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Measures of Rowing Performance

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Abstract

Accurate measures of performance are important for assessing competitive athletes in practical and research settings. We present here a review of rowing performance measures, focusing on the errors in these measures and the implications for testing rowers. The yardstick for assessing error in a performance measure is the random variation (typical or standard error of measurement) in an elite athlete's competitive performance from race to race: ~1.0% for time in 2000 m rowing events. There has been little research interest in on-water time trials for assessing rowing performance, owing to logistic difficulties and environmental perturbations in performance time with such tests. Mobile ergometry via instrumented oars or rowlocks should reduce these problems, but the associated errors have not yet been reported. Measurement of boat speed to monitor on-water training performance is common; one device based on global positioning system (GPS) technology contributes negligible extra random error (0.2%) in speed measured over 2000 m, but extra error is substantial (1–10%) with other GPS devices or with an impeller, especially over shorter distances. The problems with on-water testing have led to widespread use of the Concept II rowing ergometer. The standard error of the estimate of on-water 2000 m time predicted by 2000 m ergometer performance was 2.6% and 7.2% in two studies, reflecting different effects of skill, body mass and environment in on-water versus ergometer performance. However, well trained rowers have a typical error in performance time of only ~0.5% between repeated 2000 m time trials on this ergometer, so such trials are suitable for tracking changes in physiological performance and factors affecting it. Many researchers have used the 2000 m ergometer performance time as a criterion to identify other predictors of rowing performance. Standard errors of the estimate vary widely between studies even for the same predictor, but the lowest errors (~1–2%) have been observed for peak power output in an incremental test, some measures of lactate threshold and measures of 30-second all-out power. Some of these measures also have typical error between repeated tests suitably low for tracking changes. Combining measures via multiple linear regression needs further investigation. In summary, measurement of boat speed, especially with a good GPS device, has adequate precision for monitoring training performance, but adjustment for environmental effects needs to be investigated. Time trials on the Concept II ergometer provide accurate estimates of a rower's physiological ability to output power, and some submaximal and brief maximal ergometer performance measures can be used frequently to monitor changes in this ability. On-water performance measured via instrumented skiffs that determine individual power output may eventually surpass measures derived from the Concept II.

1. Introduction

Rowing competitions usually involve races lasting 6–8 minutes over a 2000 m regatta course. Rowing demands a high level of endurance,[1] estimates of the aerobic contribution being 70–87%.[2-4] Successful rowers tend to be tall and lean.[4-6]

There are up to 22 boat classes in international rowing regattas, consisting of heavyweight or lightweight rowers, male or female rowers, singles or crewed boats, coxed or coxless boats and sweep or sculling oars. In sculling, each rower has two oars, and boat types involve one rower (single), two rowers (double) or four rowers (quad). In sweeping, each rower has one oar and boat types include two rowers without a coxswain (coxless pair), two rowers with a coxswain (coxed pair), four rowers without coxswain (four) and eight rowers with a coxswain (eight).

Measuring changes in performance is important for monitoring the progress of rowers during training and for research assessing the effect of training and other interventions. In the only review[7] of the tools and tests available for monitoring rowing performance, the authors focused on monitoring for overtraining, with only a cursory examination of the accuracy of the various measures of rowing performance. In this review we describe these measures, their errors and the practical implications.

We used Google Scholar, SPORTDiscus™ and reference lists in reviews and research articles to search for investigations on measures of rowing performance published since 1970. To examine whether we had missed any relevant material, we undertook follow-up searches in Google Scholar and SPORTDiscus™ where we combined the term 'row' with the specific measure/s of interest 'GPS', 'Concept II', 'time-trial', 'lactate tests', etc.

The yardstick for evaluating a measure of athletic performance is the variability that top athletes show from one race or competition to the next. This variability, which is expressed as a within-subject standard deviation, is analogous to the standard error of measurement (or typical error of measurement) in a reliability study of a performance test, with the repeated trials replaced by races. The race-to-race variability in finish times for elite rowers in world cups, world championships and Olympic competitions is ~1%.[8] These races are maximal efforts for highly motivated and well conditioned rowers, so the ~1% race-to-race variability is, at first glance, an irreducible error for any measure of rowing performance. However, variability arising from environmental and other factors probably adds to the rower's inherent physiological variability in performance from race to race,[8] so measures of performance derived from a rowing ergometer can and do have standard error of measurement less than 1% in reliability studies.

A useful measure of rowing performance must have acceptable validity, as well as reliability.

Validity of a measure is determined by comparing its values with those of a criterion measure, which in rowing is competitive performance time over 2000 m. The single best validity statistic is the standard error of the estimate (or typical error of the estimate), which is a standard deviation representing the error in an individual's criterion value predicted by the test or other measure. The standard error of the estimate and the other regression validity statistics (the correlation coefficient and the regression or calibration equation) are specific to the population represented by the sample from which they are derived, and the standard error of the estimate is misleadingly smaller in samples with a narrower between-subject standard deviation. Indeed, with a homogeneous sample, the standard error of the estimate is simply the noise (standard error of measurement) in the criterion. For this reason, we have used a method[8] to adjust the standard error of the estimate from each study to a population with the widest possible range of values (infinite standard deviation). See Appendix 1 for the formulae. The standard error of the estimate is then an unbiased estimate of the error in the criterion value arising from error in the test measure and, as such, can be compared between studies for the purpose of choosing measures with the smallest errors. The adjusted standard error of the estimate of a test measure is inevitably larger than the standard error of measurement of the criterion, because the standard error of the estimate includes contributions from the standard error of measurement of the criterion, the standard error of measurement of the test measure and differences between subjects that are not accounted for by the test measure.

