work − time ($r = 0.295$, $P = 0.234$) and power − [1/time] ($r = 0.254$, $P = 0.308$) models. Table 2 shows that there were no significant differences in CP estimates between the 3-min RT and traditional CP models ($F = 0.762$, $P = 0.474$, $\eta^2 = 0.043$, $1 - \beta = 16.9\%$). It should be noted that the statistical power associated with these comparisons was moderate. Figure 4 shows the relationships and bias ±95% limits of agreement between EP and CP estimates. The standard error between EP and CP estimates derived from the work − time and power − [1/time] models were ±30 W (Fig. 4a) and ± 24 W (Fig. 4c), respectively. The WEP was significantly greater than both W' estimates provided by traditional CP models ($F = 14.264$, $P < 0.05$, $\eta^2 = 0.456$, $1 - \beta = 99.7\%$), and the work − time model W' value was also significantly greater than that of the power − [1/time] model W' (Table 2).

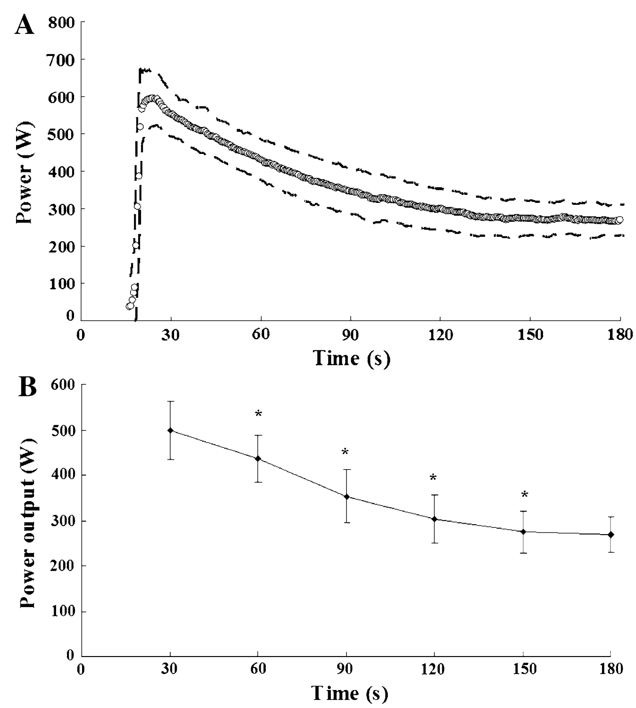

Fig. 2 The group mean power output (**a**) and power output averaged every 30 s (**b**) during the 3-min RT. In **a**, *dashed lines* represent standard deviation. In **b**, *asterisks* indicate a significant difference in power output from the previous period. Note that power output levels off during approximately the last 30 s of the test in **a**, and that end-test power output is not significantly different from the previous power output in **b**

