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The relationship between selected physiological variables of rowers and rowing performance as determined by a 2000 m ergometer test

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The aim of this study was to establish the relationship between selected physiological variables of rowers and rowing performance as determined by a 2000 m time-trial on a Concept II Model B rowing ergometer. The participants were 13 male club standard oarsmen. Their mean (± *s*) age, body mass and height were 19.9 ± 0.6 years, 73.1 ± 6.6 kg and 180.5 ± 4.6 cm respectively. The participants were tested on the rowing ergometer to determine their maximal oxygen uptake ($\dot{V}O_{2max}$), rowing economy, predicted velocity at $\dot{V}O_{2max}$, velocity and $\dot{V}O_2$ at the lactate threshold, and their velocity and $\dot{V}O_2$ at a blood lactate concentration of 4 $mmol \cdot l^{-1}$. Percent body fat was estimated using the skinfold method. The velocity for the 2000 m performance test and the predicted velocities at the lactate threshold, at a blood lactate concentration of 4 $mmol \cdot l^{-1}$ and at $\dot{V}O_{2max}$ were 4.7 ± 0.2, 3.9 ± 0.2, 4.2 ± 0.2 and 4.6 ± 0.2 $m \cdot s^{-1}$ respectively. A repeated-measures analysis of variance showed that the three predicted velocities were all significantly different from each other ($P < 0.05$). The $\dot{V}O_{2max}$ and lean body mass showed the highest correlation with the velocity for the 2000 m time-trial ($r = 0.85$). A stepwise multiple regression showed that $\dot{V}O_{2max}$ was the best single predictor of the velocity for the 2000 m time-trial; a model incorporating $\dot{V}O_{2max}$ explained 72% of the variability in 2000 m rowing performance. Our results suggest that rowers should devote time to the improvement of $\dot{V}O_{2max}$ and lean body mass.

Keywords: lactate threshold, maximal oxygen uptake, rowing, rowing economy, velocity at $\dot{V}O_{2max}$.

Introduction

Researchers have examined such physiological factors as the importance of lactate exchange and removal (Messonnier *et al.*, 1997), the effects of training on rowing ergometer performance (Womack *et al.*, 1996), the effectiveness of altitude training on sea-level rowing performance (Jensen *et al.*, 1993) and the determination of the anaerobic threshold using a non-invasive method (Droghetti, 1986). Although these studies have contributed to the scientific understanding of rowing, limited information is available on the relationship between physiological variables of rowers and rowing performance. Relating physiological variables to performance could be valuable for designing training programmes and for team selection.

During a 2000 m race, rowers are mainly dependent on aerobic metabolism, as the duration of the race is 6–7 min, depending on the type of boat and the standard of the rowers. The relative contribution to the total energy demand of a 2000 m race is about 70% aerobic and 30% anaerobic (Mickelson and Hagerman, 1982; Roth *et al.*, 1983).

The performance of a crew can be measured by their 2000 m race time. However, it is very difficult to assess physiological parameters during 'on-water' rowing. The impracticality of measuring physiological performance during rowing has led to the use of rowing ergometers for the assessment of rowing performance. The most widely used ergometer for training purposes is the Concept II wind resistance braked rowing ergometer (Concept II, Nottingham, UK). Craven *et al.* (1993) analysed the rowing stroke on a Concept II rowing ergometer and concluded that it 'provides a close approximation to the movements of the rowing stroke, and allows accurate measurements of the physiological

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changes produced by the work'. The Concept II allows standardization of testing, which is not possible during 'on-water' rowing.

Several studies have compared the physiological characteristics of elite rowers to less skilled rowers, suggesting that elite rowers have a higher maximal oxygen uptake ($\dot{V}O_{2max}$; Secher *et al.*, 1982), a larger percentage of slow-twitch muscle fibres (Roth *et al.*, 1983), a greater body mass (Secher, 1983) and a higher $\dot{V}O_{2max}$ at a blood lactate concentration of 4 $mmol \cdot l^{-1}$ than less skilled rowers (Roth *et al.*, 1983; Marx, 1988). Kramer *et al.* (1994) studied various descriptive, field and laboratory variables of 20 Canadian intercollegiate oarswomen and examined the relationship of these variables to performance. Of the variables tested, only absolute $\dot{V}O_{2max}$ had a correlation coefficient greater than 0.71 with performance.