The smallest worthwhile change in performance is another important consideration in the assessment of measures of performance. When the standard error of measurement of a performance measure is similar in magnitude to the smallest worthwhile change, the measure is sufficiently sensitive to quantify small but meaningful changes, either when monitoring individual athletes or when performing controlled trials with realistic sample sizes.[8] The smallest worthwhile enhancement of an elite athlete's performance has been defined as the change in performance time or other score that results, on average, in one extra medal in every ten competitions.[9] Simulations showed that this enhancement is a factor of 0.3 of the standard deviation of within-athlete race-to-race variability in performance, which for rowing is therefore a 0.3% change in race time ($0.3\% \times 1.0\%$). Thresholds for quantifying magnitudes based on winning three, five, seven and nine extra medals per ten races are 0.9% (moderate), 1.6% (large), 2.5% (very large) and 4.0% (extremely large).[10] To interpret the magnitude of an error (standard error of measurement or standard error of the estimate) on this scale of magnitudes, the error should be doubled.[8] A good measure of rowing performance would therefore need a standard error of measurement of less than 0.3% if one wanted to be confident about trivial changes in performance. We will see that no rowing tests reach this level of precision.

2. Measures of On-Water Rowing Performance

Although the 2000 m on-water time is the criterion measure of rowing performance, this measure has a number of limitations. Environmental conditions are the most important limitation, which contributes substantial variability to the competitive performance of elite rowers.[8] Even for a group of rowers competing together in a single race, and therefore under seemingly identical environmental conditions, rowers could be affected differently; for example, a headwind could hinder some rowers more than others, and a side wind could unfairly benefit rowers in lanes in which there is a wind shadow. Furthermore, without special instrumentation in the boat, it is not possible to quantify an individual rower's performance from the speed of a boat with two, four or eight rowers. Rowers from a crewed boat could be tested individually in single sculls, but the faster movement speeds in a crew boat could easily create a difference in technique. There are also biomechanical differences between single sculling and sweeping.[11,12] Instrumenting the boat (see below) may solve the problems of assessing the on-water performance of individual rowers in single or crewed boats. Many coaches will not permit regular maximal 2000 m on-water tests during the earlier stages of the season, owing to concerns about impairing aerobic development, but performance would be available from the competitions over 2000 m that occur regularly during the ~4-month competitive season (Smith TB, personal observations).

Despite problems with the 2000 m on-water performance tests, maximal boat speed over distances other than 2000 m is a commonly used measure in rowing.[13] The distances range from 250 m to 15 km, depending on the energy system(s) being trained in a given phase of the season (Smith TB, personal observations). A common practice in this context is the use of 'prognostic speeds', which are either world record or some other target speed for each boat class.[13,14] The performance of each boat is evaluated as a percentage of its prognostic speed to provide a ranking within a boat class and a comparison for boats from different boat classes. Environmental conditions can still affect the accuracy of the ranking, because the environment has a greater effect on boats with fewer rowers and boats with female crews.[8] The boats are often handicapped for these tests in an effort to improve the sense of competition. While handicapping does reduce environmental effects, provided that conditions do not change substantially between boats, the turbulence (boat wash) can disadvantage the trailing boats.

The development of various rowing speedometers has increased the popularity of the measurement of boat speed during training and competition.[15] These devices are more convenient than stop-watches, which require timing at each end of the course and accurate measurement of the distance. The two common speedometers are based either on an impeller or the global positioning system (GPS). The impeller measures speed relative to water (true speed), while GPS measures speed relative to land.

2.1 Impeller Measurement of Boat Speed

The two popular devices that measure rowing boat speed via impellers attached to the hull are the Nielsen Kellerman Speed Coach (Nielsen Kellerman, Boothwyn, PA, USA) and the Coxmate (Coxmate, St Peters, SA, Australia). The impeller has two advantages over the GPS. One advantage is that it can give accurate readings over any distance, whereas GPS has unacceptable error over short distances (see below). The other is that the impeller measures the speed of the boat relative to any water current, so impeller speed more accurately reflects the performance of the rowers. Windy conditions can create water currents,[16,17] and while the boat speed calculated by the impeller accounts for these currents, the impeller does not adjust for the direct effect of the wind on the boat, rowers and oars;[18,19] for example, when there is a headwind, an impeller will indicate, appropriately, a slower boat speed.

The impellers are calibrated upon installation and checked regularly thereafter, as there is anecdotal evidence that weed or other debris in the water can upset the calibration. In an effort to increase the accuracy of the impellers in flowing water, they are calibrated by travelling a known land distance upstream and downstream. The combined land distance for the two runs is compared with the combined impeller distance, which allows the appropriate calibration to be calculated for that stretch of water. Accurate measurement of speed with an impeller requires a constant speed and direction of the water current over the period of testing and through all parts of the waterway that the boats travel.

There are no published studies examining the reliability and validity of the impeller in rowing. To gain some understanding of their accuracy, one of the authors examined the Nielsen Kellerman impeller (NK) during regattas over 2000 m on various international rowing courses. In 61 observations of NK versus true boat speed over 2000 m, the NK units showed a negligible fixed error (0.1%), but there was a moderate random error of 1.2% even when wind direction and speed were taken into account (Smith TB, personal observations). While this amount of error is only slightly larger than the 1% yardstick considered appropriate to accurately monitor training, the NK is not sufficiently accurate to quantify small but meaningful changes in competitive performance.

2.2 Global Positioning System Measurement of Boat Speed

GPS requires an unobstructed view of its satellites, but this requirement is seldom a problem on the waterways where rowers train and compete. The devices are easily swapped between boats and do not require calibration.

The early GPS devices sampled and calculated position once per second (1-Hz), but with recent technical developments, units that sample as high as 20-Hz are now available. Higher sampling frequencies are needed for accurate speed measurement over shorter intervals or distances, but the 1-Hz units are still in principle adequate (<1% error) for quantifying boat speed over durations in excess of 100 seconds.

Proprietary algorithms employed by the various manufacturers of GPS are also considered to influence accuracy, so the findings from a particular GPS model should be considered to apply only to that model.[20] Previous research on inter-unit reliability has established that there is little difference between units of the same model of GPS, at least over long durations and distances,[21] so it is probably safe to assume that findings with one unit apply to all such units of a given model.

GPS technology has undergone a series of rapid advances since May 2000, when the US Government made full precision available. We have therefore limited this review to GPS studies published since then. We have included data from studies with movement patterns similar to that of rowing, that is, straight-line movements. We have also included data from movements around 400 m running tracks but have excluded zigzag or T-shaped shuttle runs. In all, three studies provided useful information for rowing,[22-24] and we have included some unpublished observations (see figure 1).