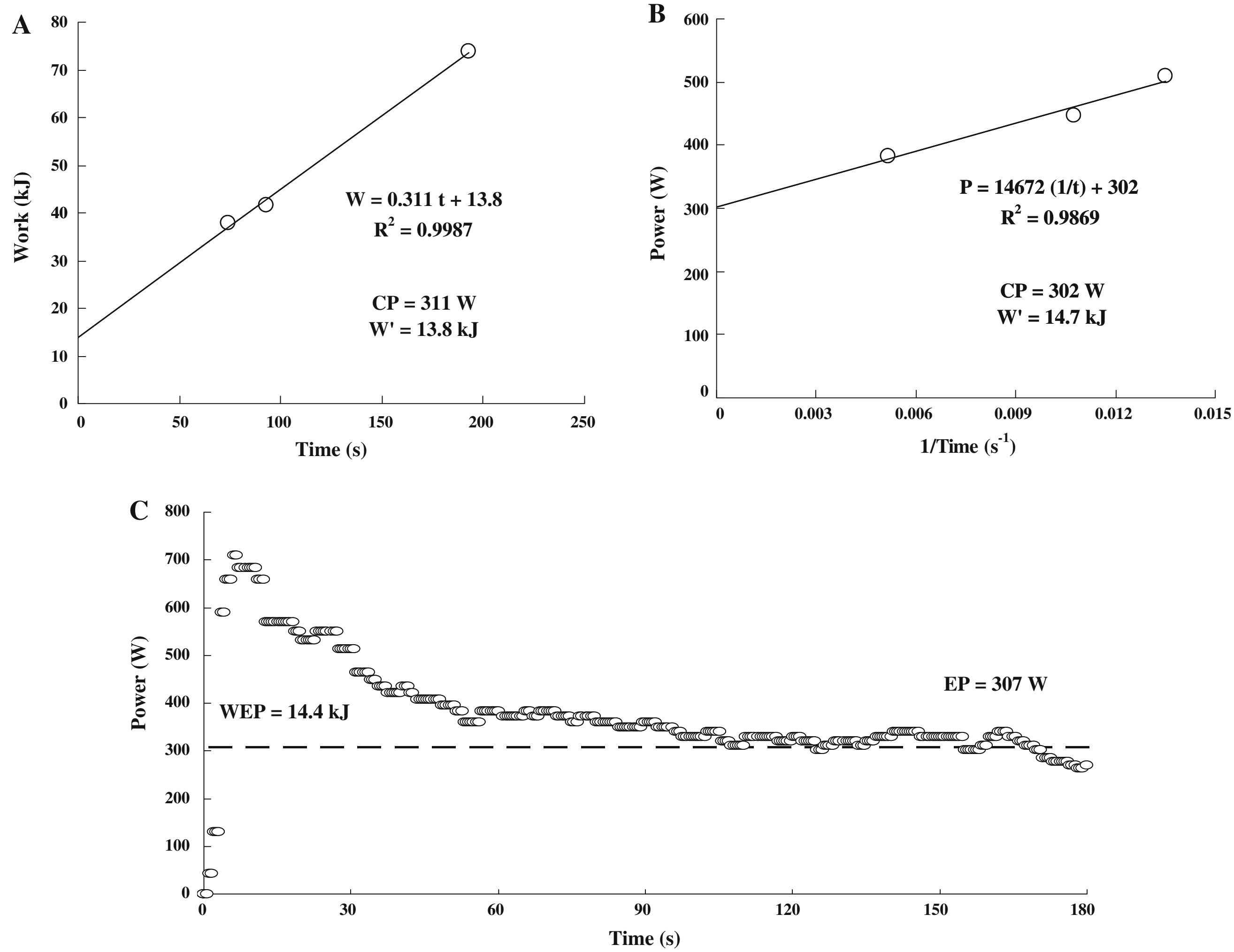

Fig. 3 The derivation of critical power (CP) and curvature constant (W') estimates from the work – time (**a**) and power – [1/time] (**b**) models, and a 3-min RT power profile (**c**) for a representative participant. Note that the CP estimates are similar to the power output at the end of the test (EP) in **c**

Correlation between 3-min RT and IRT

There were significant correlations found between IRT and the 3-min RT measurements of the physiological parameters, $\dot{V}O_{2\,max}$ and $\dot{V}O_{2peak}$ ($r = 0.664$, $P < 0.05$), HR_{max} and HR_{peak} ($r = 0.502$, $P < 0.05$), and blood lactate concentration ($r = 0.625$, $P < 0.05$). Neither the $\dot{V}O_{2peak}$ ($t = 1.645$, $P = 0.118$), nor blood lactate concentrations (3-min RT vs. IRT, 11.52 ± 2.44 vs. 10.70 ± 2.38 mmol L^{-1}, $t = 1.673$, $P = 0.113$) for the 3-min RT were significantly different from their IRT values (Table 2). However, the IRT HR_{max} value (189 ± 9 bpm) was significantly greater (~10 bpm) than HR_{peak} (180 ± 9 bpm) in the 3-min RT was ($t = 4.506$, $P < 0.05$).