Economy is defined as the volume of oxygen consumed by the working musculature at a given steady-state workload. This has received little attention in rowing research. Only one study (MacLennan *et al.*, 1994) has investigated the economy of rowing; unfortunately, the participants in the study had no rowing experience and were taught how to use a rowing ergometer. In contrast to research on rowing, several studies have examined running economy. However, the evidence is conflicting as to whether running economy is a good predictor of performance. The more heterogeneous the group, the better the prediction of endurance performance is likely to be (Wilcox and Bulbulian, 1983).

The velocity at $\dot{V}O_{2max}$ has been defined in a variety of ways and several protocols have been used to determine it (Hill and Rowell, 1996). Daniels (1985) used the linear extrapolation of the submaximal steady-state oxygen uptake–velocity relationship to estimate the velocity at $\dot{V}O_{2max}$ in runners. Daniels (1985) and Hill and Rowell (1996) both reported that the velocity at $\dot{V}O_{2max}$ is a good predictor of endurance running performance; no study has examined this velocity in rowers.

In endurance running and cycling events, blood lactate variables have been shown to be the best predictors of performance over a wide range of distances (Weltman, 1995). Wolf and Roth (1987) found that the power which elicits a blood lactate concentration of 4 $mmol \cdot l^{-1}$ is the best predictor of competition performance in trained rowers, especially those who compete in small boats. Others have demonstrated that rowers with high absolute $\dot{V}O_2$ at a blood lactate concentration of 4 $mmol \cdot l^{-1}$ perform better in 6 or 7 min maximal tests than rowers with low $\dot{V}O_2$ at the same blood lactate concentration (Roth, 1979; Marx, 1988). The higher $\dot{V}O_2$ of less skilled rowers at a blood lactate concentration of 4 $mmol \cdot l^{-1}$ suggests that they are likely to fatigue earlier than elite rowers. A possible mechanism for this fatigue is a decrease in intracellular pH resulting from glycolysis and H^+ accumulation, which has been shown to interfere with the myosin and actin interaction and to result in a decrease in force production (Jones and Round, 1990).

The aim of this study was to examine the relationship between selected physiological variables of male rowers and rowing performance as determined by a 2000 m time-trial.

Methods

Participants

Thirteen male rowers from Glasgow University Boat Club volunteered to participate. They all had experience of competitive rowing over 2000 m, ranging from 1 to 9 years, and were club standard oarsmen of varying ability. All participants trained regularly on a Concept II rowing ergometer. Informed consent was obtained from all participants and ethical approval was received from the University of Glasgow Ethical Committee. The characteristics of the participants are given in Table 1.

Protocol

The participants performed three tests on separate days with at least 2 days between tests; however, each individual completed all three tests within 14 days. On day 1, height, body mass, percent body fat (Durnin and Womersley, 1974) and $\dot{V}O_{2max}$ were measured. On day 2, a lactate profile and rowing economy test were performed; on day 3, a performance test was completed.

Equipment

A Concept II Model B rowing ergometer (Concept II, Nottingham, UK) was used for all tests. During testing, the larger of the two drive cogs was used and the vanes were kept fully closed.

Heart rate was monitored using a Sport Tester™ PE3000 heart rate monitor (Polar Electro, Kempele, Finland). As a precautionary measure during the maximal test, a Hewlett Packard 43200A ECG monitor was used.

Table 1 Characteristics of the participants (mean ± *s*)

Age (years)	19.9 ± 0.6
Height (cm)	181 ± 5
Body mass (kg)	73.1 ± 6.6
Body fat (%)	16.1 ± 3.3
Lean body mass (kg)	60.9 ± 5.2
$\dot{V}O_{2max}$ ($l \cdot min^{-1}$)	4.5 ± 0.4

For gas analysis, expired air was collected in Douglas bags. The samples were passed through a drying tube and then analysed using a PK Morgan 801D (Morgan, Rainham, UK) and Servomex 570A (Servomex, Crowborough, UK) system to determine carbon dioxide and oxygen content respectively. Volume was calculated using a Parkinson Cowan volume meter (Cranlea, Birmingham, UK) calibrated against a Tissot spirometer (Collins, Massachusetts, USA). From these data, $\dot{V}O_2$ and respiratory values were calculated.

