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Modelling the determinants of 2000 m rowing ergometer performance: a proportional, curvilinear allometric approach

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Previous studies have investigated the determinants of indoor rowing using correlations and linear regression. However, the power demands of ergometer rowing are proportional to the cube of the flywheel's (and boat's) speed. A rower's speed, therefore, should be proportional to the cube root (0.33) of power expended. Hence, the purpose of the present study was to explore the relationship between 2000 m indoor rowing speed and various measures of power of 76 elite rowers using proportional, curvilinear allometric models. The best single predictor of 2000 m rowing ergometer performance was power at $\dot{V}O_{2max}$ $(W_{VO_{2max}})^{0.28}$, that explained $R^2 = 95.3\%$ in rowing speed. The model realistically describes the greater increment in power required to improve a rower's performance by the same amount at higher speeds compared with that at slower speeds. Furthermore, the fitted exponent, 0.28 (95% confidence interval 0.226–0.334) encompasses 0.33, supporting the assumption that rowing speed is proportional to the cube root of power expended. Despite an $R^2 = 95.3\%$, the initial model was unable to explain "sex" and "weight-class" differences in rowing performances. By incorporating anaerobic as well as aerobic determinants, the resulting curvilinear allometric model was common to all rowers, irrespective of sex and weight class.

The rowing ergometer is a popular and convenient apparatus for indoor training. Not only does it provide a valuable form of controlled, weight-supported exercise that promotes health and fitness, but it is thought to provide a valid proxy for rowing on water (Mikuli et al., 2009) although some doubt as to the validity of indoor rowing ergometers to simulating rowing on water has been questioned (Nevill et al., 2009). Such is the popularity of rowing ergometers, thousands of competitors from all over the world compete in the Concept II World Indoor Rowing Championship held in Boston each year.

A number of authors have explored the physiological determinants of rowing ergometer performance (Secher, 1973; Ingham et al., 2002; Bourdin et al., 2004). Some authors have reported that ergometer rowing performance over 2000 m is best predicted by peak or maximum-power output (W_{max}) sustained during a maximal incremental test, intervals lasting 3 min (Bourdin et al., 2004), while others identified the power associated with $\dot{V}O_{2max}$ ($W_{VO_{2max}}$) as among the best predictor (Ingham et al., 2002). Performance over 2000 m on a rowing ergometer is dependent upon the functional capacity of both the aerobic and anaerobic energy pathways (Secher, 1973), with the relative amount of energy derived from anaerobic metabolism being estimated at 21–30% (Secher, 1990) or possibly a little less (Spencer and Gastin, 2001). It is likely therefore that the above measures of power, together with a measure of maximum power lasting considerably $<$ 3 min are likely to make a valuable contribution to indoor rowing performance. Invariably, however, many of these studies have investigated the determinants of indoor rowing using correlation and linear regression techniques that assume the determinants are linearly related to 2000 m ergometer rowing performance. Linear models, for example, will assume that for a similar increase in power, the same absolute improvement in rowing speed will result irrespective of the rower's level of performance (e.g. the speed of elite international rowers compared with club standard rowers).

The relationship between indoor rowing ergometer performance and power, however, is definitely not linearly related. Indeed, according to researchers at Oxford University, UK (http://www.atm.ox.ac.uk/rowing/physics/ergometer.html), the power required by the rower to rotate the air braked flywheel is proportional to the cube of the flywheel speed. A similar cube law relationship holds for the relationship between the dissipated power and boat speed/velocity. Consequently, the ergometer or boat speed achieved by the rower should also be proportional to the cube root (0.33) of the power expended. Hence, the purpose of this article was to explore the likely curvilinear relationship between 2000 m indoor rowing speed and various measures of power output using a proportional allometric model to better understand determinants and limitations of indoor Concept II rowing performance.

Methods

Following approval from the regional Ethics Committee, 76 current or former senior or under 23 World rowing or sculling finalists provided written informed consent to take part in progressive incremental rowing tests on the ergometer, a maximal ergometer power test and a maximal 2000 m ergometer time trial. The physical characteristics of the rowers, grouped according to sex and rowing weight class [heavy weight (HWT) and light weight (LWT)], are given in Table 1.

