Scand J Med Sci Sports 2010: 20: 122–127
DOI: 10.1111/j.1600-0838.2008.00874.x

SCANDINAVIAN JOURNAL OF
MEDICINE & SCIENCE
IN SPORTS

Scaling concept II rowing ergometer performance for differences in body mass to better reflect rowing in water

A. M. Nevill[1], C. Beech[1], R. L. Holder[2], M. Wyon[1]

[1]School of Sport, Performing Arts and Leisure, University of Wolverhampton, Walsall, West Midlands, UK, [2]Department of Primary Care and General Practice, The University of Birmingham, Birmingham, West Midlands, UK
Corresponding author: Alan M. Nevill, School of Sport, Performing Arts and Leisure, University of Wolverhampton, Gorway Road, Walsall WS1 3BD, UK. Tel: +44 1902 32 28 38, Fax: +44 1902 32 28 98, E-mail: a.m.nevill@wlv.ac.uk

Accepted for publication 10 September 2008

We investigated whether the concept II indoor rowing ergometer accurately reflects rowing on water. Forty-nine junior elite male rowers from a Great Britain training camp completed a 2000 m concept II model C indoor rowing ergometer test and a water-based 2000 m single-scull rowing test. Rowing speed in water (3.66 m/s) was significantly slower than laboratory-based rowing performance (4.96 m/s). The relationship between the two rowing performances was found to be R^2 = 28.9% (r = 0.538). We identified that body mass (m) made a positive contribution to concept II rowing ergometer performance (r = 0.68, $P<0.001$) but only a small, non-significant contribution to single-scull water rowing performance (r = 0.039, P = 0.79). The contribution that m made to single-scull rowing in addition to ergometer rowing speed (using allometric modeling) was found to be negative ($P<0.001$), confirming that m has a significant drag effect on water rowing speed. The optimal allometric model to predict single-scull rowing speed was the ratio (ergometer speed $\times\ m^{-0.23})^{1.87}$ that increased R^2 from 28.2% to 59.2%. Simply by dividing the concept II rowing ergometer speed by body mass ($m^{0.23}$), the resulting "power-to-weight" ratio (ergometer speed $\times\ m^{-0.23}$) improves the ability of the concept II rowing performance to reflect rowing on water.

Bigger/heavier rowers out-perform smaller/lighter rowers assuming the same level of skill (as evidenced by two distinct weight categories above and below 72.5 kg), but excess weight in the boat is detrimental to performance (e.g., excess body fat, Russell et al., 1998). However, this view is not entirely supported by the relatively small differences between 2000 m world records of lightweight and heavyweight events. The mean difference in men's events is 9 s over an average race time of 354 s. This equates to lightweight events being on average only 2.5% slower than heavyweight events (Secher & Vaage, 1983). In fact, up until the Seville world cup of 2002, the overall world best time for the men's coxless 4 was held by a lightweight crew, although we recognize that this result was achieved in favorable conditions (with a strong tailwind and in warm water). However, the difference between lightweight and heavyweight rowers' world 2000 m ergometer record times is much greater, a difference of 25 s that equates to lightweights being 7.4% slower on the ergometer than heavyweights. This obvious difference in performance between the two weight classes being less apparent on the water suggests that maybe body mass plays a different role in water locomotion compared with rowing ergometer performance.

Many rowing coaches and selectors other than international and university-funded coaches cannot access physiological factors associated with rowing performance on water due to the time, cost and availability of equipment/knowledge involved. Predictive tests of rowing performance are therefore normally conducted on a concept II indoor rowing ergometer, the most popular tests being 250, 2000 and 5000 m time trials (Redgrave, 1995). Nevertheless, there is some debate over the effectiveness of using ergometer performance as a predictor of water rowing performance (Redgrave, 1995; Sayer, 1996; Nolte, 2005).

Hence, the purpose of the present study is to establish whether the concept II indoor rowing ergometer performance accurately reflects rowing performance on water. Specifically, we assessed the agreement and relationship between a single-scull 2000 m water performance and the equivalent concept II 2000 m rowing ergometer time-trial performances of 49 junior elite Great Britain international rowers.