Whole blood was analysed for blood lactate using an Analox GM7 (Analox Instruments, London, UK).

Procedures

The time to complete 500 m at the current intensity and stroke rate (500 m split time) was calculated and displayed on the ergometer. The stroke rate was limited to 24–28 strokes $\cdot$ min^{-1} at 500 m split times of 2 min or more. At 500 m split times less than 2 min, the stroke rate was increased to 28–32 strokes $\cdot$ min^{-1}. This allowed the intensity to be increased so that the 500 m split time could be reduced to the desired value.

The restriction on stroke rate resulted in the exercise intensity being kept constant for each stage and for all participants (Mickelson and Hagerman, 1982). There were slight deviations in intensity, owing to a combination of individual variation in stroke rate and the inability to keep 500 m split time constant. Such problems are inherent in the design of the rowing ergometer and the mechanics of the rowing stroke (Mickelson and Hagerman, 1982).

A warm-up of 6 min at a 500 m split time of 2 min 30 s was performed by all participants before all tests. The participants then rested for 6 min, during which time they performed stretching exercises.

Percent body fat. The percent body fat of each participant was estimated using skinfold measurements. Skinfolds were measured using a Holtain caliper (Crosswell, Crymych, UK) following the method of Durnin and Womersley (1974).

$\dot{V}O_{2max}$ test. The participants performed a continuous incremental test to volitional exhaustion. The target duration of the test was 8–14 min. The test began with each participant exercising at a 500 m split time of 2 min 30 s. Thereafter, the split time was decreased by 5 s each minute until the participant reached volitional exhaustion. Heart rate was measured after 50 s at each exercise intensity. Once heart rate reached 170 beats $\cdot$ min^{-1}, sampling of expired gas began. Expired gas samples were collected for 1 min at each exercise intensity after this time.

Blood samples were taken from the tip of the thumb for lactate analysis at 1, 3 and 5 min after the $\dot{V}O_{2max}$ test. Two analyses were performed on each sample and the mean of the two was taken as the blood lactate concentration.

Determination of the velocity at $\dot{V}O_{2max}$. The velocity at $\dot{V}O_{2max}$ was calculated following the method recommended by Hill and Rowell (1996) to be the most accurate and appropriate for evaluating performance; that is, the linear extrapolation of the submaximal velocity–$\dot{V}O_2$ relationship.

Blood lactate profile and rowing economy test. Blood lactate concentration and rowing economy were measured using a discontinuous incremental submaximal test. The test involves a target of five stages of 5 min exercise each. The 500 m split time for the first stage was determined for each individual from the results of his $\dot{V}O_{2max}$ test. The starting split times ranged from 2 min 30 s for the rowers with the lowest $\dot{V}O_{2max}$ to 2 min 15 s for those with the highest $\dot{V}O_{2max}$. Each subsequent stage was 5 s faster than the previous one. A 30 s rest was allowed between each stage, during which a blood sample was taken from the tip of the thumb for lactate analysis. The test continued until the average blood lactate for a given stage reached 4 mmol $\cdot$ l^{-1} or more.

One-minute expired gas samples were collected between the third and fourth and the fourth and fifth minutes of each stage to assess rowing economy. The mean of these two values was recorded for each stage. Heart rate was measured 50 s into each minute of the test.

Determination of the physiological parameters. Velocity and $\dot{V}O_2$ were determined at the lactate threshold and at a blood lactate concentration of 4 mmol $\cdot$ l^{-1}. Blood lactate concentrations were plotted against the 500 m split times at which they were produced. To achieve objectivity, a mathematical regression analysis was used to model the relationship between lactate and rowing velocity (Orr *et al.*, 1982). The lactate threshold was defined as the inflection point of the lactate profile which indicated a sharp increase in blood lactate concentration (Kindermann *et al.*, 1979). A blood lactate concentration of 4 mmol $\cdot$ l^{-1} was determined from the velocity and $\dot{V}O_2$ that corresponded to a blood lactate of 4 mmol $\cdot$ l^{-1}. Two horizontal lines were drawn across from the predetermined lactate threshold and 4 mmol $\cdot$ l^{-1} concentration to intercept with the blood lactate values on the vertical axis. From these points, lines perpendicular to the intercepts were drawn down to the horizontal axis to obtain the velocity and $\dot{V}O_2$ for individual lactate thresholds and 4 mmol $\cdot$ l^{-1} blood lactate concentrations.