Height (stature) and body mass were measured using a stadiometer and beam-balance scales (Avery Berkel, Walsall, UK), respectively. The percentage body fat was estimated using the sum of four skinfold sites (Durnin & Womersley, 1974; Siri, 1956) using callipers (John Bull, British Indicators Ltd., St Albans, UK).

All evaluations were performed on a modified Concept II, model C air braked rowing ergometer (Concept2, Nottingham, UK). The test system (Avicon II, Berlin, Germany) incorporated a load cell (U9B, HBM Germany, Darmstadt, Germany) for force measurement and a rotary transducer (ROD 454 M, Heidenhain, Germany). The subjects warmed up for 10 min, then rowed two build-up strokes, followed by five consecutive maximal rowing strokes at a fixed rate of 30 strokes/min. Maximal force (F_{max}), power (W_{max}), work, stroke length and stroke rate were averaged over the five strokes. Five 4 min increments were rowed on the ergometer, with 30 s rest between stages. Work intensity was increased by 30 W for the men and by 25 W for the women and by 2 strokes/min, at each stage. Following stage 5 there was a 150 s rest followed by a 4 min maximal effort.

Pulmonary gas exchange was determined breath-by-breath. Subjects wore a nose clip and breathed through a low dead space (90 mL), low-resistance (0.1 kPa/L/s at 15 L/s) mouthpiece. Air was sampled through a 2 m small bore capillary line and analyzed for O_2 concentration using a differential paramagnetic analyzer and CO_2 concentration using a side-stream infrared analyzer (Oxycon Alpha, Viasys, Brighton, Sussex, UK), which were calibrated using gases of known concentration. Expiratory volumes were determined using a turbine volume transducer (Viasys) that was calibrated using a 3-l syringe. Computer integration of volume and gas concentration signals accounted for the delay in gas passing through the capillary line. Respiratory gas exchange variables (oxygen uptake, carbon dioxide production and minute ventilation) were calculated and displayed for every breath and averaged over the final full minute of each exercise intensity. The $\dot{V}O_{2max}$ was defined as being the highest 30 s average achieved during the 4 min maximal test (coefficient of variation for this laboratory = 5.5%). Oxygen cost of movement (ECON) was assessed by calculating the mean oxygen uptake per watt (mL/W) of the submaximal stages (coefficient of variation = 7.5%).

Solving the regression equation describing $\dot{V}O_2$ and power for the five incremental intensities of exercise calculated the power associated with $\dot{V}O_{2max}$ ($W_{VO_{2max}}$). A sample of capillary blood drawn from the earlobe was taken at the end of each stage and assayed for lactate (Analox GM7, London, UK). Plots of [La–]b against power were inspected for a nonlinear increase in [La–]b taken as a power at lactate threshold (W_{LT}), The power outputs associated with [La–]b of 2, 3 and 4 mmol/L were determined by interpolation. Heart rate was recorded using telemetry (Polar Electro, Oy, Kempele, Finland). All 2000 m time trials on the ergometer were performed on selected Concept IIC ergometers as a criterion assessment for the domestic governing body, using a drag factor of 138–140. All 2000 m tests were performed within 15 days of the laboratory visit.

Statistical methods

Pearson's product moment correlations was used to examine the relationship between individual physiological variables and 2000 m performance speed for men and women both separately and combined.

As 2000 m rowing speed increases in proportion to the rate of energy expended by the rower but will also be limited by the drag/resistance of the ergometer, our initial model to explain 2000 m rowing ergometer speed was based on the following proportional (curvilinear) allometric or power-function models (Nevill et al., 2006; Ingham et al., 2008),

$$\text{Rowing speed (m/s)} = a\,(W_{VO_{2max}})^{k_1}\,\varepsilon \qquad [1]$$

where $W_{VO_{2max}}$ is the power at $\dot{V}O_{2max}$, "a" is a constant and "k_1" is the exponents likely to provide the best predictor of rowing speed, and "ε" is the multiplicative error ratio.