The accuracy of the 5-Hz MinimaxX (Catapult, Melbourne, VIC, Australia), the 1-Hz SPI-10 and the 5-Hz SPI-Pro (GPSports, Fyshwick, ACT, Australia) was examined over a range of speeds

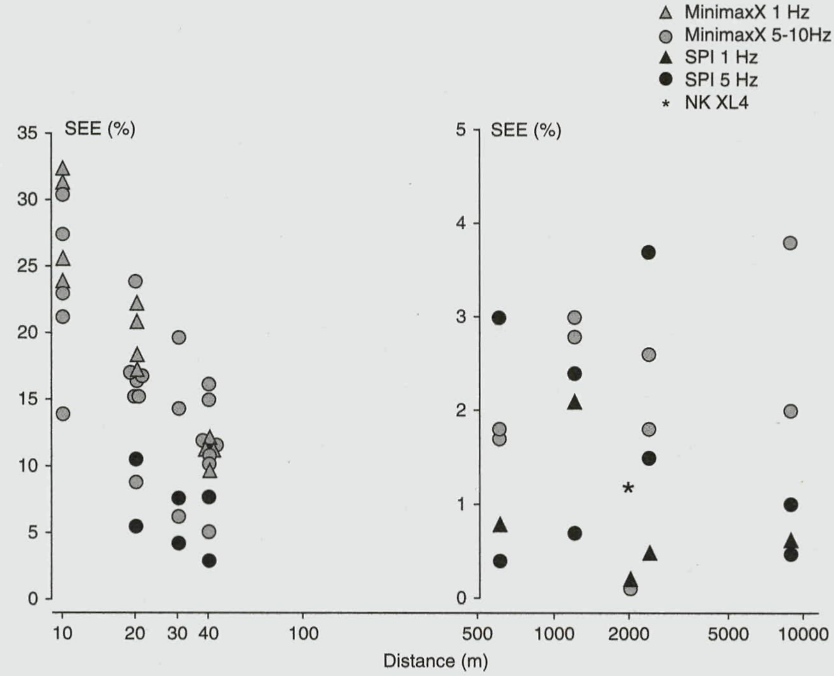

Fig. 1. Plot of the standard error of the estimate for each measurement device over various distances. **NK** = Nielsen Kellerman impeller; **SEE** = standard error of the estimate.

and distances by Petersen et al.[23] The distances recorded by the GPS were compared with the actual distances travelled on a 400 m running track for walking 8800 m through to sprinting 20 m. It is apparent in figure 1 that the accuracy of the GPS is more dependent on the manufacturer than the signal frequency. Figure 1 also shows that the 5-Hz version of the MinimaxX improved the error relative to the 1-Hz version regardless of distance and speed.[22] Pyne et al.[24] compared the 10-Hz MinimaxX with previously published results for the 5-Hz version for straight line sprinting over 10, 20 and 40 m. Not apparent in figure 1 is the fact that the accuracy of the 10-Hz version was better than that of the 5-Hz version.

Rowing has a unique problem for speed measured over a short distance. The average speed for the various boat types during competition is 4–6 m/sec, but speed varies by 2–3 m/sec during each stroke.[25,26] An aliasing error may arise from a combination of a 1-Hz sampling frequency, the large oscillations in velocity and a short sample period, and this error may worsen the already poor accuracy of the GPS over shorter durations and distances. Over the shortest distances of interest to rowers (~250 m), GPS sampling at greater frequencies (>1-Hz) would overcome this aliasing error.

The accuracy of GPS in rowing has been examined in one published study, which is available only as a conference abstract.[27] In this study the race time recorded by 5-Hz MinimaxX was compared with the official race time for 244 rowing boats during major competitions over 2000 m. The standard error of the estimate was 0.45 seconds, but not enough data were presented to convert this error to a percentage. However, if we assume the race time was 6–8 minutes, the standard error of estimate would be ~0.1%.

One of the authors also examined the accuracy of GPS in rowing by comparing the distance recorded by 10 SPI-Elite 1-Hz units with the 2000-m distance travelled by 22 rowing boats during various regattas. The standard error of the estimate was negligible (0.2%; Smith TB, personal observations) and similar to the ~0.1% estimated above from the 5-Hz MinimaxX for 2000 m rowing. The standard error of the estimate for these two GPSs are shown in figure 1 as the points with the smallest error. These errors are well within the 1% yardstick and are sufficiently low to quantify small but meaningful changes in boat speed in 2000 m time trials. Further research is required to determine the GPS accuracy during rowing over distances shorter than 2000 m, when aliasing might begin to make a substantial contribution.

From the data presented in figure 1 we make the following conclusions. The SPI elite and MinimaxX GPS are more accurate than the NK over 2000 m and the various SPI GPS units are more accurate than the MinimaxX except for 2000 m rowing. The MinimaxX has less error at higher sampling frequencies but the effect of frequency is not clear for the various SPI units. During rowing, the SPI-Elite has a smaller error than that determined over similar distances on a 400 m running track for other SPI models, even for those with a higher sampling frequency. It is therefore likely that cornering on athletic tracks increases GPS error.[20]

Environment changes will cause changes in boat speed, so regardless of how speed is measured, it can be an inaccurate method for tracking rowing performance. Even if ideal environmental conditions could be guaranteed between trials (no wind, no water currents, no changes in the composition, depth and temperature of the water), boat speed is still not an accurate measure of an individual rower's performance within a crew boat.

2.3 On-Water Ergometry

The measurement of a rower's power output in a boat is now possible with on-water ergometers, which have been constructed for both sculling and sweeping.[28] These ergometers calculate power output from kinetic data measured by sensors in the rowlock and/or oar(s).[29] Although in theory the power output from these devices should correlate strongly with boat velocity, findings have been mixed.[11,29,30] On-water ergometers are also expensive, time consuming to install and calibrate and often fragile (Smith TB, personal observations). Despite the potential benefits of these ergometers, it remains to be determined how well the power measured by their sensors represents power propelling the boat forward. We therefore advise caution in the use of on-water ergometers until the associated errors have been reported.