Rowing performance. Rowing performance was assessed by a 2000 m time-trial on the Concept II rowing ergometer. Heart rate was measured 50 s into each minute and on completion of the test. Thumb prick blood samples for lactate analysis were taken 1, 3 and 5 min after the 2000 m for comparison with values obtained for the $\dot{V}O_{2max}$ test.

Statistical analyses

Initially, a repeated-measures analysis of variance with an appropriate Bonferroni multiple comparisons follow-up was performed to identify any significant differences at the $P < 0.05$ level between the velocity for the 2000 m time-trial and the predicted velocities at the lactate threshold, at a blood lactate concentration of 4 $mmol \cdot l^{-1}$ and at $\dot{V}O_{2max}$.

Pearson correlation coefficients were used to examine the interrelationships between variables. From these simple linear regressions, a subset of the initial physiological variables (the nine variables in Table 3 showing a statistically significant relationship with velocity in the 2000 m time-trial, $P < 0.05$) were entered into a forward stepwise multiple linear regression using a variable selection procedure with time-trial velocity as the response variable. This showed which of these variables were collectively important in the prediction of time-trial velocity.

Results

$\dot{V}O_{2max}$ test

Despite the relatively low body masses of the participants, some high $\dot{V}O_{2max}$ values were recorded, the sample mean being $4.5 \pm 0.4\ l \cdot min^{-1}$. Absolute $\dot{V}O_{2max}$ ($l \cdot min^{-1}$) correlated well with velocity in the 2000 m time-trial ($r = 0.85$), the participants with higher values generally performing quicker (Fig. 1a). However, the relative values ($ml \cdot kg^{-1} \cdot min^{-1}$) did not correlate well with time-trial velocity ($r = 0.13$). The correlation between $\dot{V}O_{2max}$ divided by lean body mass and the time-trial velocity was $r = 0.01$; that between $\dot{V}O_{2max}$ expressed in $ml \cdot kg^{-2/3} \cdot min^{-1}$ and time-trial velocity was $r = -0.05$.

Rowing economy

As a result of the variation in starting velocity and individual differences in ability, only three stages at the same velocity were completed by all participants. Economy values were spread over a narrow range at all three velocities (Table 2). The $\dot{V}O_2$ at a 500 m split time of 2 min 5 s resulted in the most significant negative correlation with velocity in the 2000 m time-trial ($r = 0.62$). The other two intensities completed by all participants showed poorer correlations with time-trial velocity: $r = -0.20$ at a 500 m split time of 2 min 15 s and $r = -0.51$ at a 500 m split time of 2 min 10 s.

To assess the accuracy of the method used to determine rowing economy, a related *t*-test was performed on the $\dot{V}O_2$ values recorded in the fourth and fifth minute of each stage for each participant to identify any significant difference between the two values. This would confirm if a steady-state oxygen consumption had been reached. The differences in oxygen consumption between the fourth and fifth minute of each stage did not reach statistical significance for any participant, indicating that a steady state had been attained.

Predicted velocity at $\dot{V}O_{2max}$

The predicted velocity at $\dot{V}O_{2max}$ correlated well with time-trial velocity ($r = 0.77$; Fig. 1b). In general, the participants who achieved a high predicted velocity at $\dot{V}O_{2max}$ produced faster 2000 m times.

Blood lactate profile

The $\dot{V}O_2$ at the lactate threshold had a non-significant relationship with time-trial velocity ($r = 0.39$), whereas $\dot{V}O_2$ at a blood lactate concentration of 4 $mmol \cdot l^{-1}$ correlated well time-trial velocity ($r = 0.68$). The participants with low values of these two $\dot{V}O_2$ parameters tended to attain these blood lactate concentrations at slow speeds. The predicted velocity at a blood lactate concentration of 4 $mmol \cdot l^{-1}$ had a fairly strong relationship with time-trial velocity ($r = 0.73$).