Further determinants, known to be proportional to 2000 m rowing speed, can be added to the allometric model (eqn. [1]) and backward elimination (see Draper & Smith, 1981, Chapter 6, for a discussion of this and other methods) will be used to obtain the parsimonious model, i.e. at each step, the least important variable is dropped from the current model until all remaining predictor variables make a significant contribution to the final "parsimonious" model.

The model (eqn. [1]) can be linearized with a log-transformation, and linear regression can be used to estimate un-

Table 1. The physical characteristics (means ± standard deviations) of the rowers, grouped according to sex and rowing weight class

	HWT men	± SD	LWT men	± SD	HWT women	± SD	LWT women	± SD
N	33		15		21		7	
Age (years)	23.3	3.2	24.9	5.0	26.1	4.9	25.1	4.1
Height (cm)	192.4	5.4	181.3	4.1	179.4	4.9	167.8	1.6
Body mass (kg)	94.7	5.9	74.5	2.8	75.7	5.2	59.5	1.9
Body fat (%)	12.6	2.7	10.7	2.7	22.4	3.0	19.4	2.3

SD, standard deviation; HWT, heavy-weight rowers; LTW, light-weight rowers.

known parameters a and k_1. The log-transformed model becomes,

$$\log_e(\text{speed}) = \log_e(a) + k_1 \log_e(W_{VO_{2max}}) + \log_e(\varepsilon). \quad [2]$$

The parameter "a" can be allowed to vary between groups (e.g. sex and weight class), thus conducting a form of analysis of covariance (ANCOVA).

Results

The mean 2000 m ergometer performance time (s), speed (m/s), $\dot{V}O_{2max}$, economy (ECON), peak power (W_{max}), peak force (F_{max}), power at max $\dot{V}O_{2max}$ ($W_{VO_{2max}}$), power at 2 mmol/L ($W_{2\,mmol}$), power at 3 mmols/L ($W_{3\,mmol}$), power at 4 mmols/L ($W_{4\,mmol}$) and VO_2 at lactate threshold (VO_{2LT}), grouped by sex and weight class, are given in Table 2.

Table 3 presents the correlation coefficients for likely determinants with rowing ergometer speed for men and women separately and for all rowers combined.

ANOVA identified a difference in the mean ($\pm$ SEE) rowing speeds by weight class ($P<0.001$) and sex ($P<0.001$) but with no interaction ($P>0.05$), Fig. 1.

As an initial exploration into the determinants of 2000 m rowing speed using the log-transformed model (eqn. [2]), ANCOVA identified significant differences in rowing speeds due to the main effects "sex" and "weight class" (both $P = 0.001$) but with no sex-by-weight-class interaction. The ANCOVA also identified power at $\dot{V}O_{2max}$ ($W_{VO_{2max}}$) as a significant covariate of 2000 m rowing speeds ($P<0.0001$). The proportional allometric models can be expressed as

$$\text{Rowing speed (HWT men)} = 1.079\,(W_{VO_{2max}})^{0.28},$$
$$\text{Rowing speed (LWT men)} = 1.058\,(W_{VO_{2max}})^{0.28},$$
$$\text{Rowing speed (HWT women)} = 1.039\,(W_{VO_{2max}})^{0.28},$$
$$\text{Rowing speed (LWT women)} = 1.019\,(W_{VO_{2max}})^{0.28},$$

with $R^2 = 95.3\%$ ($k_1 = 0.28$, SEE $= \pm 0.024$) and the error ratio (the standard deviation of residuals about the fitted log-linear regression model, eqn [1]), $s = 0.0167\%$ or 1.69%, having taken antilogs.

To demonstrate the curvilinear nature of these models, the rowing speeds for the male and female HWT and LWT rowers plus the fitted allometric models are plotted in Fig. 2. Note the spread of data around the fitted curvilinear models demonstrate a "shot-gun" effect, confirming the need to incorporate a multiplicative error term "ε," that increases proportionally with the size of $W_{VO_{2max}}$ [see (eqn. [1])].

