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Critical velocity: A predictor of 2000-m rowing ergometer performance in NCAA D1 female collegiate rowers

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Abstract

The aims of this study were to examine the use of the critical velocity test as a means of predicting 2000-m rowing ergometer performance in female collegiate rowers, and to study the relationship of selected physiological variables on performance times. Thirty-five female collegiate rowers (mean $\pm$ *s*: age 19.3 $\pm$ 1.3 years; height 1.70 $\pm$ 0.06 m; weight 69.5 $\pm$ 7.2 kg) volunteered to participate in the study. Rowers were divided into two categories based on rowing experience: varsity (more than 1 year collegiate experience) and novice (less than 1 year collegiate experience). All rowers performed two continuous graded maximal oxygen consumption tests (familiarization and baseline) to establish maximal oxygen uptake ($\dot{V}O_{2max}$), peak power output, and power output at ventilatory threshold. Rowers then completed a critical velocity test, consisting of four time-trials at various distances (400 m, 600 m, 800 m, and 1000 m) on two separate days, with 15 min rest between trials. Following the critical velocity test, rowers completed a 2000-m time-trial. Absolute $\dot{V}O_{2max}$ was the strongest predictor of 2000-m performance ($r = 0.923$) in varsity rowers, with significant correlations also observed for peak power output and critical velocity ($r = 0.866$ and $r = 0.856$, respectively). In contrast, critical velocity was the strongest predictor of 2000-m performance in novice rowers ($r = 0.733$), explaining 54% of the variability in performance. These findings suggest the critical velocity test may be more appropriate for evaluating performance in novice rowers.

Keywords: *Aerobic power, maximal oxygen consumption, performance determination*

Introduction

Rowing is a sport that relies on both aerobic and anaerobic energy pathways, with the relative energy contribution during a race being 70% aerobic and 30% anaerobic (Secher, 1993; Shephard, 1998). Demanding both strength and endurance, the competition distance of 2000 m lasts 6–8 min while engaging approximately 70% of a rower's total muscle mass, and generating an average power output of 450–550 W (Steinacker, 1993). Rowers depend mainly on aerobic metabolism for the bulk of the race, maintaining an energy output at a rate greater than 90% of their maximal aerobic capacity for a period of 6 min (Jensen, Freedson, & Hamill, 1996). Maximal aerobic power of a rower has been shown to be the best predictor of performance, with competitive oarsmen recording some of the highest maximal oxygen uptakes ($\dot{V}O_{2max}$) (Secher, 1993). However, it has been suggested that the importance of this predictor decreases as the group of competitors becomes more homogenous (Morgan, Baldini, Martin, & Kohrt, 1989). Consequently, a number of studies have examined other physiological determinants of rowing performance, specifically those factors affecting 2000-m ergometer performance (Bourdin, Messonnier, Hager, & Lacour, 2004; Ingham, Whyte, Jones, & Nevill, 2002). Most of these studies used elite male rowers and reported $\dot{V}O_{2max}$, peak power output, body mass, anaerobic threshold, and power output eliciting a blood lactate concentration of 4 mmol $\cdot$ L^{-1} to be significantly correlated to 2000-m performance. Maximal strength has also been shown to be highly correlated to performance, as rowing is viewed as a power-endurance sport. Boat selection for elite teams is often based on this combination of variables; however, an alternate method may be more appropriate when examining 2000-m performance in collegiate rowers, many of whom have little or no experience when joining the team.

The critical velocity test is based on the linear relationship between total work done and time to exhaustion at that workload (Monod & Scherrer,

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1965), and provides both aerobic (critical velocity) and anaerobic (anaerobic rowing capacity) measures. McDowell and colleagues (McDowell, Kenney, Hughes, Housh, & Johnson, 1988) adapted this model by replacing total work with total distance (using the linear distance–time model) so that the critical velocity test could be applied to sports such as swimming and rowing (Kennedy & Bell, 2000; Wakayoshi et al., 1992). The critical velocity test involves a series of exhaustive work bouts at various distances, for which the total time and distance are determined. The relationship between time and distance can be expressed as TD = ARC + CV * t, where TD equals total distance (time * velocity), ARC = anaerobic rowing capacity, CV = critical velocity, and t equals time to exhaustion. Critical velocity is an estimated velocity (in metres per second) that a person can maintain without inducing fatigue, while anaerobic rowing capacity provides an estimated distance (metres) that a person can cover solely on stored anaerobic energy sources (Bull, Housh, Johnson, & Rana, 2008; Hill & Ferguson, 1999). Critical velocity has been used as a practical method to predict maximal average velocity in a variety of sports, including running and swimming. More recently, critical velocity was shown to be highly correlated to 2000-m rowing performance in male club rowers, and to be strongly correlated with $\dot{V}O_{2max}$ and mean velocity achieved during a 2000-m time trial (Kennedy & Bell, 2000). Based on the linear relationship between total work done and time-to-exhaustion, the critical velocity test can be a predictor of time over a pre-determined distance. Critical velocity has also been shown to be well correlated to maximal lactate steady state and maximal oxygen consumption in swimming (Wakayoshi et al., 1993) and running (Pepper, Housh, & Johnson, 1992).

