

# Effects of Stroke Resistance on Rowing Economy in Club Rowers Post-Season

## Authors

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## Key words

- mechanical efficiency
- economy
- oxygen uptake

## Abstract

In the sport of rowing, increasing the impulse applied to the oar handle during the stroke can result in greater boat velocities; this may be facilitated by increasing the surface area of the oar blade and/or increasing the length of the oars. The purpose of this study was to compare the effects of different rowing resistances on the physiological response to rowing. 5 male and 7 female club rowers completed progressive, incremental exercise tests on an air-braked rowing ergometer, using either low (LO; 100) or high (HI; 150) resistance (values are according to the adjustable “drag factor” setting on the ergometer). Expired air, blood lactate concentration, heart rate, rowing cadence, and ergometer

power output were monitored during the tests. LO rowing elicited significantly greater cadences ( $P < 0.01$ ) and heart rates ( $P < 0.05$ ), whereas rowing economy ( $J \cdot L \text{ O}_2 \text{ equivalents}^{-1}$ ) was significantly greater during HI rowing ( $P < 0.05$ ). These results suggest that economically, rowing with a greater resistance may be advantageous for performance. Moreover, biomechanical analysis of ergometer rowing support the notion that the impulse generated during the stroke increases positively as a function of rowing resistance. We conclude that an aerobic advantage associated with greater resistance parallels the empirical trend toward larger oar blades in competitive rowing. This may be explained by a greater stroke impulse at the higher resistance.

## Introduction

Increasing the oar blade size in rowing should, in theory, result in greater efficiency of energy provided by the participant towards moving the boat [24]. Indeed, a trend towards oar blades with greater surface area used by top-performing rowers has been observed in the past 20 years [21]. To simulate the effects of increasing or decreasing the oar surface area on an air-braked rowing ergometer, the amount of air allowed to resist the flywheel can be adjusted. The resulting resistance of the ergometer flywheel, which corresponds to the drag forces associated with manipulating oar blade surface area and/or shape in water rowing, is analogous to the crank resistances generated by altering the gear ratios on a bicycle [10]. The influence of crank resistance on cycling economy has been clearly demonstrated (reviewed in [1]). Thus, increasing the rowing ergometer resistance, or drag factor, would simulate rowing on water with larger oar blades, much as one might increase the crank resistance

when increasing the gear ratio of a bicycle (chain wheel/freewheel) when transitioning from uphill to level cycling [10].

Previously, we demonstrated an increased maximal minute ventilation ( $V_{E\max}$ ) in club rowers when exercising at a low vs. high resistance [14]. The increased  $V_E$  at the lower resistance was related to the stroke rate used by the rowers to attain a fixed power output [14]. However, these rowers were tested before the competitive spring rowing season, and may thus not reflect characteristic physiological signatures representative of performance potential. In the current study, it was hypothesized that manipulating the resistance of simulated rowing on a Concept2 ergometer in moderately trained university club rowers (i.e., immediately after the competitive season) would elicit differences in the physiological responses associated with performance. In keeping with the empirical trends of elite rowers using oar blades of increasing surface areas [21], it was hypothesized that greater rowing resistances would correspond to greater economy of

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## Bibliography

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rowing. Furthermore, we sought to explore the effects of stroke resistance on mechanical efficiency, in an effort to help explain the effects of stroke resistance on rowing economy. Rowing economy, defined previously as oxygen consumed ( $\text{VO}_2$ ) during steady-state workloads of rowing [6], and expressed as power  $\cdot \text{VO}_2^{-1}$ , has helped explain physiological rowing capacity in women [23] and men [28]. Therefore, we examined rowing economy, defined as work effectively applied to the ergometer flywheel per volume total  $\text{O}_2$  equivalents consumed ( $\text{J} \cdot \text{L O}_2^{-1}$ ), when rowing at a high vs. low resistance during simulated rowing.

## Materials and Methods



### Participants

5 male and 7 female members of the Northern Michigan University rowing club volunteered to participate in this first part of this study (physiological testing). They were  $20.3 \pm 0.4$  years of age,  $170.9 \pm 2.2$  cm in height, and weighed  $72.7 \pm 2.1$  kg and  $72.6 \pm 2.1$  kg immediately prior to the low and high-resistance tests, respectively. These participants had competitive rowing experience ranging from 0.5 to 4 years, and were non-elite, conditioned club rowers (rowing  $\text{VO}_{2\text{peak}}$ :  $3.238 \pm 0.185 \text{ L O}_2 \cdot \text{min}^{-1}$ ). The present study commenced immediately following the spring sprint regatta season, which consisted of 4 intercollegiate regattas. All participants were familiar with, and trained regularly on the Concept2 rowing ergometer. Prior to commencement of the first part of this study, Northern Michigan University Human Subjects Review Committee approval was secured. Volunteers gave written informed consent before participating in the study. One experienced male subject (age: 30y; height: 174.0cm; weight: 72.9kg) volunteered to participate in the second part of the study (biomechanical analysis). He gave his informed consent prior to participation. All participant involvement in these studies was in accordance with the Declaration of Helsinki and reference [11].