When all the variables identified in the correlation matrix (Table 3) were added to the model (eqn. [1]), backward elimination revealed the following allometric model to be the parsimonious solution to predict 2000 m rowing speed:

$$\text{Rowing speed} = 0.842\,(W_{VO_{2max}})^{0.22} \times (W_{max})^{0.073}\,VO_{2LT}^{\;0.072} \quad [3]$$

that explained $R^2 = 96.16\%$ ($k_1 = 0.22$ SEE $= \pm 0.024$, $k_2 = 0.073$ SEE $= \pm 0.019$, $k_3 = 0.072$ SEE $= \pm 0.019$) and the error ratio (the standard deviation of residuals about the fitted log-linear regression model, eqn. [1]), $s = 0.0152\%$ or 1.53%, having taken antilogs. The above model was common to all rowers irrespective of sex and weight class.

Table 3. Correlation coefficients (r) for likely determinants with rowing ergometer speed for men and women separately and for all rowers combined

	Women	Men	All
$\dot{V}O_{2max}$ (L/min)	0.74	0.82	0.94
ECON (ml/W)	– 0.46	– 0.02	– 0.33
$W_{VO_{2max}}$ (W)	0.92	0.84	0.96
W_{max} (W)	0.69	0.82	0.94
F_{max} (N)	0.69	0.81	0.93
$W_{2\,mmol}$ (W)	0.78	0.77	0.92
$W_{3\,mmol}$ (W)	0.82	0.75	0.92
$W_{4\,mmol}$ (W)	0.84	0.73	0.91
VO_{2LT} (L/min)	0.45	0.83	0.92

Table 2. The mean 2000 m ergometer performance time (s), speed (m/s), $\dot{V}O_{2max}$, economy (ECON), peak power (W_{max}), peak force (F_{max}), power at VO_{2max} ($W_{VO_{2max}}$), power at 2 mmols/l ($W_{2\,mmol}$), power at 3 mmols/l ($W_{3\,mmol}$), power at 4 mmols/l ($W_{4\,mmol}$) and VO_2 at lactate threshold (VO_{2LT}), grouped by sex and weight class

	HWT men	SD	LWT men	SD	HWT women	SD	LWT women	SD
2000 m time (s)	361.1	9.5	381.3	6.8	416.7	15.7	435.4	11.3
Speed (m/s)	5.5	0.1	5.2	0.1	4.8	0.2	4.6	0.1
$\dot{V}O_{2max}$ (L/min)	5.84	0.45	5.08	0.40	4.13	0.30	3.71	0.19
ECON (ml/W)	15.31	0.92	14.98	0.69	15.74	0.72	15.71	1.19
$W_{VO_{2max}}$ (W)	382.6	33.5	339.4	25.7	262.7	22.5	236.9	13.0
W_{max} (W)	636.0	40.4	508.2	40.6	418.6	45.4	334.6	19.4
F_{max} (N)	779.0	44.7	646.3	39.6	551.0	46.1	475.0	31.1
$W_{2\,mmol}$ (W)	320.4	34.1	283.1	27.5	225.4	23.3	205.6	18.1
$W_{3\,mmol}$ (W)	346.7	37.0	307.8	31.4	245.3	23.4	223.0	19.3
$W_{4\,mmol}$ (W)	367.8	39.7	327.3	34.7	261.6	24.4	237.7	20.2
VO_{2LT} (L/min)	4.5	0.4	3.8	0.4	3.1	0.3	2.8	0.2

SD, standard deviation; HWT, heavy-weight rowers; LTW, light-weight rowers.

Discussion

The current findings provide a novel insight into the relationship between physiological variables and 2000 m ergometer rowing performance. Previous work has adopted correlations or linear regression methods to identify either peak-power output (W_{max}) (Bourdin et al., 2004) or power at $\dot{V}O_{2max}$ (Ingham et al., 2002) as the best single predictors of 2000 m rowing ergometer performance. The present study also adopted correlations to initially explore the likely physiological determinants of 2000 m rowing ergometer performance speed, identifying power at $\dot{V}O_{2max}$ ($W_{VO_{2max}}$) as the best single predictor of indoor rowing performance (Table 3).