Limited literature has examined selected physiological variables in female rowers, and to date there has been no critical velocity model applied to female collegiate rowers. The aims of the present study were to assess the critical velocity test as a means of predicting 2000-m performance in female collegiate rowers, and to study the effect of selected physiological variables on performance times in both varsity and novice rowers.

Methods

Participants

Thirty-five NCAA D1 female collegiate rowers (mean $\pm$ s: age 19.3 $\pm$ 1.3 years; height 1.70 $\pm$ 0.06 m; weight 69.5 $\pm$ 7.2 kg) volunteered to participate in the study. Rowers were divided into two categories based on rowing experience: varsity (more than 1 year collegiate experience; age 19.7 $\pm$ 1.4 years; height 1.71 $\pm$ 0.06 m; body mass 70.2 $\pm$ 7.4 kg; $\dot{V}O_{2max}$ 3.14 $\pm$ 0.31 L $\cdot$ min^{-1}) and novice (less than 1 year collegiate experience; age 18.9 $\pm$ 1.1 years; height 1.70 $\pm$ 0.06 m; body mass 68.7 $\pm$ 7.2 kg; $\dot{V}O_{2max}$ 2.88 $\pm$ 0.20 L $\cdot$ min^{-1}). Performance tests were performed on separate days, with outside activity being limited to normal training to minimize training fatigue. All procedures received approval from the University of Oklahoma Institutional Review Board for Human Subjects, and written informed consent was obtained from each participant prior to any testing.

Design and procedure

Determination of $\dot{V}O_{2max}$, ventilatory threshold, and peak power output. All rowers performed two incremental $\dot{V}O_{2max}$ tests to volitional exhaustion on a Concept II Model D rowing ergometer to determine $\dot{V}O_{2max}$, power output at the ventilatory threshold, and peak power output. The first test was used as a familiarization trial to introduce the rowers to the protocol. Forty-eight hours following the familiarization trial, the rowers completed a baseline $\dot{V}O_{2max}$ test.

The test began at an initial workload of 125 W for 2 min, increasing to 150 W for a further 2 min. The workload then increased 25 W every minute until the participant could no longer continue, despite verbal encouragement. The resistance lever on the Concept II rowing machine flywheel was set at "3" for all testing. Respiratory gases were monitored and analysed continuously with open-circuit spirometry and used to calculate $\dot{V}O_{2max}$ and the ventilatory threshold with a metabolic cart (True One 2400® Metabolic Measurement System, Parvo-Medics Inc., Provo, UT). Oxygen and carbon dioxide were analysed through a sampling line after the gases passed through a heated pneumotach and mixing chamber.

The data were averaged over 15-s intervals. The highest 15-s $\dot{V}O_2$ value during the graded exercise test was recorded as $\dot{V}O_{2max}$ if it coincided with at least two of the following criteria: (a) a plateau in heart rate or heart rate values within 10% of the age-predicted maximum heart rate, (b) a plateau in $\dot{V}O_2$ (defined by an increase of no more than 150 mL $\cdot$ min^{-1}), or (c) a respiratory exchange ratio $>$1.15 (American College of Sports Medicine., 2010). A standardized allometric scaling method was used to express $\dot{V}O_{2max}$ relative to body mass. The following equation, based on a study examining allometric scaling and $\dot{V}O_{2max}$ in female athletes (Chia & Aziz, 2008), was used to express allometrically converted $\dot{V}O_{2max}$ values: $\dot{V}O_{2max}/BM^{0.24}$, where BM = body mass. A computer-generated program (True One 2400® Metabolic Measurement System, Parvo-Medics Inc., Provo, UT) was used for the determination of the ventilatory threshold. Regressed lines were fit to the lower and upper portions of the ventilation (V_E) vs. $\dot{V}O_2$ curve before and after the break points, respectively. The intersection of these two lines was defined as the ventilatory theshold, and the corresponding power output as power output at the ventilatory threshold. Test–retest reliability for the ventilatory theshold protocol, previously reported by Amann et al. (2004), resulted in an intraclass correlation coefficient (ICC) of 0.95 (standard error of the mean, s_x: 14.4 W). Peak power output was defined as the highest power output (W) sustained for at least 15 s before the test was terminated. Maximal oxygen uptake ($L \cdot min^{-1}$ and $mL \cdot kg^{-1} \cdot min^{-1}$), power output at the ventilatory threshold, peak power output, time-to-exhaustion, and maximal heart rate were recorded.