Figure 5 shows the $\dot{V}O_2$ response profiles during the 3-min RT and IRT for a representative participant. The $\dot{V}O_2$ rapidly increased to its maximum value during the 3-min RT, and the maximum value was similar to that in IRT. Figure 6 illustrates the relationships and bias ± 95% limits of agreement between $\dot{V}O_{2peak}$ and $\dot{V}O_{2max}$. The typical error between the two tests was ± 2.5 ml kg^{-1} min^{-1} or 4% of the mean $\dot{V}O_{2peak}$ value.

Discussion

The main findings of the present study showed that a 3-min all-out test on a rowing ergometer provided a reproducible power output profile (ICC = 0.79, CV = ~ 14%), and the critical power estimate from this test was similar to that from the traditional CP tests ($r = 0.80$, SEE = ± 24 W). However, the curvature constant (W') estimate calculated from the 3-min RT was slightly higher than those estimated from the traditional CP tests. Additionally, the greatest

Table 2 Comparison of estimated parameters of power-duration relationships and $\dot{V}O_2$ responses between the 3-min all-out rowing test and traditional exercise tests

Participant	Critical power estimates			W' estimates			Highest $\dot{V}O_2$	
	3-min RT EP (W)	Work − time model CP (W)	Power − [1/time] model CP (W)	3-min RT WEP (kJ)	Work − time model W' (kJ)	Power − [1/time] model W' (kJ)	3-min RT $\dot{V}O_{2peak}$ (ml kg^{-1} min^{-1})	IRT $\dot{V}O_{2max}$ (ml kg^{-1} min^{-1})
1	213	272	219	25.34	13.45	11.28	62	58
2	229	266	274	13.88	11.57	10.60	59	59
3	263	283	295	24.58	13.78	12.20	57	66
4	307	311	302	14.37	13.76	14.67	57	60
5	251	222	246	14.94	11.20	9.02	60	60
6	218	255	260	16.86	8.34	7.88	58	60
7	259	276	289	16.55	10.08	8.71	64	64
8	238	220	222	15.01	13.68	13.35	59	58
9	265	267	272	19.29	14.63	14.01	53	52
10	204	234	242	15.40	11.74	10.77	59	59
11	271	253	255	13.97	12.11	11.84	59	62
12	262	249	262	12.61	12.25	10.06	56	55
13	333	312	319	13.71	16.04	15.33	66	65
14	303	286	294	10.20	8.44	7.58	57	58
15	309	275	281	16.46	20.89	19.54	59	60
16	303	316	333	17.06	14.60	12.94	62	67
17	322	311	304	22.74	15.73	16.73	61	68
18	297	290	294	16.43	15.81	15.40	63	63
Mean	269	272	276	16.63	13.23[a]	12.33[a, b]	60	61
SD	39	30	32	4.03	2.99	3.23	3	4

3-min RT 3-min all-out rowing test, *IRT* incremental rowing exercise test, *EP* end-test power output, *CP* critical power, *WEP* work done above end-test power output, W' curvature constant

[a] Significantly different from 3-min RT

[b] Significantly different from the work − time model

$\dot{V}O_2$ response (60 ± 3 ml kg^{-1} min^{-1}) seen for the 3-min RT was approximately similar to the $\dot{V}O_{2max}$ value (61 ± 4 ml kg^{-1} min^{-1}) measured by the conventional incremental exercise test. This was the first study to demonstrate that is possible to determine CP and $\dot{V}O_{2max}$ in rowers using a single bout of all-out rowing exercise.

Burnley et al. (2006) found that for recreationally active males, the 3-min all-out test on the cycling ergometer had good reproducibility. Our results also showed that the 3-min all-out test on the rowing ergometer provides moderate reliability. Turpin et al. (2011) noted that significant differences exist in the force profile and muscle activities during submaximal and maximal rowing, between untrained participants and experienced rowers. Thus, we recruited reasonably experienced rowers into our study to reduce the effects of differences in personal skill levels. Further studies are needed to answer the question of how reproducible 3-min RT results are for the physiological response of sedentary individuals. Additionally, previous studies (Burnley 2009; Burnley et al. 2006; Francis et al. 2010; Vanhatalo et al. 2007, 2008) reported that the coefficients of variation for EP and WEP during a 3-min all-out test were 19–23 and 21–35%, respectively, and these reports are consistent with the results of the present study. Therefore, for experienced rowers, the 3-min RT provides moderate test–retest reliability for assessing EP and WEP.