However, in contrast with previous linear methods, the current study adopted more appropriate proportional, allometric models to explore these associations. As anticipated, when we entered power at $\dot{V}O_{2max}$ ($W_{VO_{2max}}$) into the allometric model (eqn. [1]) to predict rowing ergometer speed, the model was demonstrably curvilinear (Fig. 1), proportional to $(W_{VO_{2max}})^{0.28}$, that explained 95.3% of the variance in rowing ergometer performance speed. At this early stage of the modelling process, significant differences remained between both levels of the main effects "sex" and "weight class" using $W_{VO_{2max}}$ as the only covariate.

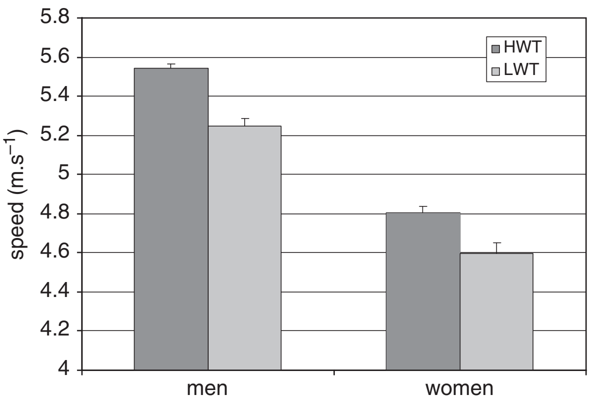

Fig. 1. The mean (± SEE) rowing speeds of heavy weight (HWT) vs light weight (LWT) rowers ($P<0.001$), by sex ($P<0.001$) but with no interaction ($P>0.05$).

The model has a practical advantage for the coach and sports scientist. Given a rower's power at $\dot{V}O_{2max}$ ($W_{VO_{2max}}$), we can use the curvilinear model (eqn. [1]) to predict the rower's average speed and hence his/her rowing time directly. To appreciate the value of fitting the proposed curvilinear allometric models, consider the following example. Suppose a HWT male rower with a $W_{VO_{2max}}$ of 300 W wishes to increase his mean estimated rowing speed from 5.18 to 5.40 m/s, the model predicts that he would need to increase his $W_{VO_{2max}}$ from 300 to 350 W, an increase of 50 W. In contrast, suppose a second HWT rower with a $W_{VO_{2max}}$ of 400 W wishes to increase his estimated mean speed by the same amount (0.22 m/s) from 5.61 to 5.83 m/s, he would require an increase in $W_{VO_{2max}}$ from 400 to 462 W, i.e., a greater increase in $W_{VO_{2max}}$ (24% more) of 62 W.

The above curvilinear power function exponent, 0.28 [SEE = 0.027, 95% confidence interval (CI) 0.226–0.334], is similar to that derived from known association between a rower's power expended (P) and the speed of the boat (u), given by $P = cu^3$, i.e. $u = (P/c)^{0.33}$ where c is a constant depending on the rowers weight, sex and boat type (http://www.atm.ox.ac.uk/rowing/physics/ergometer.html). Further support for the fitted exponent comes from the known curvilinear association between cycling speed