Determination of critical velocity and anaerobic rowing capacity. Following a 72-h rest period, each rower completed a critical velocity test for the determination of critical velocity and anaerobic rowing capacity. Each rower performed four "all-out" time-trials at varyious distances over a 2-day period, based on a protocol described by Kennedy and Bell (2000). On the first day, the rowers completed distances of 400 m and 1000 m separated by 15 min of passive rest. Forty-eight hours later, the rowers completed distances of 600 m and 800 m. Trials were preceded by a 1000-m warm-up, followed by 3 min of passive rest. All distances were programmed on the Concept II computer display, allowing the rower to view the cumulative distance, time/500-m, stroke rate, and time. Distance and time were recorded for each participant. A custom-written software program (LabView v8.2) was used to perform linear regression while employing the linear, total distance model, which is expressed as $TD = ARC + CV * t$, where TD equals total distance (time * velocity), ARC = anaerobic rowing capacity, CV = critical velocity, and t equals time to exhaustion. Critical velocity is represented as the slope of the linear regression line, while anaerobic rowing capacity is the y-intercept (Figure 1) (Florence & Weir, 1997).

Rowing performance. Forty-eight hours after the last critical velocity trial, participants completed a 2000-m time trial to assess rowing performance. The test was held during a scheduled practice time in the athletes' training facility. To best simulate race conditions, all rowers completed this test at the same time so that they could compete with each other. Total time, 500-m split times, and average stroke rate were recorded.

Statistical analysis

All values are expressed as means and standard deviations (s) for the group as a whole, as well as varsity and novice rowers separately. Pearson's product–moment correlations were employed to examine the relationship between individual physiological variables and 2000-m performance time for each group (SPSS v.14.0, SPSS Inc., Chicago, IL). All variables that had a statistically significant relationship with 2000-m performance ($P < 0.05$) were entered into a stepwise multiple linear regression to determine the single best predictor of 2000-m time-trial performance. Statistical significance was set at $P \leq 0.05$ for all tests.

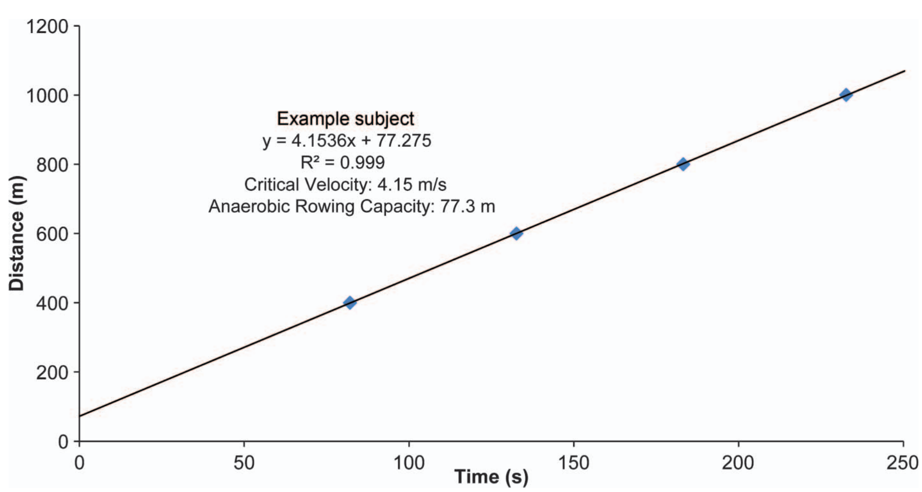

Figure 1. Determination of the distance vs. time relationship using four time-trials. The slope represents critical velocity and the y-intercept signifies anaerobic rowing capacity.