3. Measures of Off-Water Rowing Performance

The difficulties associated with assessment of on-water performance have led to widespread use of stationary ergometers that simulate the action of on-water rowing. Studies of various rowing ergometers have found some differences in arm motion,[31] handle force and acceleration profiles,[32] and consistency in stroke timing[33] between off-water and on-water rowing performance. Despite these differences, the rowing ergometer is widely used by rowers, and the 2000 m ergometer time trial is the most common measure of rowing performance.[7,34] The Concept II air-braked rowing ergometer (Morrisville, VT, USA) has led the market since the development of the IIb model in 1986. The three subsequent models (c, d and e) have maintained the same rowing motion and method for calculating work output, but have made changes to improve comfort, safety, robustness, damper settings and display options. A study to compare two Concept II models[35] was too underpowered to make meaningful conclusions, but it is reasonable to assume that the only differences between the models are cosmetic (Smith TB, personal observations).

In a recent development, the Concept II has been placed on a slide to allow back and forth motion that simulates more closely the dynamics of on-water rowing.[2,36,37] Comparisons of the static version of the Concept II with the new dynamic 'slider' version, suggested negligible differences in mean power output in time trials of 2000 m and 6 minutes, but, on the slider, peak and mean stroke force were lower and stroke rate was higher.[2,37] The slider is becoming increasingly popular in training, as there is evidence that dynamic rowing ergometry puts less strain on the lower back, which is beneficial to rowers who commonly suffer back injury.[38] Other advantages include a better 'on-water feel' and the capacity to link devices together to simulate crew rowing. The few studies comparing the static and slider versions of the Concept II lack the data to calculate the standard error of the estimate.[2,36,37] The only other rowing ergometer in contention is the Rowperfect (Devon, UK); while it may more closely simulate on-water rowing movement,[39] performance on this ergometer is less reliable (see below).

3.1 Off-Water versus On-Water Time Trials

To examine how accurately rowing-ergometer performance predicts on-water performance, we reviewed two studies where comparisons were made between 2000 m time trials conducted on water versus on a Concept II (see table I). We had to exclude two further studies comparing Concept II performance with rankings from world championships,[42,43] because the authors did not provide competitive performance times that would allow computation of a standard error of the estimate.

In a study of ten junior males whose on-water tests were single-scull competitions,[40] the standard error of the estimate was 2.6%, which in our scale of magnitudes is a very large error. Although the 'competition results' were obtained on a 'windless day', it is not clear whether the results were obtained from a single race. We therefore suspect environmental conditions contributed to the error. The limited competition experience of the young rowers (aged 18.9 ± 1.7 years) may also have contributed to the error, along with the substantial uncertainty in the estimate (90% confidence limits $\times/\div 1.54$) arising from the small sample size.

In another study,[41] 49 junior elite males completed two 1000 m time trials in single sculls, which were combined to give a 2000 m time and a standard error of the estimate of 7.2%. All tests were undertaken at a national training camp, which presumably ensured high motivation. Both single-scull time trials were conducted on the same day with winds of "approximately 2–3 m/sec, the direction being predominately a headwind" (p. 123).[41] Although there are various potential sources of error, we believe that change in wind speed and direction between trials for the different rowers was the main source of the extremely large error.

Table I. Standard error of the estimate of 2000 m single-scull performance time derived from correlations of this performance measure with measures from tests on a Concept II rowing ergometer. Measures shown in order of the adjusted standard error of the estimate (lowest to highest)

Test measures	Rowers[a]	Test measure (mean ± SD)	Correlation	SEE (%)	90% CI	Adjusted SEE (%)	References
2000 m time single-scull time	10 M	7:28 ± 0:13[b]	0.72	2.1	1.4, 3.3	2.6	Jurimae et al.[40]
Peak incremental power (W)	10 M	369 ± 37	−0.70	2.2	1.4, 3.4	2.8	
$\dot{V}O_2$ at 4 mmol/L lactate (L/min)	10 M	4.13 ± 0.63	−0.69	2.2	1.4, 3.4	2.9	
$\dot{V}O_{2max}$ (L/min)	10 M	4.85 ± 0.63	−0.64	2.4	1.5, 3.6	3.3	
Lactate at 350 W (mmol/L)	10 M	11.8 ± 4.8	0.64	2.4	1.5, 3.6	3.3	
Power at 4 mmol/L lactate (W)	10 M	275 ± 41	−0.61	2.4	1.6, 3.8	3.5	
40 sec all-out mean power (W)	10 M	614 ± 82	0.60	2.5	1.6, 3.8	3.6	
$\dot{V}O_{2max}$ (mL/kg/min)	10 M	61.5 ± 5.6	−0.33	2.9	1.9, 4.5	7.8	
2000 m time and body mass[c]	48 M	?	0.77	3.1	2.7, 3.7	?	Nevill et al.[41]
2000 m time single-scull time	48 M	9:08 ± 0:26[b]	0.54	4.1	3.5, 4.9	7.2	

a For other subject characteristics, see table II.

b Mean ± SD test measure data for 2000 m single-scull times in Jurimae et al.[40] and Nevill et al.[41] were presented in min:sec.

c Measures combined via multiple linear regression.

90% CI = 90% confidence interval for the SEE; **M** = male; **SEE** = standard error of the estimate; $\dot{V}O_2$ = oxygen uptake; $\dot{V}O_{2max}$ = maximal $\dot{V}O_2$; ? indicates not provided or estimable.

These large standard errors of the estimate do not necessarily mean that performance on the Concept II is invalid; more likely, there is large random error in the criterion measure of 2000 m on-water time, most of which is due to environmental factors.[8] When body mass was taken into account in a multiple linear allometric regression equation, the observed standard error of the estimate decreased from 4.1% to 3.1% (see table I), which is consistent with the observation that body mass provided a substantial contribution to Concept II time (r = 0.68) but a negligible contribution to single-scull time (r = 0.04).[41] The exponent of body mass in the allometric equation was approximately –0.8 so the widespread practice of expressing Concept II performance as mean power per kilogram must produce close to the optimal measure for combining body mass with ergometer performance.