Performance test

The 2000 m times varied widely, ranging from 6 min 30 s to 7 min 45 s, with speeds between 4.3 and 5.1 $m \cdot s^{-1}$. To maintain a low 500 m split time, the individual must be able to produce a large force during the stroke. Lean body mass was a significant factor ($r = 0.85$; Fig. 1c), as it identified individuals with greater muscle mass.

Statistical analyses

A repeated-measures analysis of variance showed that the velocities for the 2000 m time-trial, at the lactate threshold, at a blood lactate concentration of 4 $mmol \cdot l^{-1}$ and at $\dot{V}O_{2max}$ were different ($P < 0.001$). An appropriate follow-up analysis showed that the velocity for the time-trial was significantly different from the velocities at the lactate threshold and at a blood lactate concentration of 4 $mmol \cdot l^{-1}$, but not significantly different from the velocity at $\dot{V}O_{2max}$. Follow-up analysis also showed that the velocities at the lactate threshold, at

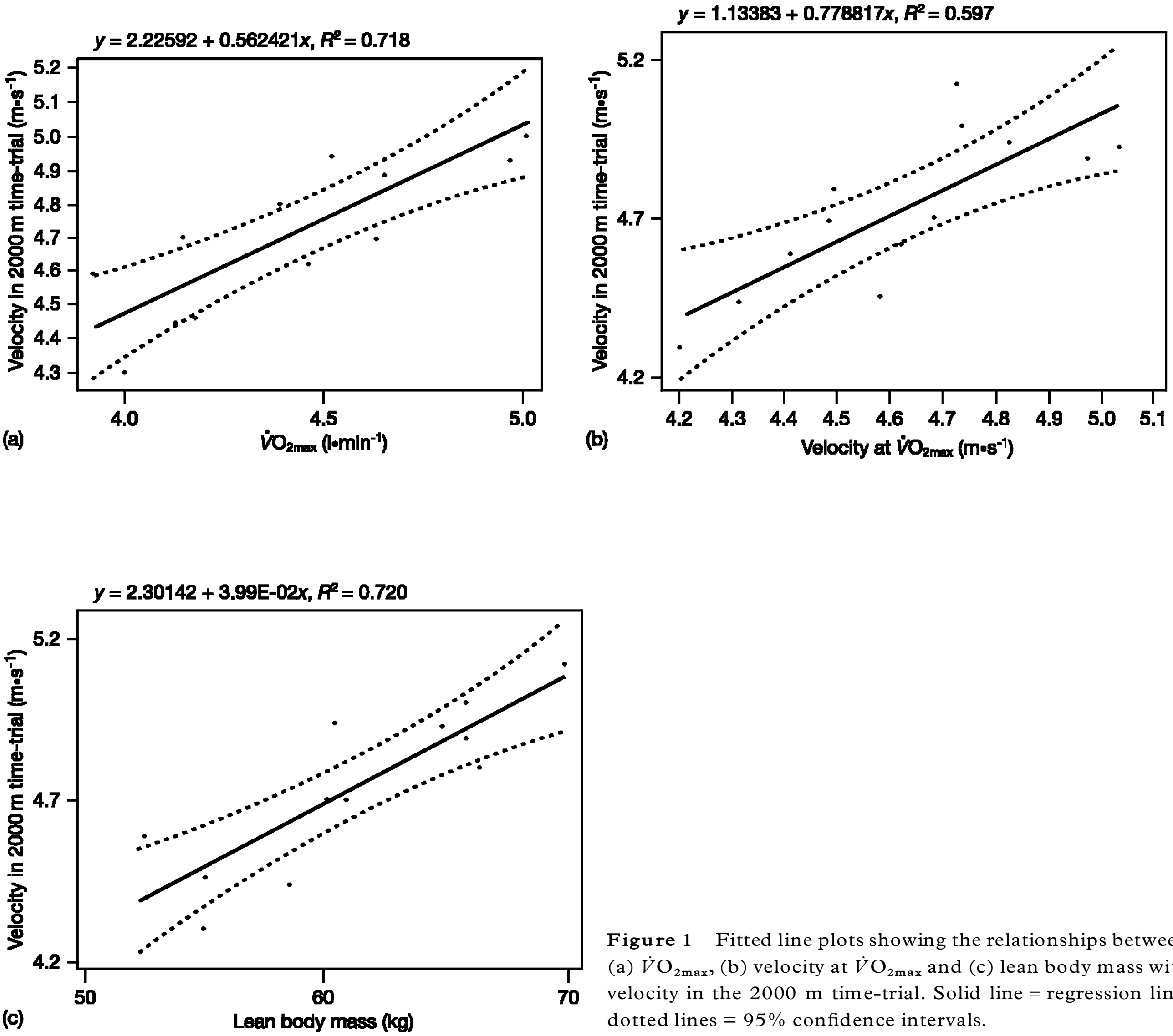

Figure 1 Fitted line plots showing the relationships between (a) $\dot{V}O_{2\max}$, (b) velocity at $\dot{V}O_{2\max}$ and (c) lean body mass with velocity in the 2000 m time-trial. Solid line = regression line; dotted lines = 95% confidence intervals.

a blood lactate of 4 $\text{mmol} \cdot \text{l}^{-1}$ and at $\dot{V}O_{2\max}$ were all significantly different from one another.

Table 3 presents correlation coefficients and P-values for a test of whether the variables had a statistically significant relationship with velocity in the 2000 m time-trials. The most significant relationships were between $\dot{V}O_{2\max}$ and time-trial performance ($r = 0.848$, $P < 0.001$) and between lean body mass and time-trial performance ($r = 0.848$, $P < 0.001$). There were also significant relationships between time-trial performance and endurance in the $\dot{V}O_{2\max}$ test ($r = 0.791$, $P = 0.001$), the