Comparison of Step-Wise and Ramp-Wise Incremental Rowing Exercise Tests and 2000-m Rowing Ergometer Performance

Stephen A. Ingham, Jamie S. Pringle, Sarah L. Hardman, Barry W. Fudge, and Victoria L. Richmond

Purpose: This study examined parameters derived from both an incremental step-wise and a ramp-wise graded rowing exercise test in relation to rowing performance. Methods: Discontinuous step-wise incremental rowing to exhaustion established lactate threshold (LT), maximum oxygen consumption (VO$_{2\text{max,STEP}}$), and power associated with VO$_{2\text{max}}$ (W VO$_{2\text{max}}$). A further continuous ramp-wise test was undertaken to derive ventilatory threshold (VT), maximum oxygen consumption (VO$_{2\text{max,RAMP}}$), and maximum minute power (MMW). Results were compared with maximal 2000-m ergometer time-trial power. Results: The strongest correlation with 2000-m power was observed for MMW ($r = .98$, $P < .001$), followed by W VO$_{2\text{max}}$ ($r = .96; P < .001$). The difference between MMW and W VO$_{2\text{max}}$ compared with the mean of MMW/W VO$_{2\text{max}}$ showed a widening bias with a greater difference coincident with greater power. However, this bias was reduced when expressed as a ratio term and when a baseline VO$_2$ was accounted for. There were no differences ($P = .85$) between measures of VO$_{2\text{max,STEP}}$ and VO$_{2\text{max,RAMP}}$; rather, the measures showed strong association ($r = .97, P < .001$, limits of agreement = –0.43 to 0.33 L/min). The power at LT and VT did not differ ($P = .6$), and a significant association was observed ($r = .73, P = .001$, limits of agreement = –54.3 to 20.2 W, SEE = 26.1). Conclusions: This study indicates that MMW demonstrates a strong association with ergometer rowing performance and thus may have potential as an influential monitoring tool for rowing athletes.

Keywords: maximum minute power, power associated with maximum oxygen uptake, maximum oxygen uptake

Rowing ergometers are widely used to simulate on-water rowing for training and assessment purposes. The determinants of performance for 2000-m ergometer rowing are well described. Such studies have demonstrated the high level of association between variables such as maximum oxygen uptake (VO$_{2\text{max}}$), lactate threshold (LT), critical velocity, power associated with VO$_{2\text{max}}$ (W VO$_{2\text{max}}$), and maximum power with performance. Such analysis derives physiological parameters from discontinuous step-wise progressive exercise tests involving, for example, approximately 5 steps of 4 minutes in duration followed by a 4-minute maximum effort to exhaustion. However, a ramp-wise progressive test of shorter duration and a faster rate of exercise intensity might be more convenient and practical to the athlete and coach who are faced with other priorities of training and competition.

For rowing tests, VO$_{2\text{max}}$ has been shown not to differ when taken from tests of stages of 1, 2, 3, and 4 minutes; however, that from a 5-minute stage duration was found to be lower. Similar studies have observed no differences between VO$_{2\text{max}}$ values derived from 60-second versus 3-minute tests and from 3- versus 5-minute tests for cycle-ergometry exercise. A comparison of lactate and ventilatory measures as surrogate markers of metabolic “threshold” has been attempted with conflicting outcomes. The first inflection in blood lactate concentration above baseline with increasing work rate has been shown to be coincident with the first ventilatory threshold (VT). However, this is not always demonstrated. It has been indicated that the training experience and, perhaps more important, the exercise protocol used will bear a consequence on the derivation of such parameters. A comparison of submaximal lactate and ventilatory parameters from ramp- and step-wise tests has not been undertaken in rowing exercise.

The ramp-wise test offers derived measures such as maximum minute power (MMW), which is used extensively for monitoring in other sports such as cycling. The MMW has been defined as the highest mean power output achieved during any 60-second period during ramp exercise. Several studies have made the same measurement but given it a different term: maximal aerobic power, peak power output, maximal ramp power output.
and, in running, peak treadmill velocity. Balmer et al. showed that MMW was associated with 16.1-km time-trial performance with a correlation coefficient of \( r = .99 \). Furthermore, in running, a range of performances from 5 to 90 km has been shown to be strongly associated with peak treadmill velocity. For rowing exercise, Bourdin et al. explored the performance relationship of a variable similar to MMW, but taken at the end of step-wise incremental exercise and adjusted to account for the workload duration. They found this “peak power” measure to be highly associated with performance \( (r = .92) \) and to differ from 2000-m power by only \( \sim 13 \) W. The association of MMW, derived from a ramp-wise exercise protocol, with rowing performance has yet to be determined.