Results

The physiological characteristics of the rowers are presented in Table I. Correlation coefficients for all variables with 2000-m rowing performance are presented in Table II. For the varsity rowers, $\dot{V}O_{2max}$ ($L \cdot min^{-1}$), allometrically scaled $\dot{V}O_{2max}$ ($L \cdot min^{-1} \cdot kg^{-0.24}$), power output at the ventilatory threshold, peak power output, and critical velocity all correlated with 2000-m performance ($P \leq 0.007$). The highest correlation coefficient was obtained for $\dot{V}O_{2max}$, accounting for 84.3% of the variance in performance times. Stepwise regression analysis demonstrated that $\dot{V}O_{2max}$ and peak power output significantly influenced variation in 2000-m performance, explaining 88.9% of the variance in the varsity rowers (Table III). In contrast, all physiological variables for novice rowers, except for allometrically scaled $\dot{V}O_{2max}$, were significantly correlated to 2000-m performance, with critical velocity the main determinant of performance, explaining 50.4% of the variance. The inclusion of the ventilatory threshold and anaerobic rowing capacity improved the prediction of 2000-m performance; the model with all three predictors explained 83.5% of the variance (Table IV).

Discussion

The present study is the first to examine both aerobic and anaerobic indices in collegiate female rowers to determine which variables best predict 2000-m performance. The primary finding of this investigation was that absolute $\dot{V}O_{2max}$ was the strongest predictor of rowing performance in varsity rowers, while critical velocity was the strongest predictor of 2000-m performance in novice rowers.

The current findings demonstrate a strong correlation between absolute $\dot{V}O_{2max}$ and 2000-m ergometer performance in varsity collegiate rowers, which is in agreement with previous researchers who found a strong relationship between $\dot{V}O_{2max}$ and 2000-m time-trial velocity in international male rowers and intercollegiate female rowers (Kramer, Leger, Paterson, & Morrow, 1994; Secher, 1993). During competition, a rower depends mainly on

Table I. Performance characteristics (mean $\pm$ *s*).

	Combined ($n = 35$)	Varsity ($n = 19$)	Novice ($n = 16$)
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	3.02 ± 0.29	3.14 ± 0.31	2.88 ± 0.20
$\dot{V}O_{2max}$ ($L \cdot min^{-1} \cdot kg^{-0.24}$)	1.09 ± 0.09	1.10 ± 0.09	1.08 ± 0.08
P_{VT} (W)	132 ± 12	134 ± 12	130 ± 10
Peak power output (W)	246 ± 29	261 ± 27	228 ± 20
Critical velocity ($m \cdot s^{-1}$)	4.01 ± 0.13	4.06 ± 0.15	3.95 ± 0.08
Anaerobic rowing capacity (m)	64.9 ± 13.6	68.7 ± 13.1	60.3 ± 13.2
2000-m time-trial performance (s)	475.9 ± 17.3	467.6 ± 17.8	485.8 ± 10.3

Note: P_{VT} = power output at the ventilatory threshold.

Table II. Relationships between selected physiological variables and 2000-m performance.

	Varsity ($n = 19$)	Novice ($n = 16$)
$\dot{V}O_{2max}$ ($L \cdot min^{-1}$)	$r = -0.923$*	$r = -0.558$*
	$P < 0.001$	$P = 0.012$
$\dot{V}O_{2max}$ ($L \cdot min^{-1} \cdot kg^{-0.24}$)	$r = -0.790$*	$r = -0.394$
	$P < 0.001$	$P = 0.131$
P_{VT} (W)	$r = -0.549$*	$r = -0.536$*
	$P = 0.007$	$P = 0.016$
Peak power output (W)	$r = -0.866$*	$r = -0.637$*
	$P < 0.001$	$P = 0.004$
Critical velocity ($m \cdot s^{-1}$)	$r = -0.856$*	$r = -0.733$*
	$P < 0.001$	$P = 0.001$
Anaerobic rowing capacity (m)	$r = -0.196$	$r = -0.524$*
	$P = 0.221$	$P = 0.019$

*Significantly correlated to 2000-m performance ($P \leq 0.05$).

Table III. Stepwise multiple regression with 2000-m performance as the criterion variable (varsity).

Step	Variable entered	R^2	*F* change	Sig. *F* change
1	$\dot{V}O_{2max}$	0.843	97.736	$P < 0.001$
2	Peak power output	0.889	8.016	$P = 0.012$

Table IV. Stepwise multiple regression with 2000-m performance as the criterion variable (novice).