### Design

The Concept2 air-braked rowing ergometer is arguably the most popular piece of equipment with respect to off-water, sport-specific training by rowers. The resistance of the air-braked flywheel mechanism is adjusted by altering a vent damper on the flywheel housing, which controls the amount of resistive air ventilated into the flywheel. In order to operationally define the resistance of the rowing exercise, we used the ergometer manufacturer's numerical expression: drag factor, a multiple of the drag force coefficient ( $C_D$ ), derived from the measured deceleration of the ergometer flywheel between strokes [4,22]. Recommendations and observations (personal correspondence) indicate that drag factors used for testing and training rowers increases with skill level of the athlete. For example, the Amateur Rowing Association (ARA, UK) recommends drag factor settings ranging from 100 to 140 for junior beginner rowers to heavyweight oarsmen, respectively [22]. In water rowing, the oar blade drag force  $F_D$ , can be described as

$$F_D = 0.5 C_D \cdot \rho \cdot A \cdot V^2$$

where  $\rho$  is the density of the fluid,  $A$  is the oar blade surface area, and  $V$  is velocity of the oar blade relative to the water. There are also significant lift forces generated during the stroke in water

rowing due to the curvature of the blade; these lift forces are determined by a formula similar to the  $F_D$ , with the exception that a lift coefficient ( $C_L$ ) is included instead of  $C_D$ . In ergometer rowing, the dimensionless  $C_D$  is used to calculate drag torque at the level of the flywheel, from which pace and power are calculated by the ergometer's on-board computer [4]. In competitive water rowing, athletes aim to cover the race distance as quickly as possible. To achieve this aim, rowers do physiological work in order to transfer mechanical energy to the boat by applying force to the oar handle. The rate at which this energy is transferred, or power ( $P_W$ ) can be defined as:

$$P_W = F_H \cdot \omega \cdot L_{in}$$

Where  $F_H$  is force applied to the oar handle,  $\omega$  is the oar angular velocity, and  $L_{in}$  is the inboard length of the oar. In ergometer rowing, power ( $P_E$ ) can be defined as:

$$P_E = F_H \cdot V_H$$

$L_{in}$  is not applicable to ergometer rowing, due to the direct transfer of force from the ergometer handle to the flywheel; and velocity of the ergometer handle,  $V_H$  may be substituted for  $\omega$  due to linear displacement of the ergometer handle. Therefore, in order to increase power during ergometer rowing, one will need to increase either  $F_H$ ,  $V_H$ , or both. Increasing  $V_H$  is linked to increased stroke rate, or cadence.

Each participant was tested at both drag factors 100 (low resistance, LO) and 150 (high resistance, HI) following the spring racing season on a Concept2 model D air-braked rowing ergometer (Concept2, Inc, Morrisville, VT). The order of trials between the LO and HI drag factors was randomized to minimize order effects. The 2 trials were separated by 1 week for each participant, and were conducted at the same time of day for each participant.

### Rowing test

Individualized test stage intensities for the progressive test were adapted from Hahn et al. [9]: Test protocol was based on seven 3-min increments of progressive work. Each subject's average per 500-meter pace from his or her best 6000-meter ergometer performance from the preceding fall rowing season gave the pace the rower was asked to maintain in the sixth stage of the test. Successive amount of 6 s were added to the stage 6 pace to determine the preceding stage target workloads. For stage 7, subjects were asked to self-select and maintain their fastest possible pace for the 3-min period. Subjects were allowed to self-select for stroke rate throughout each stage of the test. Subjects maintained their target workload by watching the per 500-m pace feedback on the ergometer's digital display. Power (W) was computed from paced values by the ergometer's onboard computer. Subjects were asked to abstain from heavy training for 2 days preceding the test, to abstain from consuming caffeine in the 2 h prior to testing, and to maintain their normal high carbohydrate diet [19,27].

### Measurements

Blood lactate concentration (BLC) was determined from fingertip capillary blood with a YSI 1500 lactate analyzer (Yellow Springs, OH). Breath-by-breath expired air was analyzed with a SensorMedics VMax29c metabolic system (Yorba Linda, CA), calibrated with standardized, manufacturer-supplied reference

gases. Heart rate was measured with a Polar heart rate monitor (Oy, Finland) and transmitted via a Polar remote receiver to the Concept2 Performance Monitor 3 (PM3) and recorded by the PM3 logcard (Morrisville, VT). Average power was computed from pace scores by the PM3. Average power and stroke rate for each test stage were recorded to the logcard by the PM3. Anaerobic  $O_2$  equivalents were calculated from the difference in BLC between each stage and the preceding stage, multiplied by  $3.3 \text{ mL } O_2 \cdot \text{kg}^{-1} \cdot \text{mM}^{-1} \text{ lactate} \cdot 3 \cdot \text{min}^{-1} \text{ stage}$  [7]. This resulting value was converted to an absolute  $VO_2$  equivalent, and combined with the absolute  $VO_2$  recorded during the last minute of the respective test stage to give total  $VO_2$  equivalent. Rowing economy was determined as the average power generated ( $W, J \cdot s^{-1}$ ), divided by the total  $VO_2$  equivalent ( $L O_2 \cdot \text{min}^{-1}$ ):

$$(J \cdot 60 s^{-1}) \cdot (L O_2 \cdot \text{min}^{-1})^{-1} = J \cdot L^{-1} O_2$$