Even when environment and body mass are taken into account, it is inevitable that some rowers perform better on the Concept II than on water and *vice versa*, so the Concept II cannot predict on-water ability perfectly. For a better estimate of the validity of performance on a Concept II, the standard error of the estimate needs to be obtained with a good sample size of top rowers under ideal environmental conditions.

3.2 Reliability of the Off-Water Time Trial

If we accept that the performance on a Concept II has adequate validity, at least for physiological power output, an important issue is whether this ergometer has adequate reliability for tracking changes in performance. Reliability for tests on a Concept II has been reported in two studies. Schabort et al.[44] examined 2000 m time-trial speed on a Concept II for eight well trained rowers who rowed on three occasions at 3-day intervals and reported a 0.6% standard error of measurement. In the second study, 15 elite rowers performed five 500 m time trials each on a Concept II and Rowperfect ergometer and later performed a 2000 m time trial on 3 consecutive days on one ergometer.[45] The standard error of measurement for 2000 m time were 0.4% and 1.1% on the Concept II and Rowperfect, respectively, while the standard error of measurement for the 500 m trials were 0.7% and 1.1%. Combining these studies, the standard error of measurement of ~0.5% is half the standard error of measurement for competitive on-water performance (our 1% yardstick) and is only just outside the 0.3% threshold to quantify smallest meaningful changes in competitive performance. Although this reliability is not ideal, it is unusual for tests of athletic performance to be this good.[46] This higher reliability of performance on the Concept II is likely a result of less technical demands of the ergometer and environmental effects causing less variability to performance on a rowing ergometer, compared with on-water rowing. In comparison, the Rowperfect was inferior, and it is unclear whether its reliability would reach that of the Concept II with enough familiarization.

3.3 Other Off-Water Test Measures

The rowing community was aware of the value of performance testing on the Concept II long before any reliability and validity studies were performed.[1,7] Indeed, the 2000 m time trial on the Concept II has become the most commonly used selection tool for national rowing organizations (Smith TB, personal observations). Furthermore, other measures derived from the performance test on the Concept II have been investigated for their ability to predict rowing performance. In one study,[39] the relationship of these measures to on-water 2000 m performance has been quantified, but, by far, the majority of the studies has used the 2000 m Concept II time trial as the criterion measure.

In the one study that used 2000 m single-scull performance,[40] the standard error of the estimate was moderate to large (2.1–2.8%), probably because of the different effects of environment, technique and body mass on performance on water versus on the ergometer (table I). Approximately half of the remaining studies had enough data to calculate the standard error of the estimate. For these studies the subject characteristics are included in table II, while the standard errors of the estimate for the various measures are in table III. The measures that come close to the ~1.0% yardstick are peak incremental power, maximal oxygen consumption ($\dot{V}O_{2max}$), some measures of lactate power and power in the 30-second modified Wingate. These measures have adequate validity

Table II. Subject characteristics for studies used to calculate the standard error of the estimate in 2000 m ergometer performance time for measures from rowing tests

Study	Rowers	Body mass (kg)[a]	$\dot{V}O_{2max}$ (L/min)[a]	2000 m time (min:sec)[a]
Bourdin et al.[47]	31 national and international heavyweight M	88.6±5.1	5.68±0.32	6:04±0:10
	23 national and international lightweight M	74.0±1.8	5.05±0.20	6:21±0:07
	54 combined	82.4±8.3	5.41±0.42	6:12±0:12
Cosgrove et al.[48]	13 club-level M	73.1±6.6	4.5±0.4	7:05±0:11
Faff et al.[49]	8 M (?) teenagers	85±14	4.97±0.48	6:45±0:14
Gillies and Bell[50]	10 competitive M	82.3±7.5	4.38±0.42	7:07±0:14
	22 competitive F	71±10	3.19±0.57	8:17±0:30
	32 combined	75±11	3.62±0.84	7:55±0:42
Jurimae et al.[40]	10 experienced M	79.3±7.3	4.85±0.63	6:38±0:18
Nevill et al.[51]	48 current/former senior A/B M	88±11	5.60±0.56	6:07±0:13
	28 current/former senior A/B F	71.7±8.5	4.03±0.33	7:01±0:17
	76 combined	82±13	5.02±0.91	6:27±0:30
Nevill et al.[41]	48 elite junior M	83±7	?	6:44±0:11
Riechman et al.[52]	12 competitive F	67±12	3.18±0.35	7:47±0:12
Russell et al.[53]	19 elite schoolboys	85±8	4.6±1.5	6:43±0:16
Womack et al.[54]	10 college M (pre-Fall)	86.1±7.3	5.25±0.69	6:48±0:18
	10 college M (post-Fall)	86.1±7.3	5.28±0.62	6:42±0:18

a Data are presented as mean ± SD.

F = female; **M** = male; $\dot{V}O_{2max}$ = maximal oxygen uptake; ? indicates not provided or estimable.

Table III. Standard error of the estimate of 2000 m ergometer performance time derived from correlations of this performance measure with aerobic physiological test measures. All tests were performed on a Concept II rowing ergometer. Measures shown in order of the adjusted standard error of the estimate (lowest to highest)