Therefore, this study aimed to examine the relationships between parameters derived from both an incremental step-wise and a ramp-wise graded rowing exercise test in relation to 2000-m ergometer rowing performance.

**Methods**

After ethics approval was obtained from the local ethics committee, 18 (mean \pm SD; age 23.3 \pm 3.1 y, body mass 71.1 \pm 9.3 kg, height 179.7 \pm 8.9 cm) participants provided informed consent to undertake 2 exercise tests and 1 performance test. The participants had 9.1 \pm 3.2 years experience of regional- or national-standard rowing training and competition from each of the competitive rowing classes (4 lightweight female, 6 lightweight male, 4 open-class female, 4 open-class male).

**Experimental Design**

Participants were familiarized with laboratory exercise-testing procedures before the administration of tests. All rowing-exercise tests were performed on an air-braked rowing ergometer (Concept II C, Nottingham, UK) with a drag factor of 138 to 140. Mean speed and body on designated, well-serviced Concept II C ergometers with a drag factor of 138 to 140. Mean speed and power were recorded.

**Ergometer 2000-m Time-Trial Performance**

All 2000-m ergometer time trials were performed as a criterion assessment for the domestic sport-governing body on designated, well-serviced Concept II C ergometers with a drag factor of 138 to 140. Mean speed and power were recorded.

**Pulmonary Gas Exchange and Lactate Response**

Expired air was monitored continuously during STEP and RAMP tests. Subjects wore a nose clip and breathed through a low-dead-space (90 mL), low-resistance (0.1 kPa · L^{-1} · s^{-1} at 15 L/s) mouthpiece and turbine assembly. Inspiratory and expiratory gas-volume and -concentration signals were sampled via a capillary line at 60 mL/min and analyzed for O2 by a differential paramagnetic analyzer and for CO2 concentration by a side-stream infrared analyzer (Oxycon Pro, Viasys, UK). Gases were calibrated before each test with gases of known concentration. A computer integrated the volume and concentration signals, with account taken of the gas transit delay through the capillary. Respiratory gas-exchange variables (VO2, VCO2, and VE) were calculated and displayed for every breath. The coefficient of variation for VO2 at a standard submaximal exercise intensity in this laboratory was 2.3%, intratest (12 exercise bouts over 8 mo) and 1.4% intertest (8 measures within the same exercise bout). VO2max was determined as the highest value recorded in any 30-second period during STEP and RAMP tests.
Solving the regression equation describing VO₂ and power for sub-LT exercise intensities calculated the W VO₂max. The VT was defined as the VO₂ at which a non-linear increase in carbon dioxide production (VCO₂) and an increase in minute ventilation and V̇e/VO₂ equivalent with no corresponding increase in V̇e/VCO₂ equivalent were evident. Two independent investigators reviewed the plots of each index to establish VT (CV between reviewers = 6.9%). Correction was made for the lag time in VO₂ that occurs during ramp-wise exercise.

Capillary blood samples were collected at the end of each incremental exercise stage for STEP and assayed for blood lactate concentration ([HLa⁻]) using a GM7 Analox analyzer (Analox, London, UK) calibrated with 8- and 2.6-mM solutions. LT was determined by 2 experienced, independent reviewers (CV between reviewers = 5.3%) as the breakpoint in the profile of [HLa⁻] against VO₂ where a marked and sustained increase in [HLa⁻] (>1 mM) was observed from baseline.

**Statistical Analysis**

Data were analyzed to determine if the distributions were normal using the Shapiro-Wilk normality test. Comparative data from STEP and RAMP were compared using 2-tailed independent *t* tests, and limits of agreement, including ratio comparisons, between measurement methods were investigated by plotting the individual differences between methods against their respective means. Data were associated with the criterion performance measure, 2000-m ergometer time-trial power, using Pearson product–moment correlation coefficient and standard error of the estimate. The alpha level was set at 5%.

**Results**

The associations between parameters are shown in Table 1. Tests of normality indicated that data were normally distributed. The strongest correlation with 2000-m power was observed for MMW (Figure 1, *r* = .98, *P* < .001, SEE = 14.6), followed by W VO₂max (Figure 1; *r* = .96, *P* < .001, SEE = 23.1). The difference between W VO₂max and 2000-m power was negatively associated with performance time (*r* = .82, *P* < .001). Thus, a widening bias was observed between MMW-W VO₂max versus the mean of MMW/W VO₂max (Figure 2[A]) on a Bland Altman plot (20 W at mean 235 W, 135 W at mean 422 W). When W VO₂max was expressed in ratio terms as a percentage of MMW versus mean of MMW/W VO₂max, bias was reduced (*r* = −.62, *P* = .006) and further still if the baseline VO₂ was accounted for and the maximum gain in VO₂ was used to calculate W VO₂max (Figure 2[B]; *r* = −.38, *P* = .12).