The average power generated was also divided by the average stroke rate for each test stage to give ergometer stroke efficacy:

$$(J \cdot 60 s^{-1}) \cdot (\text{strokes} \cdot \text{min}^{-1})^{-1} = J \cdot \text{stroke}^{-1}$$

The stroke rate was also divided by the total  $VO_2$  equivalent to give ergometer stroke economy:

$$(\text{strokes} \cdot \text{min}^{-1}) \cdot (L O_2 \cdot \text{min}^{-1})^{-1} = \text{strokes} \cdot L^{-1} O_2$$

### Statistics

All data are presented as mean  $\pm$  SEM. Rowing test variables were compared across ergometer drag factors using two-way ANOVA with repeated measures (SPSS 15.0). Bonferroni post-hoc tests were used to identify specific differences among comparisons. An  $\alpha$ -level of 0.05 was set for assessing statistical significance between all comparisons. Bivariate one-tailed Pearson correlation analysis was performed using SPSS 15.0. Effect sizes for dependent variables were estimated using partial  $\eta^2$  ( $\eta_p^2$ ), where  $\eta_p^2 = \text{effect variance} / (\text{effect variance} + \text{error variance})$ . The magnitude scale for effect size classification of  $\eta_p^2$  was 0.25 to 0.549 = medium effect,  $> 0.55$  = large effect [5].

### Biomechanical analysis

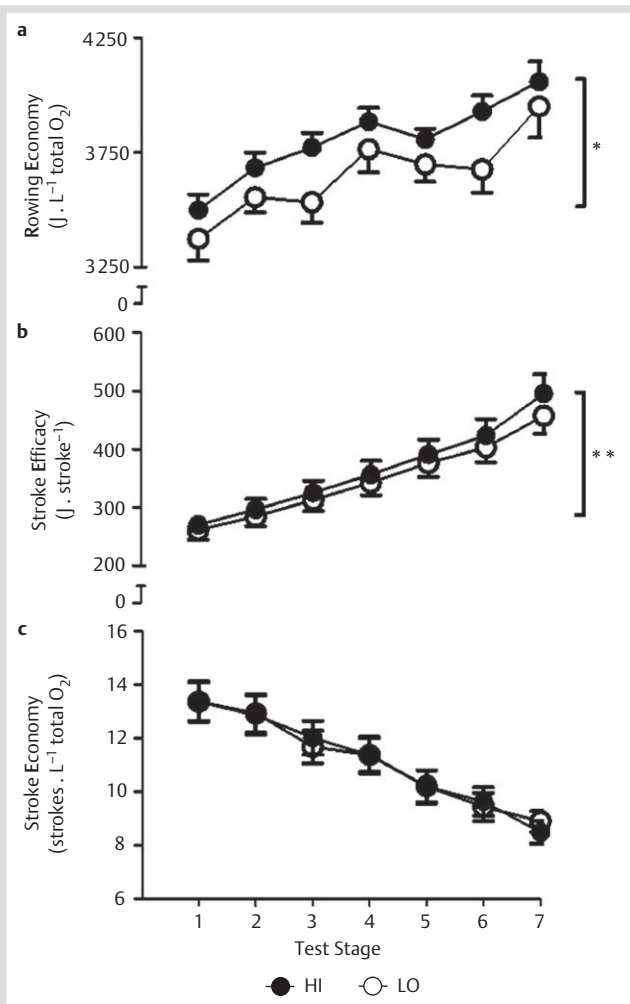
In order to gain a deeper insight into the effect of varying the rowing resistance on key performance variables, kinematic and kinetic data were collected from a single male participant using the Concept2 ergometer. Data were collected at 3 drag factors (100, 150, 200) while the participant rowed at either, one of 3 target workloads (300 W, 350 W, 400 W), or one of 3 target stroke rates (25 SPM, 30 SPM, 35 SPM). This resulted in 18 separate trials, which were repeated to affirm reliability using a 95% Limits of Agreement procedure. Force data were collected at 240 Hz using a load cell (MLP-300, Transducer Technology, Rio Nedo Temecula, CA), which was placed in series between the handle and the chain of the ergometer. Force data were passed through a 12 bit AtoD converter (Type 9243, A-Tech Instruments Ltd., Montreal, QC) before being recorded on a computer. Video data were collected synchronously using a Sony HDV HDR-HC7 Handycam. The camera lens was oriented perpendicular to the plane of motion (sagittal) of the participant's movement at a distance of 6 m. The camera collected images at 60 Hz and the shutter speed was set to 1/500 Hz. Two 1000 W lights placed behind the camera illuminated the capture area. Horizontal and vertical