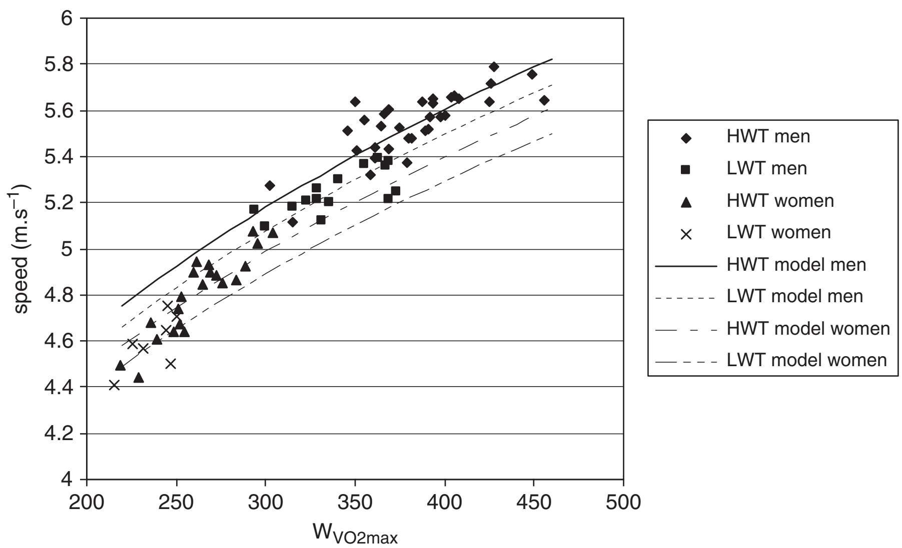

Fig. 2. The rowing speeds for the male and female heavy weight (HWT) and light weight (LWT) rowers plus their fitted allometric models.

and energy expenditure (Nevill et al., 2005). On level ground, the power demand of cycling (also predominantly due to air resistance) is thought to be proportional to the cube of the cyclists' speed (Olds et al., 1995). Consequently, the speed of a cyclist should also be proportional to the cube root (0.33) of the power expended.

One of the most insightful finding of the modelling process reported above came from the backward elimination of likely determinants of indoor rowing performance (variables reported in Table 2). The parsimonious solutions (eqn. [3]) identified $W_{VO_{2max}}$ as before, plus two additional covariates that made significant contributions to rowing ergometer performance speed, these being peak power (W_{max}) recorded over five maximal strokes and VO_2 at lactate threshold (VO_{2LT}).

As described earlier, 2000 m rowing ergometer performance depends on the functional capacity of both the aerobic and anaerobic energy pathways (Secher, 1973). The parsimonious model (eqn. [3]) would appear to confirm the need for high functionality from both pathways. The maximum power output (W_{max}) averaged over the five maximal strokes will provide an estimate of anaerobic capability. The two components of $W_{VO_{2max}}$ and VO_2 at lactate threshold (VO_{2LT}) will both provide estimates of aerobic energy supply. Together, the selection of aerobic and anaerobic variables in the model that explained $R^2 = 96.16\%$ of rowing ergometer speed confirm the need and describe the interplay between the dual aerobic and anaerobic energy pathways when performing a 2000 m rowing ergometer performance trials. We do recognize, however, that the energy demands of ergometer rowing are very complex. For example, even the energy required to move the seat back and forth could help to account for some of the unexplained (3.84%) variance.

A further reassuring aspect of the parsimonious model (eqn. [3]) was the absence of the grouping effects, "sex" and "weight class." When only the aerobic component of power at $\dot{V}O_{2max}$ ($W_{VO_{2max}}$) was incorporated into our initial exploration of the determinants of 2000 m rowing, the model was inadequate, incapable of explaining the differences due to "sex" and "weight class." Simply by incorporating further aspects of energy supply, in particular maximum power (W_{max}), the more complete or comprehensive model (eqn. [3]) were common to all rowers, i.e. the models were able to explain the rowing performances of all athletes, irrespective of sex and weight class.

Given that the present study predicts rowing ergometer speed based on a range of different work determinants, the absence of these group differences might well have been anticipated. We recognize that the stepwise linear regression model reported by Ingham et al. (2002) with $R^2 > 98\%$, was also absent of the grouping factors "sex" and "weight class." However, the fact that the model reports a rowing speed intercept of 3.26 (m/s) for zero values of the predictors (e.g., power outputs) further highlights the limitations of fitting and reporting such linear models.