Methods

Subjects

Forty-nine elite male junior athletes were recruited during the "Great Britain rowing junior international potential training camp" at the National Water-Sports Centre, Holme Pierrepont, Nottingham, UK (October 24–29, 2005). Participants for the study had undergone a number of selection regattas before their invitation to the camp, many of whom had competed at the world junior championships the previous year. The invited rowers were considered by the Amateur Rowing Association to be the best 49 junior rowers in the country, justifying the use of the term "elite." Before participating in the training camp and study, all athletes produced a statement of informed consent signed by either them or their parents/guardians. Ethical approval was granted by the Research Centre for Sport, Exercise and Performance, University of Wolverhampton. The participants were a selection of the best junior rowers in the country. Physical characteristics of the participants are given in Table 1.

Protocol

All rowers completed a 2000 m test on a rowing ergometer and a 2000 m (2 × 1000 m) time trial in a single scull. All subjects completed the protocol on the same day in a controlled training camp environment. The rowers had all subscribed to follow the same training program for at least the previous 6 months and had undergone identical routines for the previous 4 days including training sessions/times and meals.

2000 m ergometer test

The subjects completed a 2000 m test on a concept II model C indoor rowing ergometer. The drag factor was set at 135, as recommended for junior and lightweight performance athletes by the concept II indoor rowing training guide, found at the concept II website, http://www.concept2.co.uk/guide/guide.php?article=damper_leverr, although we recognize that the choice of 135 as the drag factor for these junior rowers may increase the static contraction at the beginning of the stroke and result in a lower rate, even if the power produced is matched. This difference in resistance setting may introduce a dissimilarity between land and water rowing, which may be critical when a direct comparison is required. Subjects were allowed 20 min to warm up as they would usually before the test commenced. Results were recorded from the ergometer's monitor for total time (s) and speed (m/s).

2000 m sculling time trial

The subjects completed a 2000 m single-scull time trial that was divided into two 1000 m splits on the 2000 m course at the national center, Holme Pierrepont (1000 m splits being routinely used in the 4-day training camp as part of their performance/training assessment). The initial timing gate was situated at the 750 m station; the final time was taken at the 1750 m station. Both trials were started from a rolling start, subjects beginning to row at the 500 m station. Each stage was completed in the same direction with the athletes returning to the start at a "steady pace" immediately after finishing the first run. The resulting 1000 m split times were added to produce a total 2000 m time-trial performance score. Based on data recorded at a local weather station, wind speed was approximately 2–3 m/s, the direction being predominately a headwind.

Table 1. Physical characteristics of the rowers

N	Age (years)	SD	Body mass (kg)	SD	Height (m)	SD
49	16.7	0.5	83.3	7.0	1.89	0.064

Values are expressed as means ± SD.
SD, standard deviation.

Statistical methods

Box and Cox (1964) and more recently Nevill et al. (2005, 2006) recognized the need to record performance time as average speed (i.e., using the inverse transformation) to make performance data more symmetric and normally distributed. For this reason, rowing performance times were converted to average speeds (m/s).

A small number of observations were absent/missing. These were treated as unknown parameters and estimated using the expectation-maximization algorithm as implemented in SPSS version 12. A complete data set was thus formed and then subjected to various linear and log-linear regression analyses as described below and in the results section.

Agreement between the ergometer- and water-based rowing speeds were assessed using a paired sample *t*-test, a test–retest standard deviation (SD) of differences, the 95% limits of agreement (Bland & Altman, 1986; Atkinson & Nevill, 1998), coefficient of variation (CV) and regression analyses carried out using the statistical software package MINITAB (1995).

In order to investigate the nature of the relationship between ergometer- and water-based rowing speeds, linear and proportional allometric models were fitted to the data using the following two equations, respectively:

$$\text{Water-based speed (m/s)} = a_1 + b(\text{ergometer speed}) + \varepsilon_1 \quad (1)$$

$$\text{Water-based speed (m/s)} = a_2(\text{ergometer speed})^k \times \varepsilon_2 \quad (2)$$

Note that the allometric model (eqn. [2]) can be linearized with a log-transformation, and simple linear regression can be used to estimate unknown parameters a_2, and k. The log-transformed model becomes, $\log_e(\text{water speed}) = \log_e(a_2) + k \times \log_e(\text{ergometer speed}) + \log_e(\varepsilon_2)$.