highest value obtained in the velocity at $\dot{V}O_{2\max}$ test ($r = 0.773$, $P = 0.002$), and velocity at a blood lactate concentration of 4 $\text{mmol} \cdot \text{l}^{-1}$ ($r = 0.734$, $P = 0.004$). Less significant relationships were noted between time-trial performance and body mass, the lactate maximum 5 min after the $\dot{V}O_{2\max}$ test, and the lactate maximum 5 min after the performance test ($r = 0.698$, $P = 0.008$; $r = 0.579$, $P = 0.038$; $r = 0.584$, $P = 0.036$, respectively). The three rowing economy variables all showed a negative relationship with performance, although only rowing economy at a 500 m split time of 2 min 5 s displayed statistical significance ($r = -0.62$, $P = 0.024$).

A stepwise multiple regression was carried out with velocity in the 2000 m time-trial as the response variable, and the nine variables that had shown some statistically significant correlation with performance as the explanatory variables. The results of this analysis are presented in Table 4. The analysis showed that $\dot{V}O_{2\max}$ was the best single predictor of time-trial velocity; a model incorporating $\dot{V}O_{2\max}$ explained 72% of the variance in 2000 m rowing performance. The inclusion of blood lactate concentration 5 min after the performance test improved the prediction of time-trial velocity;

Table 2 Economy scores ($l \cdot min^{-1}$) at the three submaximal intensities (500 m split time) completed by all participants

Participant	$\dot{V}O_2$ at 2 : 15 min : s	$\dot{V}O_2$ at 2 : 10 min : s	$\dot{V}O_2$ at 2 : 05 min : s
A	2.60	2.65	3.22
B	2.63	2.94	3.19
C	2.48	2.85	3.17
D	2.68	2.94	3.19
E	2.75	3.10	3.29
F	2.56	2.90	3.19
G	2.80	3.06	3.45
H	2.63	3.14	3.21
I	2.64	3.20	3.45
J	2.74	3.23	3.57
K	2.66	2.99	3.23
L	2.73	3.05	3.34
M	2.68	2.88	3.28
Mean ± *s*	2.66 ± 0.09	2.99 ± 0.16	3.29 ± 0.13

the model with these two predictors explained 87% of the variance in 2000 m rowing performance.