Measure	Rowers	Test measures[a]	Correlation	SEE (%)	90% CI	Adjusted SEE (%)	References
Peak incremental performance							
Power (W)	10 M	369 ± 37	–0.97	1.2	0.9, 1.9	1.2	Jurimae et al.[40]
	54 M	422 ± 37	–0.92	1.3	1.1, 1.5	1.4	Bourdin et al.[47]
	31 M, HW	441 ± 34	–0.89	1.3	1.0, 1.6	1.4	
	23 M, LW	396 ± 23	–0.76	1.2	0.9, 1.5	1.4	
	28 F	256 ± 23	–0.92	1.6	1.3, 2.0	1.7	Nevill et al.[51]
Speed ?	13 M	?	–0.77	1.7	1.3, 2.5	?	Cosgrove et al.[48]
Power (W)	48 M	369 ± 37	–0.84	1.9	1.6, 2.3	2.3	Nevill et al.[51]
	28 F, 48 M	328 ± 64	–0.96	2.2	1.9, 2.5	2.3	
Speed (m/min)	10 M	307 ± 17	–0.82	2.7	2.0, 4.3	3.3	Womack et al.[54] post-Fall
	10 M	304 ± 17	–0.77	3.0	2.2, 4.8	3.8	Womack et al.[54] pre-Fall
Power (W)	22 F	243 ± 45	–0.77	3.9	3.2, 5.3	5.1	Gillies and Bell[50]
	10 M, 22 F	285 ± 46	–0.81	5.3	4.4, 6.7	6.5	
	10 M	377 ± 72	–0.04	3.5	2.6, 5.7	>10	
Peak incremental $\dot{V}O_2$							
$\dot{V}O_{2max}$ (L/min)	13 M	4.5 ± 0.4	–0.85	1.4	1.0, 2.0	1.6	Cosgrove et al.[48]
	23 M, LW	5.05 ± 0.20	–0.70	1.3	1.0, 1.7	1.7	Bourdin et al.[47]
	54 M	5.41 ± 0.42	–0.84	1.8	1.5, 2.1	2.1	
	48 M	5.60 ± 0.56	–0.82	2.0	1.7, 2.4	2.5	Nevill et al.[51]
	10 M, 22 F	3.62 ± 0.84	–0.96	2.5	2.1, 3.1	2.6	Gillies and Bell[50]
	22 F	3.19 ± 0.57	–0.92	2.4	1.9, 3.2	2.6	
	10 M	5.25 ± 0.69	–0.87	2.3	1.7, 3.7	2.7	Womack et al.[54] post-Fall
	28 F, 48 M	5.02 ± 0.91	–0.94	2.7	2.4, 3.1	2.8	Nevill et al.[51]
	31 M, HW	5.68 ± 0.32	–0.68	2.0	1.6, 2.5	2.9	Bourdin et al.[47]
	10 M	5.28 ± 0.62	–0.84	2.5	1.9, 4.1	3.0	Womack et al.[54] pre-Fall
	10 M	4.38 ± 0.42	–0.75	2.3	1.7, 3.8	3.0	Gillies and Bell[50]
	8 M ?	4.97 ± 0.48	–0.71	2.6	1.8, 4.6	3.6	Faff et al.[49]
	28 F	4.03 ± 0.33	–0.74	2.8	2.3, 3.5	3.7	Nevill et al.[51]
	10 M	4.85 ± 0.63	–0.76	3.1	2.2, 5.0	4.1	Jurimae et al.[40]
	12 F	3.18 ± 0.35	–0.50	2.3	1.7, 3.5	4.5	Riechman et al.[52]

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Table III. Contd

Measure	Rowers	Test measures[a]	Correlation	SEE (%)	90% CI	Adjusted SEE (%)	References
$\dot{V}O_{2max}$ (mL/kg/min)	22 F, 10 M	48.4±7.4	–0.81	5.3	4.4, 6.7	6.5	Gillies and Bell[50]
	22 F	45.1±5.9	–0.66	4.6	3.7, 6.2	7.0	
	10 M	55.8±4.3	–0.39	3.2	2.4, 5.2	8.0	
$\dot{V}O_{2max}$ (L/min)	19 M	4.6±1.5	–0.43	3.7	3.0, 5.1	8.4	Russell et al.[53]
$\dot{V}O_{2max}$ (mL/kg/min)	12 F	47.4±5.3	–0.11	2.7	2.1, 4.2	>10	Riechman et al.[52]
	10 M	61.6±5.6	–0.13	4.8	3.5, 7.7	>10	Jurimae et al.[40]
Submaximal lactate-related measures							
Power at 4 mmol/L (W)	10 M	275±41	–0.96	1.3	0.9, 2.1	1.4	Jurimae et al.[40]
Lactate at 350 W (mmol/L)	10 M	11.8±4.8	0.96	1.3	0.9, 2.1	1.4	
$\dot{V}O2$ at 4 mmol/L (L/min)	10 M	4.66±0.75	–0.94	1.6	1.2, 2.6	1.7	Womack et al.[54] pre-Fall
Power at 1 mmol/L above baseline (W)	12 F	138±27	–0.82	1.5	1.1, 2.3	1.8	Riechman et al.[52]
Speed at 4 mmol/L (m/min)	10 M	282±17	–0.93	1.7	1.2, 2.7	1.9	Womack et al.[54] post-Fall
Power at 4 mmol/L (W)	8 M ?	222±23	0.89	1.7	1.2, 2.9	1.9	Faff et al.[49]
%$\dot{V}O_{2max}$ at 4 mmol/L (%)	31 M, HW	89.9±5.2	–0.79	1.7	1.4, 2.1	2.1	Bourdin et al.[47]
$\dot{V}O_2$ at 1 mmol/L above baseline (L/min)	12 F	2.24±0.36	–0.77	1.7	1.3, 2.6	2.2	Riechman et al.[52]
Speed at 4 mmol/L (m/sec)	13 M	?	–0.73	1.8	1.4, 2.7	?	Cosgrove et al.[48]
Speed at 4 mmol/L (m/min)	10 M	274±18	–0.90	2.0	1.5, 3.3	2.2	Womack et al.[54] pre-Fall
$\dot{V}O_2$ at lactate inflection (L/min)	48 M	4.3±0.5	–0.83	2.0	1.8, 2.5	2.4	Nevill et al.[51]
$\dot{V}O_2$ at 4 mmol/L (L/min)	13 M	?	–0.68	2.0	1.5, 2.9	?	Cosgrove et al.[48]
Power at 4 mmol/L (W)	28 F	256±25	–0.84	2.2	1.8, 2.8	2.6	Nevill et al.[51]
$\dot{V}O_2$ at 4 mmol/L (L/min)	10 M	4.13±0.63	–0.87	2.4	1.7, 3.9	2.7	Jurimae et al.[40]
Power at 3 mmol/L (W)	28 F	240±24	–0.82	2.4	2.0, 3.0	2.8	Nevill et al.[51]
Power at 2 mmol/L (W)	48 M	309±36	–0.77	2.3	2.0, 2.8	2.9	
Power at 3 mmol/L (W)	48 M	335±40	–0.75	2.4	2.1, 2.9	3.1	
Power at 2 mmol/L (W)	28 F	221±24	–0.78	2.6	2.1, 3.3	3.3	
$\dot{V}O_2$ at 4 mmol/L (L/min)	10 M	4.74±0.71	–0.82	2.7	2.0, 4.3	3.3	Womack et al.[54] post-Fall
Power at 4 mmol/L (W)	48 M	355±42	–0.73	2.4	2.0, 2.9	3.3	Nevill et al.[51]
Power at 3 mmol/L (W)	28 F, 48 M	300±58	–0.92	3.1	2.8, 3.6	3.3	
$\dot{V}O_2$ at lactate inflection (L/min)	28 F, 48 M	3.8±0.8	–0.92	3.1	2.8, 3.6	3.3	
Power at 2 mmol/L (W)	28 F, 48 M	276±54	–0.92	3.1	2.8, 3.6	3.3	
Speed at lactate inflection (m/sec)	13 M	?	–0.39	2.5	1.9, 3.7	?	Cosgrove et al.[48]