Finally, in order to investigate to what extent body mass (m) might improve our understanding of the association between water- and ergometer-based rowing performance, the following allometric power-function model, adopted from Nevill et al. (1992), was used to explore the optimal relationship between water-based rowing speed, concept II ergometer speed and body mass (m)

$$\text{Water-based speed (m/s)} = a_3(\text{ergometer speed})^{k_1} \times m^{k_2} \times \varepsilon \quad (3)$$

where a_3 is a constant and k_1 and k_2 are the exponents likely to provide the best predictor of water-based rowing speed and ε is the multiplicative error ratio. As before, the model can be linearized with a log-transformation, and multiple linear regression can be used to estimate unknown parameters a_3, k_1 and k_2. The log-transformed model becomes

$$\log_e(\text{water speed}) = \log_e(a_3) + k_1\log_e(\text{ergometer speed}) + k_2\log_e(m) + \log_e(\varepsilon)$$

Note that the parameter a can be allowed to vary between groups (heavyweight vs lightweight rowers), thus conducting a form of analysis of covariance.

Results

Data from both the single-scull 2000 m water, and the concept II rowing ergometer time trials are presented in Table 2.

The paired sample *t*-test identified a significant bias with the mean water-based speed (3.66 m/s) being 1.30 m/s slower than the ergometer-based time-trial speed (4.96 m/s) ($t_{48} = 59.98$, $P < 0.001$). Despite the large difference (bias) in rowing speeds, the SD of differences was small, given by ± 0.15 m/s that yielded a CV = (SD/mean) × 100 = (0.15/4.31) × 100 = 3.51%. The 95% limits of agreement (3) was found to be 1.30 ± 0.30 m/s, confirming the overwhelming bias but a relatively small unexplained within-subject test–retest error.

The linear regression relationship between water-based speed and the concept II ergometer-based speed for the 2000 m time trials was given by

$$\text{Water-based speed } (m/s) = 0.146 + 0.709 \times \text{ergometer speed (m/s)}$$

with $R^2 = 28.9\%$ (correlation of $r = 0.538$) and the SD of residuals about the regression line being $s = 0.148$ m/s. The intercept term 0.146 (SEE = 0.80) m/s was not significant ($P = 0.86$), suggesting that single-scull rowing speed in water is proportional to the concept II rowing ergometer speed (i.e., the line passing through the origin).

This was confirmed when the proportional allometric model relationship between water-based speed and the concept II ergometer-based speed for the 2000 m time trials was found to be

$$\text{Water-based speed (m/s)} = 0.79 \times [\text{ergometer speed (m/s)}]^{0.96}$$

with $R^2 = 28.2\%$ (correlation of $r = 0.531$) and the SD of residuals about the fitted regression line of $s = 0.0408$, giving the error ratio of $s = 1.042$ or 4.2%, having taken antilogs. Clearly the association between rowing speed in water and ergometer-based speed is approximately linear (see Fig. 1), indicated by the exponent of 0.96, and water-based rowing speed is approximately 80% of that achieved on the concept II rowing ergometer, as given by the proportional slope parameter of 0.79.

The correlation between concept II rowing ergometer speed and body mass was significant, $r = 0.68$ ($P < 0.001$), but between single-scull rowing speed and body mass was considerably less, $r = 0.039$ ($P = 0.79$). Body mass makes an important and significant positive contribution on the concept II rowing ergometer performance but only a small, non-significant contribution to single-scull water rowing performance.

In order to investigate to what extent body mass might improve our understanding of the proportional relationship between single-scull water rowing performance and the concept II rowing performance, the proportional allometric power-function model (eqn. [3]) was used to predict single-scull water rowing performance speed, using concept II rowing ergometer performance speed and body mass (m) as the predictor variables. The resulting model was

$$\text{Water-based speed (m/s)} = 1.19 \times (\text{ergometer speed})^{1.87} \times m^{-0.425} \quad (4)$$

with $R^2 = 59.2\%$ and the SD of residuals about the fitted regression line being $s = 0.031$, giving the error ratio of $s = 1.031$ or 3.1%, having taken antilogs (m/s). Both the ergometer speed exponent (1.87; SEE = 0.23) and body mass exponent parameters (-0.425; SEE = 0.072) were significant ($P < 0.001$). Note that the above allometric model (eqn. [4]) can be expressed as $(\text{ergometer speed})^{1.87} \times (m)^{-0.425} = (\text{ergometer speed} \times m^{-0.23})^{1.87}$. Indeed when we correlated the single-scull water speed with the ratio (eqn. [4]), the correlation was 0.771 ($P < 0.001$), as seen in Fig. 2. Note that if we ignore the 1.87 exponent and simply correlate (ergometer speed × $m^{-0.23}$) with single-scull water speed, the correlation remains at $r = 0.77$.