scaling was initiated by videoing a  $1.5 \text{ m} \times 3 \text{ m}$  box with reflective markers placed on the corners. A single reflective marker was placed on the load transducer at the base of the rowing handle. Video data were first analyzed using MaxTRAQ® (Innovision Systems Inc., Columbiaville, MI), and the displacement of the handle was determined by digitizing the point on the force transducer. Both force and displacement data were imported into a custom designed Matlab (Mathworks Inc., Natick, MA) program and were passed through a 4<sup>th</sup> order zero lag low-pass Butterworth filter, with cut-off frequencies of 50 Hz (force) and 5 Hz (displacement). The displacement data were then fit to a quintic spline and analytically differentiated to obtain velocity curves. The displacement and velocity curves were then resampled at 240 Hz to match the force data. The following variables were calculated for each trial based on the time, force, displacement, and velocity of each stroke: stroke rate, impulse, mean power, and work.

### Results



With the exception of height ( $P=0.021$ ), participant characteristics did not differ between sexes; none of the characteristics differed between HI and LO tests. When included as a covariate, height was determined not to impact any of the variables measured or calculated in the present study. Resting BLC immediately prior to the LO and HI rowing tests were  $0.87 \pm 0.12$  and  $1.00 \pm 0.31$ , respectively; resting BLC did not significantly differ between LO vs. HI ( $P=0.413$ ). All participants completed each test as prescribed for both drag factors, and the power ratings for each stage were unaffected by drag factor (• **Table 1**). Main effects for drag factor were observed for stroke rate ( $P=0.001$ ; • **Table 1**). This implies that rowing at LO may require an increase in stroke rate in order to optimally achieve an equivalent power output at HI, as stroke rates were self-selected by participants during the tests. As expected, increased stroke rate at LO was accompanied by greater heart rates (main effect:  $P<0.026$ ; • **Table 1**), which would be expected to be associated with greater oxygen uptake. A significant main effect for drag factor on rowing economy was also observed ( $J \cdot L^{-1}$  total  $O_2$ ;  $P=0.018$ ; • **Fig. 1a**). This suggests that rowing at the HI drag factor may provide a physiological advantage over LO during simulated rowing. Moreover, significant main effect for drag factor on stroke efficacy ( $J \cdot \text{stroke}^{-1}$ ;  $P=0.001$ ; • **Fig. 1b**) indicates greater work per stroke with the HI resistance, which may also contribute to the effects of resistance on rowing economy. Surprisingly, however, the stroke economy (i.e., the  $\text{strokes} \cdot L^{-1}$  total  $O_2$ ) was not affected by the 2 drag factors (• **Fig. 1c**), suggesting that the energetic cost of rowing will increase as a function of stroke rate independent of HI vs. LO resistance. The partial  $\eta^2$  values (• **Table 2**) indicate that drag factor exerted a “large” or “medium” effect size for 5 of the dependent variables, accounting for 67.4, 66.5, 41.4, 37.4, 29.2 and 28.7% of the variability in stroke rate, stroke efficacy, rowing economy, heart rate,  $VO_2$ , and  $V_E$ , respectively. The results presented in • **Table 2** therefore illustrate how rowing with different resistances may alter considerably the response to the task, particularly with regard to stroke rate and stroke efficacy. To explore the potential role of stroke resistance on entrainment of breathing to stroke rate in rowing, we investigated the relationship between the difference in  $V_E$  across LO-HI conditions for each test stage (LO-HI  $V_{E\text{diff}}$ ), with the difference in corresponding stroke rates (LO-HI

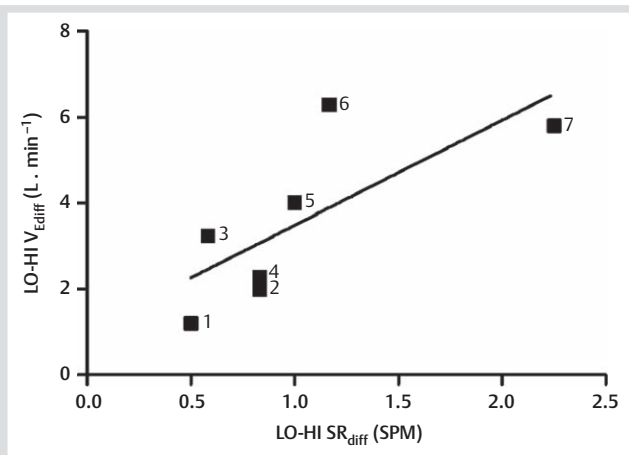


**Fig. 1** Effects of resistance on rowing economy. **a** Rowing economy, the work performed at the ergometer flywheel ( $J$ ) per total  $O_2$  equivalents ( $L$  total  $O_2$ ) consumed (see Methods for total  $O_2$  determination). A significant main effect ( $*P < 0.05$ ) for ergometer resistance (HI vs. LO) was observed on rowing economy across all 7 rowing test stages. **b** Stroke efficacy, the energy applied to the ergometer flywheel ( $J$ ) per rowing stroke (see Methods for  $J \cdot \text{stroke}^{-1}$  determination). A significant main effect ( $**P < 0.01$ ) for ergometer resistance was observed on stroke efficacy across all 7 rowing test stages. **c** Stroke economy, the rowing strokes performed per total  $O_2$  equivalents ( $L$  total  $O_2$ ) consumed (again, see Methods for total  $O_2$  determination). No effect for resistance was observed on the stroke economy across the 7 rowing test stages.