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Table III. Contd

Measure	Rowers	Test measures[a]	Correlation	SEE (%)	90% CI	Adjusted SEE (%)	References
$\dot{V}O_2$ at lactate inflection (L/min)	13 M	?	–0.39	2.5	1.9, 3.7	?	
Power @ 4-mM lactate (W)	28 F, 48 M	319±61	–0.91	3.3	2.9, 3.8	3.6	Nevill et al.[51]
$\%\dot{V}O_{2max}$ at 4 mmol/L lactate (%)	54 M	90.0±4.8	–0.49	2.8	2.4, 3.3	5.7	Bourdin et al.[47]
$\dot{V}O_2$ at lactate inflection (L/min)	28 F	3.0±0.3	–0.45	3.7	2.1, 4.8	8.0	Nevill et al.[51]
Submaximal $\dot{V}O_2$-related measures							
Gross efficiency (%)	23 M, LW	18.6±0.8	–0.51	1.5	1.2, 2.0	2.7	Bourdin et al.[47]
	31 M, HW	18.5±1.0	–0.64	2.1	1.7, 2.6	3.2	
$\dot{V}O_2$ at 4.00 m/sec (L/min)	13 M	3.29±0.13	0.62	2.1	1.6, 3.1	3.3	Cosgrove et al.[48]
$\dot{V}O_2$ at 3.85 m/sec (L/min)	13 M	2.99±0.16	0.51	2.3	1.7, 3.4	4.3	
$\dot{V}O_2$ at ? W (mL/min/W)	28 F	15.73±0.84	0.46	3.7	3.1, 4.8	7.8	Nevill et al.[51]
$\dot{V}O_2$ gross efficiency (%)	54 M	18.5±0.9	–0.35	3.0	2.6, 3.5	8.5	Bourdin et al.[47]
$\dot{V}O_2$ at 3.70 m/sec (L/min)	13 M	2.66±0.09	0.20	2.6	2.0, 3.9	>10	Cosgrove et al.[48]
$\dot{V}O_2$ at ? W (mL/min/W)	48 M	15.21±0.86	0.02	3.6	3.1, 4.3	>10	Nevill et al.[51]
$\dot{V}O_2$ at ? W (mL/min/W)	28 F, 48 M	15.40±0.88	0.33	7.4	6.6, 8.6	>10	
VT measures							
$\dot{V}O_2$ (L/min)	22 F	2.41±0.49	–0.72	4.3	3.4, 5.7	5.9	Gillies and Bell[50]
	22 F, 10 M	3.30±0.64	–0.83	5.0	4.2, 6.4	6.0	
	10 M	3.31±0.47	–0.49	3.0	2.2, 4.9	6.0	
Power (W)	22 F	149±31	–0.65	4.7	3.8, 6.3	7.2	
Power (W)	22 F, 10 M	170±46	–0.74	6.0	4.9, 7.6	8.1	
Power (W)	10 M	215±39	–0.13	3.4	2.6, 5.6	>10	
Short-term measures							
30 sec Wingate minimum power (W)	12 F	358±60	–0.89	1.2	0.9, 1.9	1.3	Riechman et al.[52]
30 sec Wingate mean power (W)	12 F	368±60	–0.87	1.3	1.0, 2.0	1.5	
30 sec Wingate peak power (W)	12 F	380±63	–0.85	1.4	1.0, 2.2	1.6	
5-stroke all-out mean power (W)	48 M	596±72	–0.82	2.0	1.7, 2.4	2.5	Nevill et al.[51]
5-stroke all-out mean force (N)	48 M	738±75	–0.81	2.1	1.9, 2.6	2.5	
5-stroke all-out mean power (W)	28 F, 48 M	523±117	–0.94	2.7	2.4, 3.1	2.9	
5-stroke all-out mean force (N)	28 F, 48 M	662±121	–0.93	2.9	2.6, 3.4	3.1	
40 sec all-out mean power (W)	10 M	614±82	–0.76	3.1	1.6, 3.3	4.1	Jurimae et al.[40]
5-stroke all-out mean force (N)	28 F	532±54	–0.69	3.0	2.5, 3.8	4.3	Nevill et al.[51]