A similar absence of the grouping effect "sex" was identified by Nevill et al. (2008) when reporting relative contributions of anaerobic and aerobic energy supply during 100, 400 and 800 m track running performance. Using accumulated oxygen deficit (AOD) and $\dot{V}O_{2max}$ to predict running performances, the three regression models were able to confirm that once the researchers had controlled for differences in the dominant energy supplies of AOD and $\dot{V}O_{2max}$, there was no significant difference between men and women's running speeds. It would appear that 100, 400 and 800 m track running performances as well as 2000 m rowing performances can be determined entirely by the appropriate contributions of aerobic and anaerobic energy supply, irrespective of the athletes' gender and size.

Recently, Nevill et al. (2009), was able to demonstrate that in order to predict single sculling rowing speed of elite junior male rowers on water, a greatly improved prediction was obtained by including a combination (as a ratio) of both Concept II rowing ergometer performance and body mass (m). The authors found that water-based rowing speed (m/s) was proportional to the following ratio (allometric model), $\cdot$ [ergometer speed]$^{1.87}m^{-0.425}$. If, as reported above, the best single predictor of rowing ergometer speed is $(W_{VO_{2max}})^{0.28}$, we can estimate that single sculling rowing speed is likely to be proportional to [ergometer speed]$^{1.87}m^{-0.425} = [(W_{VO_{2max}})^{0.28}]^{1.87} m^{-0.425} = (W_{VO_{2max}})^{0.52}m^{-0.425}$. As reported above, 2000 m rowing ergometer speed is dependent on absolute aerobic and anaerobic power output that are both known to benefit from *greater* body mass. In contrast, it would appear that single sculling rowing speed in water is likely to be dependent on a greater power-to-weight ratio, given by $(W_{VO_{2max}})^{0.52}m^{-0.425}$ or $(W_{VO_{2max}}m^{-0.82})^{0.52}$. We do recognize, however, that this power-to-weight ratio is somewhat speculative, given that the ratio has been derived from data taken from two separate studies. In order to establish whether this power-to-weight ratio optimally predicts rowing in water, preferably all data (power output plus the ergometer and water based rowing performances) should be obtained from the same rowers.

Similar to our work, several researchers have proposed performance determinant models that consider a contribution from a low-intensity metabolic "threshold"; a maximal and/or functional aerobic capacity; and where possible an indicator of anaerobic/maximal power capability (in this study, $\dot{V}O_{2LT}$, $W_{VO_{2max}}$, W_{max}, respectively), (Coyle, 1995; Jones & Carter, 2000; e.g. Heugas et al., 2006). These approaches have shown some variation in the factors deemed important and deterministic to middle distance performance. However, commonality is found in the selection of parameters/capabilities from along the breadth of the exercise intensity continuum. Physiologically, the contribution of wide ranging abilities makes particular logical sense considering the need for high capacity from aerobic and anaerobic ATP resynthesis pathways for overall middle distance performance.

Perspectives

Previous studies have investigated the determinants of indoor rowing using correlations and linear models. Linear models however assume that for a similar increase in power, the same improvement in rowing speed will result irrespective of the rower's level of performance (e.g. elite, club standards). The proposed allometric model more realistically describes the greater increase in power required to improve a rower's speed at an elite level, compared with that required of a club-standard rower at a slower speed. The best single predictor of Concept II rowing ergometer performance was found to be the power at $\dot{V}O_{2max}$ $(W_{VO_{2max}})^{0.28}$, that was able to explain 95.3% of the variance in rowing speed. The fitted exponent, 0.28 (95% CI 0.226–0.334) is similar to the exponent 0.33, based on the assumption that theoretically a rower's speed is proportional to the cube root (0.33) of the power expended. Furthermore, simply, by incorporating both anaerobic as well as further aerobic determinants, the allometric curvilinear model identified power at $\dot{V}O_{2max}$ ($W_{VO_{2max}}$), plus peak power (W_{max}) and VO_2 at lactate threshold (VO_{2LT}) as key proportional determinants of 2000 m rowing performance that was common to all rowers, irrespective of sex and weight class.

Key words: rowing ergometer performance, power at $\dot{V}O_{2max}$ ($W_{VO_{2max}}$), allometric models, curvilinear power function.

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