Table 3 Pearson correlation coefficients (*r*) for each variable versus 2000 m time-trial performance *P*-values

Variable	*r*	*P*
Height	0.207	0.497
Body mass	0.698	0.008
Percent body fat	−0.254	0.402
Lean body mass	0.848	< 0.001
$\dot{V}O_{2max}$	0.848	< 0.001
Velocity at $\dot{V}O_{2max}$	0.773	0.002
Endurance time	0.791	0.001
Lactate maximum 5 min after $\dot{V}O_{2max}$ test	0.579	0.038
Rowing economy		
$\dot{V}O_{2max}$ at 2 : 15 min : s	−0.200	0.513
$\dot{V}O_{2max}$ at 2 : 10 min : s	−0.514	0.072
$\dot{V}O_{2max}$ at 2 : 05 min : s	−0.619	0.024
$\dot{V}O_2$ at lactate threshold	0.39	0.190
Velocity at lactate threshold	0.39	0.190
$\dot{V}O_2$ at 4 $mmol \cdot l^{-1}$	0.68	0.011
Velocity at 4 $mmol \cdot l^{-1}$	0.734	0.004
Lactate maximum 5 min after the performance test	0.584	0.036

Table 4 Stepwise multiple regression with 2000 m performance as the response variable

Step	Variable entered	R^2	Beta weights
	Constant		1.96
1	$\dot{V}O_{2max}$	0.720	0.497
2	Lactate maximum 5 min after performance test	0.870	0.0499

Discussion

The main finding of this study is that $\dot{V}O_{2max}$ and lean body mass are the best predictors of rowing performance, indicating their importance for success in rowing. The strong correlation between absolute $\dot{V}O_{2max}$ and velocity in the 2000 m time-trial ($r = 0.85$, $P < 0.001$) is in line with the results of Secher *et al.* (1982), Secher (1983) and Kramer *et al.* (1994). Steinacker (1993) emphasized that a high oxidative capacity is needed to maintain a high speed throughout a race. Although a high $\dot{V}O_{2max}$ is a good predictor of rowing performance, there was a poor relationship with relative $\dot{V}O_{2max}$ ($ml \cdot kg \cdot min^{-1}$). The large body mass of elite rowers results in a low relative $\dot{V}O_{2max}$ compared with elite endurance runners. A large muscle mass does not penalize rowers, whose body weight is supported in the boat.

Nevill *et al.* (1992) showed that rowing performance is related to both $\dot{V}O_{2max}$ and body mass and that these two variables are directly related. Secher (1983) reported that rowers with a large body mass are at an advantage, quoting an average value of 93 kg for international oarsmen. The mean body mass of the present rowers was much lower (73 kg), but did show a fairly strong relationship with velocity in the 2000 m time-trial ($r = 0.70$). The correlation between time-trial velocity and lean body mass, and between time-trial velocity at $\dot{V}O_{2max}$, was 0.85. However, some doubt exists regarding the validity of calculating lean body mass using a skinfold technique. Consequently, one should have some reservations about the strength of the relationship between lean body mass and rowing performance. There is some error in the Durnin and Womersley (1974) method of estimating body fat, indicating that caution should be exercised when the relationship between lean body mass and rowing performance is examined. The equations of Durnin and Womersley were based on a West of Scotland population. As we recruited participants from the same region, we considered it appropriate to use their equations. As $\dot{V}O_{2max}$ and lean body mass were highly correlated and had the same correlation coefficient with time-trial velocity, we decided to force $\dot{V}O_{2max}$ into the regression model.

During the performance tests, we noted that the rowers who were able to obtain lower 500 m split times tended to produce faster performance times. Obtaining a low 500 m split time involves an element of dynamic strength and the ability to produce a large force during the stroke (Secher, 1983). This could explain the high correlation between lean body mass and time-trial velocity ($r = 0.85$). Individuals with a high lean body mass possess a larger muscle mass than individuals with a low lean body mass and, therefore, are potentially able to produce a greater force during the stroke.

The high correlation between lean body mass and velocity in the 2000 m time-trial shows that muscle mass is an important variable in rowing performance. The implications of this are that less heavy individuals in the lightweight rowing category (<72.5 kg) should increase their lean body mass and, where appropriate, reduce their body fat to allow them to maximize their muscle mass while remaining within their weight category. As no 'true' heavyweight rowers took part in this study, the relationship between lean body mass and velocity in the 2000 m time-trial cannot be determined for individuals in this category. Future research needs to investigate this relationship in a group of heavyweight rowers.