Discussion

In this article, we report the relationship between the concept II rowing ergometer speed and single-scull rowing speed to be $R^2 = 28.9\%$ ($r = 0.538$). However, when we explored the contribution that body mass made to single-scull rowing speed in addition to the concept II ergometer rowing speed (using allometric

Table 2. The concept II ergometer- and water-based 2000 m time-trial results

Trial	*N*	Time (s)	SD	Split 1 (s)	Split 2 (s)	Speed (m/s)	SD
Water	49	547.6	26.2	271.8	275.8	3.66	0.17
Ergo	49	403.8	10.6			4.96	0.13
Diff		143.7***	22.5			1.30***	0.15

Values are expressed as means ± SD.
***$P < 0.001$.
SD, standard deviation.

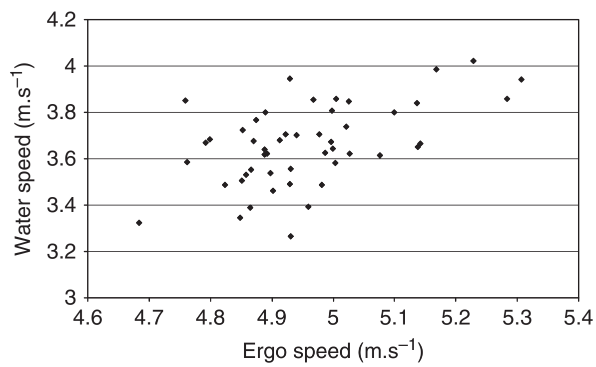

Fig. 1. Single-scull water speed (m/s) vs concept II ergometer speed (m/s), the coefficient of determination $R^2 = 28.2\%$ ($r = 0.538$).

modeling), we found that the body mass exponent was negative ($P<0.001$), confirming that body mass has a significant drag effect on water rowing speed. The optimal allometric model to predict single-scull rowing speed was found to be the ratio (ergometer speed $\times m^{-0.23})^{1.87}$ that increased R^2 from 28.2% to 59.2%. This suggests that by dividing the concept II rowing ergometer speed by body mass ($m^{0.23}$), the resulting "power-to-weight" ratio (ergometer speed $\times m^{-0.23}$) will greatly improve the ability of the concept II rowing performance to reflect rowing on water.

The difference between 2000 m single-scull water-based rowing time and the equivalent 2000 m rowing ergometer time (547.6 vs 403.8 s) was more than 2 min (143.7 s). This translates to a significant difference or bias in rowing speeds (3.66 vs 4.96 m/s), respectively ($P<0.001$). The difference or bias in rowing speeds could of course be due to a number of extraneous factors including wind speed, water temperature, etc. However, the relationship between the two rowing performances should provide a much better insight into the intriguing question "Can the concept II rowing ergometer performance reflect single-scull rowing in water?"

The linear and log-linear regression analysis (based on the linear and allometric models given by eqns. [1] and [2]) identified the concept II ergometer performance speed was able to predict $<30\%$ of single-scull rowing performance (correlation of $r=0.538$ and 0.531, respectively). These findings seriously question the ability of the concept II ergometer to accurately reflect water-based rowing performance alone.

The significant correlation between concept II rowing ergometer speed and body mass ($r=0.68$, $P<0.001$) but the non-significant correlation between single-scull rowing speed and body mass may provide a valuable insight into the above poor relationship between ergometer- and water-based rowing performance speeds. It is well known that ergometer rowing performance over 2000 m is best predicted by peak-power output (P_{peak}) sustained during a maximal incremental test (Bourdin et al., 2004), and the power associated with $\dot{V}O_{2max}$ also assessed during a maximal incremental rowing test (Ingham et al., 2002). However, because power output is also known to be strongly associated with body mass, the observed correlation of $r=0.68$ is entirely plausible. The non-significant correlation between single-scull rowing performance and body mass is also reasonable, given that heavyweight rowers can only perform approximately 2.5% faster than lightweight rowers in water (Secher & Vaage, 1983). Clearly, body mass plays a significant, positive role in predicting concept II rowing performance. However, the role that body mass plays in predicting single-scull rowing performance in water is much less clear.