$SR_{\text{diff}}$ ). **Fig. 2** illustrates the significant relationship between  $V_{\text{Ediff}}$  and  $SR_{\text{diff}}$  (Pearson  $r = 0.741$ ;  $P = 0.028$ ), which suggests that entrainment of breathing may link stroke resistance to  $V_E$  via SR in simulated rowing.

## Discussion

In the present study, it was hypothesized that the physiological response to rowing would differ between 2 resistances, or drag factors, during simulated rowing. While the outcome variables in this study were not themselves direct performance measurements, they do illustrate some potentially important consequences of rowing at 2 different resistance levels. Clearly, altering the ergometer resistance not only affects stroke rate (accounting for 67.4% of SR variability, observed power: 0.991), but also the



**Fig. 2** Relationship between the difference in minute ventilation ( $V_{\text{Ediff}}$ ) across LO-HI rowing ergometer resistances, and the difference in stroke rate ( $SR_{\text{diff}}$ ) across LO-HI rowing ergometer resistances. Data are averages for each stage (data labels identify test stage). Pearson correlation  $r = 0.74$ ;  $P < 0.05$ .

energy applied to the ergometer flywheel per stroke (observed power: 0.989). Perhaps most importantly, rowing economy was observed to significantly differ between the 2 drag factors tested (**Fig. 1a**). The effect of altering the resistance of the rowing ergometer between drag factors 100 and 150 accounted for 41.4% of the difference in rowing economy between the tests (observed power: 0.718). The results of the present study suggest that rowing at a higher resistance confers an energetic advantage to the activity. Rowing economy has been linked to rowing performance in men [6], and shown to be a potential determinant of rowing success in collegiate women [23]. The competitive objective of Olympic standard rowing involves covering a distance of 2000 meters in the shortest time. Races of this type are often won or lost by fractions of a second. Thus, any competitive advantage, even when small, may have enormous implications for the sport of rowing.

Nolte [21] recently suggested that rowers adapt to using shorter oars with a greater blade surface area in order to optimize rowing propulsive forces. Empirical observation clearly demonstrate that both oar blade surface area has increased in recent decades, concurrent with decreased outboard oar length and faster rowing performances [21]. However, for sweep rowing, the outboard oar length has decreased from 1982 to 2007 by less than 6% (i.e., 2.66 vs. 2.51 m; calculated from data contained in table 2 of [21]). Contrast this with a 25% increase in blade surface area (i.e., 971 vs. 1212  $\text{cm}^2$ ; [21]) occurring over the same time frame. Moreover, inboard oar length has remained relatively constant from 1982 to 2007, increasing less than 1% [21].

For a given oar blade speed relative to the water, the blade surface area will increase the force of the water on the blade. The force of the water on the blade, when conducting a mechanical analysis, is often resolved into drag and lift components. While increasing blade surface area will increase both components, the drag component is the main contributor to the propulsion of the boat.

Consider the following equation describing the dynamics of the oar [21], which will facilitate a discussion on the relative effects increasing blade surface area vs. reducing the outboard length. Note that according to Nolte, the inertial term ( $I\alpha$ ) from the dynamical equation can be neglected.

**Table 1** Data (mean  $\pm$  SEM) from the rowing ergometer tests. Average power, SR stroke rate, HR heart rate,  $\text{VO}_2$  oxygen uptake,  $\text{V}_E$  minute ventilation, BLC Blood lactate concentration, RER respiratory exchange ratio measured during rowing tests at drag factors 100 (LO resistance) or 150 (HI resistance).