Vanhatalo et al. (2007) suggested that the end-test power, developed at the end of a 3 min all-out cycling test, could offer an advantageous alternative to the conventional protocol of multiple exhaustive exercise tests to determine CP. Vanhatalo et al. (2007, 2008) reported that the standard error for the estimation of CP using EP was approximately 6–11 W, or 2–5% of the mean EP value. In our study, we also found that the EP significantly correlated with the CP values derived from the work − time or power − [1/time] models. The standard error between EP and CP estimates in the present study was approximately 24 W or 9% of the mean EP value. Although sample sizes used in our study

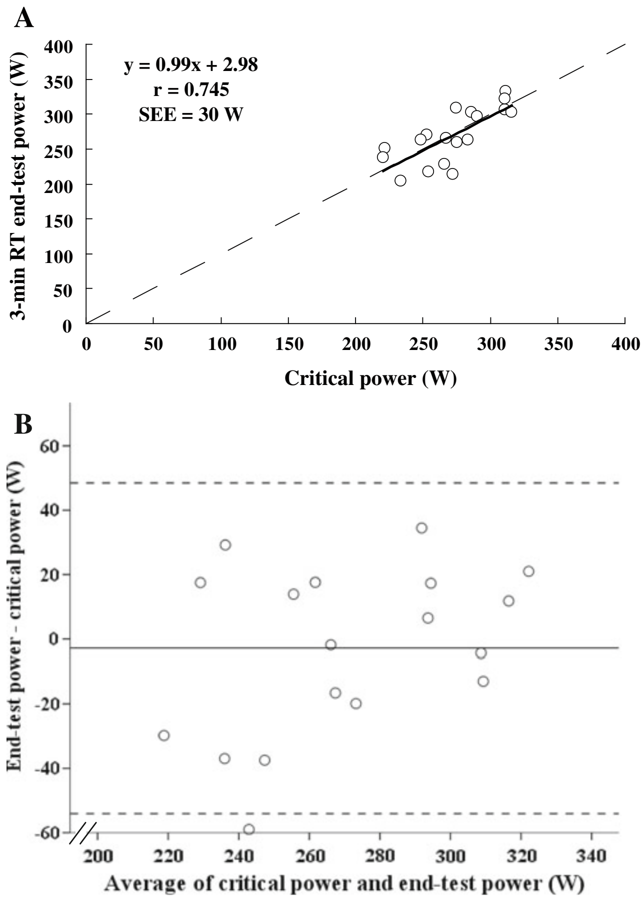

Fig. 4 Correlation and Bland-Altman analyses for differences in end-test power (EP) and critical power (CP) estimates between the 3-min RT and the work − time model (**a**, **b**), and the 3-min RT and the power − [1/time] model (**c**, **d**). In **a** and **c**, the *solid line* is the best-fit linear regression, and the *dashed line* is the line of identity. In panels **b** and **d**, the *solid line* represents the mean difference between the EP and CP estimates, and the *dashed line* represents the 95% limits of agreement