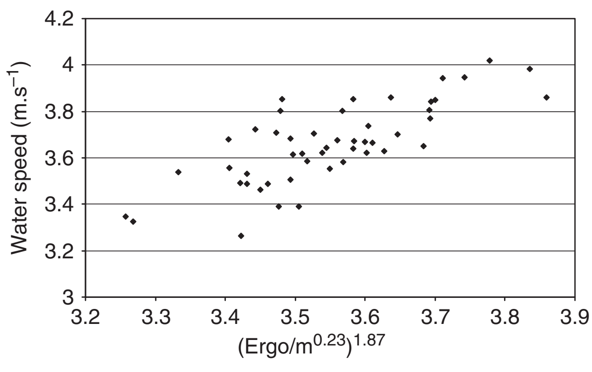

Fig. 2. Single-scull water speed (m/s) vs the "power-to-mass" ratio (ergometer speed $\times m^{-0.23})^{1.87}$, the coefficient of determination $R^2=59.2\%$ ($r=0.771$).

For this reason, we explored the nature of relationship between water-based single-scull rowing speed and both concept II rowing speed and body mass as the predictor variables, using allometric model (eqn. [3]). The resulting allometric model identified the following ratio (ergometer speed $\times m^{-0.23})^{1.87}$ as the best predictor of single-scull rowing speed, that explained $R^2=59.2\%$ of the variance (see eqn. [4]). Indeed, when we calculated the simple ratio (ergometer speed $\times m^{-0.23}$) and correlated it with single-scull rowing speed, the correlation remained almost the same at $r=0.77$. Given the strong association between 2000 m rowing ergometer performance and maximal power output recorded during incremental rowing tests [either P_{power} ($r=0.92$, $P<0.001$, Bourdin et al., 2004) or power at $\dot{V}O_{2max}$ ($r=0.95$, $P<0.001$, Ingham et al., 2002)], the above ratio can be interpreted as the best "power-to-weight" ratio, estimated by the ratio (ergometer speed $\times m^{-0.23}$), to predict single-scull rowing performance.

Similar findings have been reported for 40 km time-trial cycling speeds (Nevill et al., 2005, 2006). For example, Nevill et al. (2006) was able to report the optimal "power-to-mass" ratios to predict flat time-trial cycling speeds, obtained from three independent studies, to be $(W_{MAP} \times m^{-0.48})^{0.54}$, $(W_{VT} \times m^{-0.48})^{0.46}$ and $(W_{AVG} \times m^{-0.34})^{0.58}$ that explained 69.3%, 59.1% and 96.3% of the variance in time-trial cycling speeds, respectively (W_{MAP} is the maximum aerobic power; W_{VT} the power output at ventilatory threshold; and W_{AVG} the average power output, recorded during a 1-h performance test). Based on the results of the present study and results from time-trial cycling studies, body mass appears to have a significant negative or drag effect (as evidenced by the body-mass denominator terms in all the allometric ratios) when predicting rowing or cycling locomotion in the field. Thus despite the need for rowers to be heavier/larger to generate more power, there appears to be an optimal "power-to-mass" ratio that better reflects real-life locomotion in events such as road cycling and, in particular, rowing in water.

These findings have important implications for the applied sports sciences involved in rowing, principally in identifying the discrepancy between concept II ergometer- and water-based rowing performances. This investigation has identified the major role played by body mass in explaining ~30% more of the variance between water- and ergometer-based rowing performance ($R^2 = 28.2\%$ vs 59.2%). For practical purposes, the simple ratio (ergometer speed × $m^{-0.23}$) can be used to adjust a concept II rowing performance, to more accurately reflect the equivalent single-scull water-based rowing performance. However, we recognize that this research has a number of limitations. The above "power-to-mass" ratio is based on the performance of junior elite rowers that may not have the same level of skill and hence rowing efficiency as senior elite rowers. Clearly, further research is required to establish whether the same "power-to-mass" ratio can be used to predict other water-based rowing performances (e.g., using different boat types other than the single scull) of male and female, lightweight and heavyweight senior rowers. Another limitation would be that a 2000 m continuous water-based time trial would have been marginally slower than the 2 × 1000 m trials used in the present study, given the opportunity for a modest recovery during the "steady-pace" return-to-start. However, given that the 2000 m (2 × 1000 m) speed was already significantly slower than the concept II ergometer speed by 1.3 m/s, the difference in speeds would have been even greater, simply reinforcing the inability of the unadjusted concept II ergometer speeds to accurately reflect water-based rowing performance.