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**Table 1 Parameters Derived From Step- and Ramp-Wise Tests (Mean ± SD)**

<table>
<thead>
<tr>
<th>Test parameter</th>
<th>Mean ± SD</th>
<th>r (SEE)*a</th>
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<tbody>
<tr>
<td><strong>Step</strong></td>
<td></td>
<td></td>
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<tr>
<td>lactate threshold (W)</td>
<td>202.0 ± 37.3</td>
<td>.91* (32.2)</td>
</tr>
<tr>
<td>power associated with VO₂max (W)</td>
<td>285.0 ± 44.5</td>
<td>.96* (23.1)</td>
</tr>
<tr>
<td>VO₂max (L/min)</td>
<td>4.62 ± 0.82</td>
<td>.90* (33.5)</td>
</tr>
<tr>
<td>maximum blood lactate concentration (mM)</td>
<td>10.1 ± 1.1</td>
<td>.16</td>
</tr>
<tr>
<td>maximum heart rate (beats/min)</td>
<td>187.0 ± 6.8</td>
<td>−.33</td>
</tr>
<tr>
<td>maximum respiratory-exchange ratio</td>
<td>1.19 ± 0.06</td>
<td>.40</td>
</tr>
<tr>
<td><strong>Ramp</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ventilatory threshold (W)</td>
<td>213 ± 43</td>
<td>.68 (57.2)</td>
</tr>
<tr>
<td>maximum minute power (W)</td>
<td>352.0 ± 68.2**</td>
<td>.98* (14.6)</td>
</tr>
<tr>
<td>VO₂max (L/min)</td>
<td>4.67 ± 0.85</td>
<td>.88* (36.6)</td>
</tr>
<tr>
<td>maximum blood lactate concentration (mM)</td>
<td>8.1 ± 1.3**</td>
<td>.52</td>
</tr>
<tr>
<td>maximum heart rate (beats/min)</td>
<td>186.0 ± 1.3</td>
<td>−.01</td>
</tr>
<tr>
<td>maximum respiratory-exchange ratio</td>
<td>1.19 ± 0.06</td>
<td>.46</td>
</tr>
<tr>
<td><strong>Performance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>speed (m/s)</td>
<td>4.96 ± 0.36</td>
<td></td>
</tr>
<tr>
<td>power (W)</td>
<td>346.5 ± 75.5</td>
<td></td>
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</tbody>
</table>

*Abbreviations: VO₂max indicates maximum oxygen consumption.

*Correlation coefficients are shown for association between test parameter vs 2000-m performance power (SEE shown for correlations showing *P* < .001).

*P* < .05, **P* < .01.
Figure 1 — The association between maximum minute power (closed circles, $y = 0.887x + 44.42, r = .98, P < .001, SE = 14.6)$, power associated with maximum oxygen consumption (VO$_{2\text{max}}$, open squares, $y = 117.0x - 295.0, r = .96, P < .001, SE = 23.1$), and 2000-m rowing-ergometer time-trial performance power. Dashed line is the line of identity.

Figure 2 — (A) Maximum minute power (MMW) minus power associated with maximum oxygen consumption (W VO$_{2\text{max}}$) vs the mean of MMW and power associated with VO$_{2\text{max}}, r = .82, P < .001$. (B) Power associated with VO$_{2\text{max}}$ (recalculated using the gain of VO$_2$ above baseline) as a percentage of MMW vs the mean of MMW associated with VO$_{2\text{max}}$ (recalculated as above), $r = -.38, P = .12$.

There were no significant differences ($P = .85$) between measures of VO$_{2\text{max}}$STEP and VO$_{2\text{max}}$RAMP; rather, the measures showed strong association (Figure 3[A], $r = .97, P < .001$; Figure 3[B], limits of agreement $= -0.43$ to $0.33$ L/min, SEE $= 0.19$). The power at LT and VT did not differ ($P = .6$), and a significant association was observed ($r = .73, P = .001$, limits of agreement $= -54.3$ to $+20.2$ W, SEE $= 26.1$). Maximum respiratory-exchange ratio and heart rate showed moderate associations between STEP and RAMP ($r = .65$ and $.55$, respectively) and poor association for [HLa–] ($r = .27$).

**Discussion**

Previously, W VO$_{2\text{max}}$ has been shown to be one of the strongest correlates of 2000-m ergometer rowing performance.$^3$ This study concurs with this strength of relation ($r = .96$); MMW, a previously uninvestigated parameter, demonstrates a similarly strong association of $r = .98$.