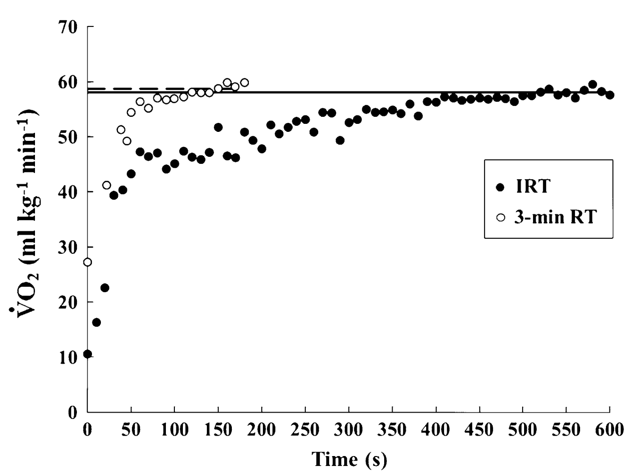

Fig. 5 Comparison of oxygen uptake profile between incremental rowing exercise test (IRT) and 3-min RT for a representative participant. The *solid line* represents maximal oxygen uptake ($\dot{V}O_{2max}$, 58.1 ml kg^{-1} min^{-1}) during IRT; *dashed line* represents the peak oxygen uptake ($\dot{V}O_{2peak}$, 58.7 ml kg^{-1} min^{-1}) during 3-min RT

and other studies (Burnley 2009; Burnley et al. 2006; Vanhatalo et al. 2007, 2008) are insufficient for generalizing to a wider population, these results do provide evidence that CP can, in principle, be obtained and estimated using one bout of an all-out exercise test. Therefore, our results provide further evidence that a single-bout 3-min all-out test can be applied successfully to rowers.

Vanhatalo et al. (2007) noted that the WEP parameter, as calculated from the 3-min all-out cycling test was close to traditional CP model estimates for W'. However, the results in our study failed to confirm any relationships between WEP and W'. The WEP in the present study was slightly higher than the two traditional CP model estimates for W'. Although the power output profile of the 3-min RT during the final 30 s was relatively stable (Fig. 2), in agreement with previous reports (Burnley et al. 2006), there was a gradual decline in power output over the first 90 s. Indeed, Burnley et al. (2006) reported that the power output gradually dropped during the first 60 s. Since the WEP was calculated as the sum of the work done above the

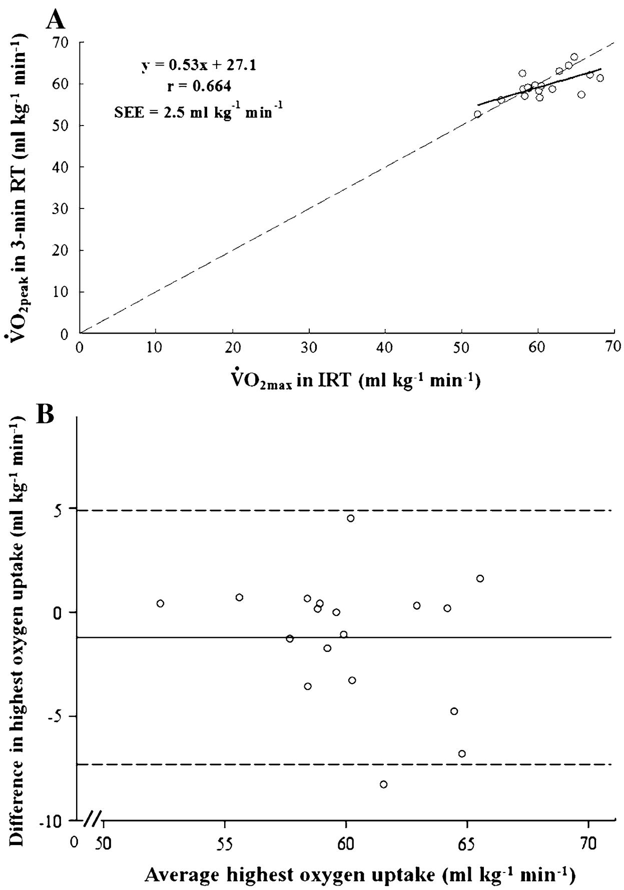

Fig. 6 Bland–Altman plots of the relationship (**a**) and limits of agreement (**b**) for differences between $\dot{V}O_{2peak}$ and $\dot{V}O_{2max}$ measured during the 3-min all-out rowing test (3-min RT) and incremental rowing exercise test (IRT). In **a**, the *solid line* is the best-fit linear regression, and the *dashed line* is the line of identity. In **b**, the *solid line* represents the mean difference between the two measures, and the *dashed line* represents the 95% limits of agreement

EP, the inconsistent results between our study and previous studies could be partly explained by the different power—time curves.