| Variable                                     | Ergometer resistance | Test Stage       |                  |                  |                  |                  |                  |                    |
|----------------------------------------------|----------------------|------------------|------------------|------------------|------------------|------------------|------------------|--------------------|
|                                              |                      | 1                | 2                | 3                | 4                | 5                | 6                | 7                  |
| power (W)                                    | LO                   | 98.6 $\pm$ 5.5   | 110.4 $\pm$ 6.4  | 123.0 $\pm$ 7.6  | 141.3 $\pm$ 9.0  | 162.3 $\pm$ 10.9 | 187.0 $\pm$ 13.2 | 255.8 $\pm$ 18.4   |
|                                              | HI                   | 100.3 $\pm$ 5.8  | 111.0 $\pm$ 6.5  | 124.8 $\pm$ 7.9  | 142.2 $\pm$ 9.3  | 162.2 $\pm$ 11.1 | 188.2 $\pm$ 13.7 | 259.3 $\pm$ 19.7   |
| SR (SPM)**                                   | LO                   | 22.8 $\pm$ 0.5   | 23.3 $\pm$ 0.5   | 23.7 $\pm$ 0.6   | 24.8 $\pm$ 0.7   | 25.9 $\pm$ 0.7   | 27.8 $\pm$ 0.6   | 33.5 $\pm$ 0.6     |
|                                              | HI                   | 22.3 $\pm$ 0.5   | 22.5 $\pm$ 0.5   | 23.1 $\pm$ 0.5   | 24.0 $\pm$ 0.6   | 24.9 $\pm$ 0.7   | 26.6 $\pm$ 0.8   | 31.3 $\pm$ 0.7     |
| HR (BPM)*                                    | LO                   | 125.4 $\pm$ 2.4  | 135.7 $\pm$ 2.4  | 143.1 $\pm$ 2.5  | 152.4 $\pm$ 2.5  | 162.8 $\pm$ 2.0  | 175.0 $\pm$ 2.0  | 191.2 $\pm$ 1.5    |
|                                              | HI                   | 123.4 $\pm$ 2.9  | 131.7 $\pm$ 2.9  | 139.8 $\pm$ 2.6  | 148.6 $\pm$ 2.9  | 159.7 $\pm$ 2.1  | 172.2 $\pm$ 2.0  | 187.9 $\pm$ 1.8    |
| $\text{VO}_2$ (L $\cdot$ min $^{-1}$ )       | LO                   | 1.70 $\pm$ 0.09  | 1.87 $\pm$ 0.10  | 2.04 $\pm$ 0.11  | 2.25 $\pm$ 0.13  | 2.53 $\pm$ 0.15  | 2.83 $\pm$ 0.18  | 3.24 $\pm$ 0.19    |
|                                              | HI                   | 1.67 $\pm$ 0.09  | 1.79 $\pm$ 0.10  | 1.98 $\pm$ 0.12  | 2.19 $\pm$ 0.13  | 2.45 $\pm$ 0.16  | 2.68 $\pm$ 0.18  | 3.09 $\pm$ 0.22    |
| $\text{V}_E$ (L $\cdot$ min $^{-1}$ )        | LO                   | 41.47 $\pm$ 1.78 | 46.76 $\pm$ 2.28 | 53.78 $\pm$ 2.10 | 60.00 $\pm$ 3.65 | 73.64 $\pm$ 5.34 | 84.62 $\pm$ 7.26 | 123.53 $\pm$ 10.17 |
|                                              | HI                   | 40.27 $\pm$ 1.95 | 44.77 $\pm$ 2.12 | 50.53 $\pm$ 2.79 | 57.72 $\pm$ 3.25 | 66.63 $\pm$ 4.08 | 78.33 $\pm$ 5.94 | 117.73 $\pm$ 8.92  |
| BLC (mM)                                     | LO                   | 1.17 $\pm$ 0.13  | 1.16 $\pm$ 0.11  | 1.42 $\pm$ 0.12  | 1.44 $\pm$ 0.14  | 2.00 $\pm$ 0.19  | 3.23 $\pm$ 0.20  | 6.63 $\pm$ 0.35    |
|                                              | HI                   | 1.29 $\pm$ 0.13  | 1.41 $\pm$ 0.18  | 1.44 $\pm$ 0.15  | 1.47 $\pm$ 0.17  | 2.09 $\pm$ 0.25  | 3.09 $\pm$ 0.35  | 7.08 $\pm$ 0.58    |
| $\text{VO}_2$ Equiv (L $\cdot$ min $^{-1}$ ) | LO                   | 1.75 $\pm$ 0.08  | 1.87 $\pm$ 0.11  | 2.09 $\pm$ 0.12  | 2.25 $\pm$ 0.13  | 2.63 $\pm$ 0.16  | 3.05 $\pm$ 0.19  | 3.85 $\pm$ 0.17    |
|                                              | HI                   | 1.72 $\pm$ 0.09  | 1.81 $\pm$ 0.11  | 1.98 $\pm$ 0.11  | 2.19 $\pm$ 0.13  | 2.55 $\pm$ 0.17  | 2.86 $\pm$ 0.19  | 3.80 $\pm$ 0.23    |
| RER                                          | LO                   | 0.87 $\pm$ 0.01  | 0.92 $\pm$ 0.01  | 0.95 $\pm$ 0.01  | 0.97 $\pm$ 0.01  | 0.99 $\pm$ 0.02  | 1.03 $\pm$ 0.02  | 1.21 $\pm$ 0.02    |
|                                              | HI                   | 0.87 $\pm$ 0.02  | 0.93 $\pm$ 0.01  | 0.95 $\pm$ 0.01  | 0.97 $\pm$ 0.01  | 0.99 $\pm$ 0.01  | 1.02 $\pm$ 0.01  | 1.22 $\pm$ 0.02    |

Main effect for resistance, \* $P$ <0.05, \*\* $P$ <0.01

**Table 2** Effect size (partial eta squared,  $\eta_p^2$ ) of resistance on stroke rate, stroke efficacy, rowing economy, heart rate, minute ventilation ( $\text{V}_E$ ), oxygen uptake ( $\text{VO}_2$ ), power, blood lactate concentration (BLC), respiratory exchange ratio (RER), and stroke economy.