The $\dot{V}O_2$ at the highest submaximal workload completed by all participants showed a significant negative relationship with time-trial velocity ($r = -0.62$). The $\dot{V}O_2$ at the next highest workload showed a negative relationship with time-trial velocity that approached significance ($r = -0.51$), but $\dot{V}O_2$ at the lowest workload demonstrated a very poor negative relationship with time-trial velocity ($r = -0.20$).

The economy scores at the highest workload showed a stronger relationship to 2000 m time than those at the lower workloads; this might have been anticipated. The highest workload was closest to that experienced during a 2000 m race. Had economy scores been obtained for the rowers at true race workloads (a 500 m split time of approximately 1 min 40 s for this group), an even stronger relationship with time-trial performance might have been demonstrated. That the rowers in this study had very similar economy values suggests that this variable might not be important for rowing. Running studies have shown that economy can be a distinguishing feature between athletes with similar $\dot{V}O_{2max}$ values. If rowers could reduce the oxygen cost of rowing at a given velocity, they could probably enhance their performance.

Studies using heterogeneous groups in terms of running economy have found a good relationship between running economy and performance; those using homogeneous groups have not (Wilcox and Bulbulian, 1983). The economy values were relatively homogeneous in the present study, and this could explain why the correlation with 2000 m time-trial performance was poor.

Evans *et al.* (1995) and Hill and Rowell (1996) demonstrated a positive relationship between the velocity at $\dot{V}O_{2max}$ and performance in runners. We also found a significant positive relationship between these two variables ($r = 0.77$). No comparison can be made with other groups of oarsmen, as we could find no other reports of the velocity at $\dot{V}O_{2max}$ for oarsmen in the literature. It might have been anticipated that velocity at $\dot{V}O_{2max}$ would correlate well with time-trial performance, as the velocity was close to that in the 2000 m performance test, whereas the blood lactate variables demonstrated velocities much lower than that at $\dot{V}O_{2max}$. Our results suggest that the velocity at $\dot{V}O_{2max}$ for rowers is worth investigating, as it correlates well with performance.

The $\dot{V}O_2$ at a blood lactate concentration of 4 $mmol \cdot l^{-1}$ in the present study showed a positive relationship with time-trial velocity ($r = 0.68$). This is in line with the results of Wolf and Roth (1987) and Steinacker (1993), who found a strong relationship between these two variables. Individuals with high $\dot{V}O_2$ scores at a blood lactate concentration of 4 $mmol \cdot l^{-1}$ generally produce faster times. As all of the participants in the present study had similar rowing economy, those with high $\dot{V}O_2$ at a blood lactate concentration of 4 $mmol \cdot l^{-1}$ would have reached this concentration at a higher workload. As our participants are capable of rowing at higher workloads before accumulating blood lactate in significant quantities, it is to be expected that their rowing performance will be better than that of individuals who accumulate blood lactate at lower workloads.

Rowing economy has received scant attention in previous studies. More research is required to determine the extent to which this variable influences performance. We have noted a positive relationship between rowing economy and performance, which became significant at the highest workload completed by all participants. The velocity at $\dot{V}O_{2max}$ of endurance runners has previously been demonstrated to be a good predictor of performance. In the present study, velocity at $\dot{V}O_{2max}$ was a fairly strong predictor of 2000 m time in rowers. However, further studies are needed to investigate this variable further.

The best predictors of rowing performance were $\dot{V}O_{2max}$ and lean body mass, followed by endurance time in the $\dot{V}O_{2max}$ test, velocity in the $\dot{V}O_{2max}$ test and velocity at a blood lactate concentration of 4 $mmol \cdot l^{-1}$. The best single predictor of velocity in the 2000 m time-trial was $\dot{V}O_{2max}$; the model incorporating $\dot{V}O_{2max}$ only explained about 72% of the variance in 2000 m rowing performance. The addition of blood lactate concentration 5 min after the performance test improved the prediction of time-trial performance. The model incorporating these two predictors explained 87% of the variability in 2000 m rowing performance. Rowers and coaches could use these findings when designing training programmes. More time should be devoted to the improvement of $\dot{V}O_{2max}$ and lean body mass.

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