A study by Burnley found that WEP, calculated from 5 min maximal voluntary contractions (3-s contraction, 2-s rest) of the quadriceps, was significantly larger than the value of W' (Burnley 2009). A possible explanation for the discrepancy between WEP in our study, and W' as determined by the traditional models, could be the rowing exercise movement pattern. The rowing cycle is divided into a drive phase (from the frontal to the rear movement reversal) and a recovery phase (from the rear reversal to the next frontal reversal) (Janshen et al. 2009). Turpin et al. (2011) found that most of the recorded 23 muscles involved, including both the upper and lower body muscle groups, were activated during the drive phase and relaxed during the recovery phase. Thus, alternation of the drive and recovery phases may provide a rest interval for the muscles, and delay the power output decline; thereby then producing an apparent increased WEP capacity. Further studies are needed to clarify the effects of rest interval on the WEP.

Previous studies suggest that W' correlates well with indices of anaerobic capacity, such as the 30-s Wingate test, work done in intermittent high-intensity exercise, and oxygen deficit (Hill 1993; Hill and Smith 1993, 1994; Jenkins and Quigley 1991; Murgatroyd et al. 2011). However in our study, neither WEP correlated well with P_{max} ($r = 0.201$, $P = 0.424$), and nor did estimates for W', as derived from the work − time ($r = 0.350$, $P = 0.155$) or power − [1/time] ($r = 0.373$, $P = 0.127$) models. Green and Dawson (1993) suggested that the notion of anaerobic capacity is a theoretical construct, and thus the measurement errors involved in assessing anaerobic work make it difficult to investigate the W' concept (Dekerle et al. 2008). It seems that the W' may not be a simple anaerobic parameter. Burnley (2009) reported that the WEP and W' might not represent the same physiological quantity, because the WEP was higher than W'. Further research is required to determine any relationship between W', WEP, and anaerobic work capacity.

The present study revealed that the $\dot{V}O_{2peak}$ for the 3-min RT significantly correlated with $\dot{V}O_{2\,max}$ for the IRT, and these parameters-values were not significantly different between the 3-min RT and IRT tests. These results are in agreement with the study of Burnley et al. (2006) who found that the peak $\dot{V}O_2$ value was associated with the maximum $\dot{V}O_2$ response during a ramped cycling protocol. Since the eta-squared value ($\eta^2 = 0.137$) between the $\dot{V}O_{2peak}$ and $\dot{V}O_{2\,max}$ is large in our study, it is reasonable to consider that maximum oxygen uptake is obtainable from the 3-min all-out test, at least for rowers. However, in our study, the 3-min RT HR_{peak} was significantly lower than the HR_{max} measured during IRT. It seems that the 3 min period was insufficient to induce maximum heart rate. The lower heart rates seen for the 3-min RT could, in part, be explained by delayed heart rate responses during acute exercise (Brooks et al. 2004). Nevertheless, for the measurement of maximum oxygen uptake, the 3-min RT is a potential alternative to the conventional incremental exercise protocol.

Conclusions

The present study demonstrated that the 3-min RT has moderate test–retest reproducibility, and is able to provide a closely approximate estimate of the aerobic capacity in experienced male rowers, especially for CP and $\dot{V}O_{2\,max}$. Our findings indicate that the 3-min RT can be an appropriate alternative for traditional CP tests, and incremental exercise tests. This simple, noninvasive and inexpensive method is appropriate and recommended for monitoring and evaluating aerobic endurance in rowers. It is also recommended that studies focusing on the relationships between the WEP, W', and anaerobic work capacity should be conducted in the future.

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Conflict of interest The authors declare that they have no conflicts of interest.

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