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Table III. Contd

Measure	Rowers	Test measures[a]	Correlation	SEE (%)	90% CI	Adjusted SEE (%)	References
5-stroke all-out mean power (W)	28 F	398±55	–0.69	3.0	2.5, 3.8	4.3	
30 sec Wingate fatigue (%)	12 F	6.2±4.8	0.24	2.6	2.0, 4.1	>10	Riechman et al.[52]
Accumulated oxygen deficit (L)	19 M	2.1±1.4	0.10	4.1	3.3, 5.6	>10	Russell et al.[53]
Other measures							
Lactate 5 min post 2 km test (mmol/L)	13 M	?	–0.58	2.2	1.7, 3.2	?	Cosgrove et al.[48]
Lactate 5 min post $\dot{V}O_{2max}$ test (mmol/L)	13 M	?	–0.58	2.2	1.7, 3.2	?	
Critical power (W)	8 M?	275±28	–0.74	2.5	1.8, 4.4	3.3	Faff et al.[49]
Heart rate at VT (beats/min)	10 M	164.2±9.4	0.54	2.9	2.1, 4.7	5.3	Gillies and Bell[50]
Lactate at $\dot{V}O_{2max}$ (mmol/L)	12 F	14.1±2.7	–0.37	2.5	1.8, 3.8	6.6	Riechman et al.[52]
Power at 170 heart rate (W)	8 M ?	242±20	0.45	3.3	2.4, 5.7	7.3	Faff et al.[49]
Heart rate at VT (beats/min)	22 F	166±13	0.08	6.2	5.0, 8.3	>10	Gillies and Bell[50]
Heart rate at VT (beats/min)	22 F, 10 M	166±12	0.15	8.9	7.4, 11.3	>10	

a Data for test measures are presented in mean ± SD.

90% CI = 90% confidence interval for the SEE; **F** = female; **HW** = heavyweight rowers; **LW** = lightweight rowers; **M** = male; **pre-Fall, post-Fall** = pre and post the autumn competitive season; **SEE** = standard error of the estimate; $\dot{\mathbf{V}}\mathbf{O_2}$ = oxygen uptake; $\dot{\mathbf{V}}\mathbf{O_{2max}}$ = maximal oxygen uptake; **VT** = ventilatory threshold; ? indicates not provided or estimable.

for assessing moderate differences in rowing performance between rowers.

In four studies, multiple linear stepwise regression analyses provided best combinations of measures to predict 2000 m, Concept II time-trial performance. The sample sizes were far too low in three of these studies to perform such analyses, so the relatively low standard error of the estimate of 0.5–1% we obtained from their data must be substantial underestimates of the true error. In the other study, Nevill et al.[51] combined data from 48 males and 28 females to obtain a reasonable sample size, but the result is effectively a prediction equation for distinguishing between genders. Nevertheless, the resulting standard error of the estimate was relatively low (1.6%), so there may still be some value in combining several measures for predicting 2000 m performance on the ergometer, and especially on water. Definitive studies need to be performed.

A low standard error of the estimate for a performance measure is desirable, but measures with higher standard error of the estimate may still be useful if they have standard error of measurement low enough to reliably track an athlete's change in performance. Unfortunately, only one rowing study provided data to calculate the standard error of measurement for performance measures other than the 2000 m time trial.[55] Owing to a complex research design in this study, we were only able to calculate the standard error of measurement for various measures of lactate threshold and for peak lactate in an incremental test. The standard error of measurement for lactate threshold were relatively low (0.5–1.8%) but there is considerable error arising from the small sample size of ten elite male rowers.

The lack of reliability studies in rowing led us to examine the reliability of similar performance measures for other modes of exercise in a comprehensive meta-analytic review.[46] The measure of reliability in the review was the standard error of measurement of power output; we have therefore divided the standard error of measurement by 3 to obtain an equivalent standard error of measurement for performance time, as explained in that review. The most reliable tests that might be applicable to rowing were peak incremental power (standard error of measurement for time ~0.3%), $\dot{V}O_{2max}$ and lactate threshold (~0.5%). While all tests are well within the 1% yardstick, only peak incremental power could track smallest worthwhile changes. These measures also have the lowest standard error of the estimate for predicting 2000 m time-trial performance on a Concept II (see table III). The only other measure with a low standard error of the estimate in our review is the modified 30-second Wingate test on the Concept II, but the standard error of measurement of Wingate measures was somewhat larger (~1.2%) than that of the other two measures in the meta-analytic review.[46] Thus, it is possible that Wingate performance is more reliable on the Concept II than on other ergometers.

In summary, peak incremental power, $\dot{V}O_{2max}$, some measures of lactate threshold power and possibly 30-second power, have measurement properties that make them potentially valuable for assessing rowing performance. In our view, $\dot{V}O_{2max}$ provides no information additional to that provided by peak incremental power, which along with 30-second power has the advantage of requiring no equipment other than the Concept II. These tests can be performed weekly at any time of the year, with little impact on the training programme. Whether the measures can track performance adequately on the rowing ergometer, and more importantly on water, is a question that needs to be addressed with further research.

4. Conclusion

Measures of on-water rowing performance are very noisy, owing to the effects of environment, and they do not measure performance of an individual in a crew. Performance testing on the Concept II eliminates these problems. Peak incremental power and 30-second power on this ergometer are likely to be useful for frequent monitoring of a rower's physiological power output. However, the Concept II does not adequately address the skill component of performance on water. Instrumentation to measure each rower's on-water power output should provide the best measure of rowing performance, but it remains to be seen whether the errors are acceptably low.

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Appendix

Calculation of the standard error of the estimate.[56]

If X and Y are the practical and criterion in the validity study, r is their correlation, e_X and e_Y are their random errors, n is the sample size, SD is standard deviation, and SEE is the standard error of the estimate, then:

$$e_X = \sqrt{\left[SD_X^2\ \left(1 - r^2\ SD_Y^2 / \left(SD_Y^2 - e_Y^2\right)\right)\right]};$$

$$\text{observed slope of regression line} = r\left(SD_Y / SD_X\right);$$

$$\text{observed SEE} = SD_Y\sqrt{\left[\left(1-r^2\right)(n-1)/(n-2)\right]};$$

$$\text{true slope} = (\text{observed slope}) / \left(1 - e_X^2 / SD_X^2\right);$$

$$\text{true SEE without criterion error} = (\text{true slope})\ e_X;$$

$$\text{true SEE with criterion error} = \sqrt{\left[(\text{true SEE})^2 + e_Y^2\right]}.$$

The adjusted SEE shown in the tables is the true SEE with criterion error. The random error in the criterion, e_Y, was assumed to be 1% for 2000 m single-scull performance time (see table I) and 0.5% for 2000 m Concept II performance time (see table III).

This approach cannot be used for measures derived by multiple linear regression unless the authors provide the mean and standard deviation of the predicted values.

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