Step	Variable entered	R^2	*F* change	Sig. *F* change
1	Critical velocity	0.504	16.222	$P = 0.001$
2	P_{VT}	0.772	17.516	$P = 0.001$
3	Anaerobic rowing capacity	0.835	5.910	$P = 0.032$

Note: P_{VT} = power output at the ventilatory threshold.

aerobic metabolism, as energy stores and glycolysis are limited to the start of the race and the final sprint (Steinacker, 1993). Therefore, a high oxidative capacity is essential to maintain a high speed throughout a race (Steinacker, 1993). Cosgrove and colleagues (Cosgrove, Wilson, Watt, & Grant, 1999) found $\dot{V}O_{2max}$ to be the best single predictor of time-trial velocity in male rowers, explaining 72% of the variance in 2000-m rowing performance. The current study supports the findings of Cosgrove et al., as $\dot{V}O_{2max}$ explained 84% of the variance in performance times for the varsity rowers. Although allometrically scaled $\dot{V}O_{2max}$ was significantly correlated to 2000-m performance ($r = -0.790$, $P \leq 0.001$), the inclusion of the variable in the prediction model did not explain any significant additional variance in 2000-m times, suggesting body weight is not a strong predictor of rowing performance. This finding is similar to those of Bourdin et al. (2004) and Secher (1993), who found body mass had no significant influence on 2000-m performance.

The addition of peak power output in the model helped to explain almost 90% of variance in performance times, suggesting that greater aerobic power and strength strongly correlate to successful rowing performance, measured by 2000-m time-trials. Bourdin et al. (2004) observed similar results, citing a significant relationship between peak power and $\dot{V}O_{2max}$ in elite international male rowers. Other markers of aerobic capacity correlated to performance included power output at the ventilatory theshold and critical velocity ($r = 0.549$ and $r = 0.856$, respectively), although these variables were not significant predictors within the model. In agreement with the previously cited research, aerobic power measured by $\dot{V}O_{2max}$ appears to be the best predictor of performance times in experienced female rowers.

Critical velocity estimates have been used to predict performance in a variety of sports, including running (Pepper et al., 1992), swimming (Wakayoshi et al., 1992), and triathlons (Zaryski, Smith, & Wiley, 1994). Although it is well established that aerobic power is a strong factor in predicting rowing performance in well-trained rowers (Yoshiga & Higuchi, 2003a, 2003b), critical velocity estimates may provide a practical alternative to the traditional $\dot{V}O_{2max}$ tests for coaches when determining cardiorespiratory fitness in novice athletes. Based on the current results and those of Kennedy and Bell (2000), estimation of critical velocity may be an accurate method of predicting 2000-m performance in rowers with less than one year of experience. The results showed critical velocity to be the single best predictor of 2000-m time in novice rowers, accounting for 50.4% of the variance in performance times. In line with this, Kennedy and Bell (2000) demonstrated a strong correlation between critical velocity estimates and 2000-m velocity in male university and club rowers. Shorter distances and the field-based nature of the protocol may limit the psychological effects associated with performing maximal graded exercise tests to exhaustion. In many cases, freshmen rowers are recruited based on overall athletic ability and size, with few athletes having previous rowing experience. Performing shorter tests that do not require uncomfortable headgear required by a $\dot{V}O_{2max}$ or all-out performances at the standard racing distance may be less stressful and better tolerated by athletes new to the sport. Therefore, the critical velocity test provides an opportunity to evaluate novice rowers over shorter distances in an environment that encourages maximal effort. The distances employed during the current study did not exceed 50% of the race distance of 2000 m to reduce the use of pacing strategies and to encourage exhaustive performances by the rowers. The selection of both aerobic (critical velocity and ventilatory threshold) and anaerobic (anaerobic rowing capacity) variables into a stepwise regression model explained close to 84% of the variance in rowing performance, suggesting the anaerobic contribution is greater in novice rowers, perhaps due to a lack of traditional rowing training, which places an emphasis on endurance training to improve aerobic power (Secher, 1993; Steinacker, 1993).

Conclusions

The results of the present study demonstrate that there is no single predictor that can be used to evaluate performance in rowers of varying experience. While varsity rowers showed a strong correlation between rowing performance and $\dot{V}O_{2max}$, critical velocity was the strongest predictor of performance in novice rowers. Despite the overall accuracy of $\dot{V}O_{2max}$ in predicting performance in rowers with at least one year of experience, the critical velocity test may be a more desirable test for coaches and athletes to evaluate performance in rowers new to the sport.

While the current investigation did not evaluate whether these variables related to on-water rowing performance, future research should examine whether on-water performance and boat assignments can be determined from ergometer testing. On-water rowing requires not only speed and power, but technique, balance, and timing that must be developed specifically through on-water training. While testing on an indoor ergometer cannot take such factors into account, such testing may be practical when conducting physiological evaluations in a more controlled environment without weather-related complications and the possibility of uncooperative water conditions, especially when testing novice athletes. Performance testing on a rowing ergometer may also be a more practical tool when monitoring the effects of a training programme during the off-season, or with developmental programmes, with limited access to water.

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