|                                                          | $\eta_p^2$<br>resistance |
|----------------------------------------------------------|--------------------------|
| stroke rate (SPM)                                        | 0.674**                  |
| stroke efficacy (J $\cdot$ stroke $^{-1}$ )              | 0.665**                  |
| rowing economy (J $\cdot$ L $^{-1}$ total O $_2$ )       | 0.414*                   |
| heart rate (BPM)                                         | 0.374*                   |
| $\text{VO}_2$ (L $\cdot$ min $^{-1}$ )                   | 0.292*                   |
| $\text{V}_E$ (L $\cdot$ min $^{-1}$ )                    | 0.287*                   |
| power (W)                                                | 0.129                    |
| BLC (mM)                                                 | 0.022                    |
| RER                                                      | <0.001                   |
| stroke economy (strokes $\cdot$ L $^{-1}$ total O $_2$ ) | <0.001                   |

Partial  $\eta^2$  values are classified according to the size effect scale (see Methods):

\*\*large effect, \*medium effect

$$F_H \cdot L_{in} = F_B \cdot L_{out}$$

Where  $F_H$  is the force the rower applies to the handle,  $L_{in}$  is the inboard length,  $F_B$  is the force of the water on the blade, and  $L_{out}$  is the outboard length. The above equation can be rearranged to

$$F_H = L_{out} \cdot L_{in}^{-1} \cdot F_B$$

It follows that while increasing the oar blade surface area increases  $F_B$  and, in turn,  $F_H$ , there will be a decrease in  $F_H$  experienced as a result of shortening the oar through reducing  $L_{out}$ . As mentioned,  $L_{out}$  has decreased less than 6% from 1982 to 2007. Considering this logic, it is possible that the increase in oar blade area size is what has permitted and/or necessitated shortening of the outboard length of the oar in past decades. While oars have become shorter over the last 25 years, the global resistance, (analogous to manipulating the drag factor in ergometer rowing) that the typical rowing athlete training and/or competing with today's equipment will encounter likely exceeds that experienced in 1982. Indeed, such an increase in the load

per stroke has been implicated in the etiology of increased rib stress fractures in elite rowers following the introduction of the Big Blade in 1992 [15].

In their review of rowing biomechanics, Baudouin and Hawkins summarize the idea of an optimal stroke rate and rigging setup in water rowing for the most effective boat velocities [2]. While higher stroke rates in water rowing may be beneficial in terms of reducing oscillations in boat velocity, they acknowledge that this places greater physiological demands on the rower [2]. Interestingly, more recent studies have raised questions about the supposed improvements in efficiency [13] and performance [12] attributed to higher stroke rates. In fact, it has even been suggested that elite crews may improve performance by moderately decreasing stroke rate, so long as stroke force production increases to compensate [12].

The results of the current study support the idea that increasing the resistance of the oar will result in better economy of the rowing ergometer exercise. Rowing at lower resistances, on the other hand, will require greater acceleration during the drive phase of the stroke, and/or greater stroke rates to achieve similar rowing speeds, which may result in increased heart rate (see Table 1). The resistances that rowers can tolerate, and still experience improvements in economy await investigation. However, it is likely that for individual rowers, there will be a point at which the return on economy is diminished by the mechanical cost of rowing with very high resistances. Indeed, the relationship between power output optima and resistance is thought to involve the force-velocity characteristics of the skeletal muscle employed in the exercise [25]. In the current study, we chose drag factors at the low end (i.e., 100) of what is recommended for training and what the Concept2 ergometer is capable of producing, and drag factor 150, slightly above the upper limit of what has been recommended for training by the ARA [22]. In the biomechanical analysis, we examined simulated rowing additionally at drag factor 200, still below the ergometer's drag factor 220 capability [22]. It is interesting to note that when a mid-season 2000m ergometer time trial was conducted as a part of the athlete's regular monitoring of training, the self-

selected drag factors used in the 10 participating athletes was  $119.0 \pm 2.4$ . This observation suggests that rowers may benefit from a combination of increased stroke rate and increased stroke resistance, such that an optimal ratio, perhaps occurring somewhere within the range of the drag factors tested in the current study, is achieved.