This study supports MMW as a valid and useful parameter in understanding and monitoring rowing performance. Bourdin et al$^{25}$ explored a similar variable (termed peak power) in rowing derived from the final
stages of a step-wise exercise test. In that instance the high associations with performance power were similar to the results \((r = .92)\) found in the current study. Complementarily, Bourdin et al\(^2\) reported a difference between peak power and 2000-m performance power of ~13 W, and in the current study MMW and 2000-m power differed by ~6 W. In other modes of exercise, Balmer et al\(^2\) found that the MMW parameter (termed peak power output) was both highly reproducible (coefficient of variation = 1.3\%) and strongly associated with 16.1-km (~22 min) cycling time-trial power \((r = .99)\) for male endurance cyclists. Similarly, Hawley and Noakes\(^2\) examined the relationship between MMW and 20-km cycling time-trial performance in 100 trained cyclists, showing a strong association with performance of \(r = .97\). Such a relationship has also been observed in running, where the parameter was termed peak treadmill velocity\(^2\) in marathon runners, where the association with 42.2- and 90-km running performance was of a similarly strong level at \(r = .91\) to .97. Further anecdotal support comes in the form of extensive use of the measure as a deterministic and influential parameter for tracking training and for selection purposes by the British Cycling team, who in the last 10 years have administered over 1000 ramp-wise tests to determine MMW (E. Taylor, British Cycling physiologist, personal communication).

The association observed for the difference between W V\(_{O2max}\) and 2000-m power versus performance time might indicate that for athletes for whom 2000 m takes longer (420–460 s), W V\(_{O2max}\) is more closely aligned to 2000-m performance power, and less so for those that complete the race in a shorter time (375–385 s). By inference, the Bland-Altman plot of MMW minus W V\(_{O2max}\) versus the mean of MMW/W V\(_{O2max}\) shows a bias, with an increase as mean MMW/W V\(_{O2max}\) power increases. However, when W V\(_{O2max}\) was expressed as a percentage of MMW and plotted against the mean MMW/W V\(_{O2max}\), bias was reduced, and further still when the baseline V\(_{O2}\) was accounted for and the maximum gain in V\(_{O2}\) was used to calculate W V\(_{O2max}\). Thus, we suggest that it is necessary to express differences in relative terms when handling such a broad range of physiological capabilities and, thus, a spread of data as encountered with a weight-category sport of rowing. In turn, the absolute V\(_{O2}\) will vary through the range of abilities, and thus gain above baseline might be a more representative slope to relate against exercise intensity to calculate W V\(_{O2max}\).

V\(_{O2max}\) from both the STEP (4-min all-out) and the RAMP showed a strong association \((r = .97)\). This finding is in agreement with the study by Pierce et al\(^8\) that investigated tests of different stage duration in rowing. Comparisons of similar tests have shown the V\(_{O2max}\) to not differ with a stage duration of 1 to 4 minutes, but it did differ for stages of 5 minutes.\(^8\),\(^9\) Similarly several studies have shown a strong relationship between MMW and V\(_{O2max}\), with relationships from \(r = .86\)\(^19\) to \(r = .97\).\(^2\)\(^9\) In the current study the association was of a similar strength \((V_{O2maxSTEP} vs MMW r = .89; V_{O2maxRAMP} vs MMW r = .86)\).

The power at LT showed a similar association \((r = .9\) with performance as previously reported (Ingham et al\(^3\)). Compared with other measures described herein, VT showed only a moderate association with performance \((r = .68)\). LT and VT did not differ from each other \((P = .6\) and, furthermore, a strong association was observed \((r = .73)\) between the 2 measures. However, the limits of agreement indicated that interchangeability between the power associated with LT and VT is limited \((-54.3\ to 20.2 W)\). This finding adds to the conflicting observations from several studies examining ventilatory and metabolic...
“thresholds.” There are several studies that support the notion of agreement \(^{11,12,30}\) and several that indicate that agreement is not observed. \(^{13-15}\) The large variability in exercise protocols, use of visual inspection, and threshold-determination methods across studies will confound the comparison of responsive physiological profiles. \(^{16}\)

**Practical Applications**

Previous investigations into rowing performance have largely used step-wise incremental tests, from which several parameters have been shown to associate well with 2000-m ergometer rowing performance. This study is the first to examine how the parameters derived from a ramp exercise test relate to the step-wise test and 2000-m performance. The findings show that not only does the primary measure of VO\(_{2max}\) not differ from a step protocol, but also the ramp-test measure of MMW is as strongly associated with 2000-m performance as VO\(_{2max}\) given the stronger correlation coefficient and its close association with 2000-m performance power. Care should be taken when interpreting these results, where associations are facilitated by a large range of physiological capabilities.

Furthermore, the ramp test offers a viable alternative exercise test to monitor physiological status in rowers for whom training demands are already high. Further work should consider the validation of training prescription from rowing-ergometer ramp-test-derived parameters.

**References**