Perspectives

The concept II rowing ergometers are frequently used by rowing coaches to provide them with an indication of training progress and potential rowing performance. In this study, we have identified that performance on a concept II rowing ergometer of junior elite rowers demonstrates poor agreement between, and a weak association with, their equivalent single-scull rowing performance in water. The rowing speeds in water was significantly slower (1.33 m/s) than laboratory-based rowing performance ($P < 0.001$). The relationship between the two rowing performances was also poor resulting in a coefficient of determination $R^2 = 28.2\%$ and a correlation of $r = 0.531$. However, when we used allometric modeling to investigate the contribution that body mass could make to single-scull water rowing performance using both concept II rowing ergometer performance speed and body mass (m) as the predictor variables, the explained variance increased from $R^2 = 28.2\%$ to 59.2%. These findings confirm that, on its own, the concept II rowing ergometer is a relatively poor predictor of water-based single-scull rowing performance. However, by simply dividing the concept II rowing ergometer speed by body mass ($m^{0.23}$), the resulting "power-to-weight" ratio (ergometer speed × $m^{-0.23}$) will greatly improve the ability of the concept II rowing performance to accurately reflect rowing performance on water.

Key words: body mass, power-to-mass ratio, allometric models, single-scull rowing performance, drag effect.

Acknowledgements

The authors would like to thank the two helpful reviewers for their valuable comments when revising the manuscript. We should also like to thank all the rowers that took part in the "Great Britain rowing junior international potential training camp" at the national Water-Sports Centre, Holme Pierrepont in Nottingham (October 24–29, 2005).

References

Atkinson G, Nevill AM. A review of the statistical methods employed to assess measurement error (reliability) in variables relevant in sports medicine. Sports Med 1998: 26: 217–238.

Bland JM, Altman DG. Statistical methods for assessing agreement between two methods of clinical measurement. Lancet 1986: i: 307–310.

Bourdin M, Messonnier L, Hager J-P, Lacour J-R. Peak power output predicts rowing ergometer performance in elite male rowers. Int J Sports Med 2004: 25: 368–373.

Box GEP, Cox DR. An analysis of transformations (with discussion). J R Stat Soc B 1964: 26: 211–252.

Ingham S, Whyte G, Jones K, Nevill A. Determinants of 2000 m rowing ergometer performance in elite rowers. Eur J Appl Physiol 2002: 88(3): 243–246.

Nevill AM, Jobson SA, Davison RCR, Jeukendrup AE. Optimal power-to-mass ratios when predicting flat and hill-climbing time-trial cycling. Eur J Appl Physiol 2006: 97(4): 424–431.

Nevill AM, Jobson SA, Palmer GS, Olds TS. Scaling maximal oxygen uptake to predict cycling time-trial performance in the field: a non-linear approach. Eur J Appl Physiol 2005: 94: 705–710.

Nevill AM, Ramsbottom R, Williams C. Scaling physiological measurements for individuals of different body size. Eur J Appl Physiol 1992: 65: 110–117.

Nolte V. Rowing faster. Champaign, IL: Human Kinetics, 2005: 195–203.

Redgrave S. Complete book of rowing. London: Partrige Press, 1995: 92–94.

Russell AP, Rossignol PFL, Sparrow WA. Prediction of elite schoolboy 2000-m rowing ergometer performance from metabolic, anthropometric and strength variables. J Sports Sci 1998: 16(8): 749–754.

Sayer B. Rowing and sculling, the complete manual. London: Hale, 1996: 73.

Secher NH, Vaage O. Rowing performance, a mathematical model based on analysis of body dimensions as exemplified by body weight. Eur J Appl Physiol 1983: 52(1): 88–93.

Minitab Inc. MINITAB reference manual. State College, PA: Minitab Inc., 1995.