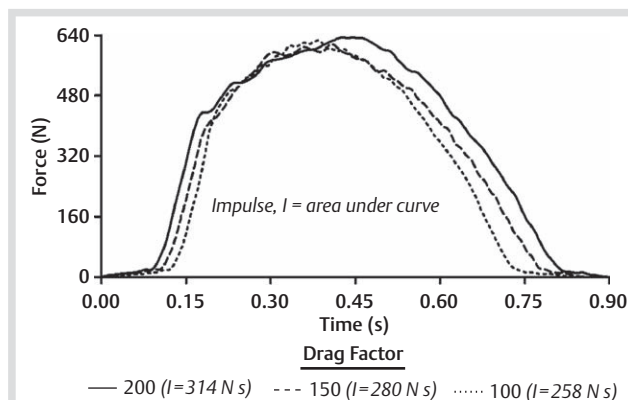
To help explain the apparent physiological advantage to rowing at the HI drag factor, we analyzed video recordings of one male subject rowing with 3 target stroke rates (25, 30 and 35 SPM) and mean power outputs (300, 350 and 400 W), with the ergometer damper settings at either the LO (100) or HI (150) drag factors. As expected, the impulse (i.e., force-time, N-s) achieved when rowing at the 150 drag factor was greater than the impulse at the 100 drag factor (• Fig. 3). To clarify whether this relationship continues beyond drag factor 150, we also tested the subject rowing with a drag factor of 200. Interestingly, the impulse appears to increase additionally at drag factor 200 compared to 150 (• Fig. 3). Moreover, this relationship holds over a range of stroke rates, mean power, and workloads (J) (• Fig. 4).

In a study examining optimal paddle blade surface areas for competitive kayaking, Spriggins et al. [25] concluded that increasing the surface area of the paddle by 5–10% would improve the power output for elite kayakers. Interestingly, they recommended that the sub-elite kayakers studied retain their

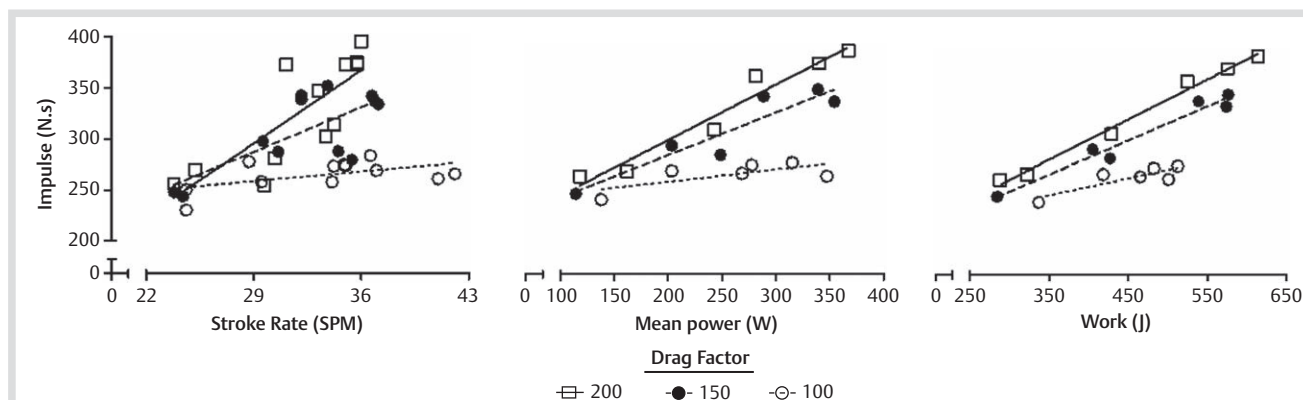
current paddle blade profiles, as the instantaneous peak power generated on a kayaking ergometer corresponded to paddle blade surface areas not markedly different from those they were already using [25]. Whether a similar recommendation, reinforced by the results of the present study, should be made to rowers interested in improving performance, would likely require personalized analysis. Nevertheless, it does appear that the trend for competitive rowers to adopt the larger “big blade” over the smaller “Macon blade” is justified by the results of the present study, and appears to apply even to club-level male and female athletes.

The results of this study support the hypothesis that greater resistances in rowing ergometer exercise are met with lower stroke rates in trained club-level athletes for a given workload (• Table 1). Analogous to altering the flywheel setting on the Concept2 rowing ergometer, different chain combination ratios alter the pedal crank resistances in cycling exercise [10]. Unlike the implications of the present study with regards to lower stroke rates at greater loads in rowing however, cycling with higher gear ratios (greater crank resistances) has been shown to elicit greater self-selected pedal cadences [10]. Although a tendency for individuals to increase pedal cadence may slightly reduce the efficiency of cycling [8], even professional cyclists spontaneously adopt a cadence on level terrain greater than those thought to be most economical [16]. Whether rowers alter stroke rate dependent on that which is most economical, or due to some other factor (e.g., strength-velocity relationship of muscle fiber contractions), awaits formal investigation.

Among the limitations of the current study, the participants were not elite rowers. Future research examining elite rowers may help to eliminate potentially confounding variables such as conditioning level and experience. An important delimitation was the nature of the test protocol. It would be perhaps even more applicable to conduct a time trial test (e.g., 2000 m) instead of the progressive incremental test employed in the current study. Such a study may shed light on the actual performance implications for varying stroke resistance. An even better study would examine on-water rowing with various oar lengths and/or blade area sizes. While such a study would have its own inherent limitations (e.g., participant familiarity with specific oar style), it may nonetheless better inform coaches, trainers and athletes as to the benefits (or lack thereof) of increasing oar blade size, for example. Additionally, considerations for athlete mood and fatigue states may also be surveyed.



**Fig. 3** Representative force-time curves for rowing at 3 different drag factors while generating similar mean power. The mean powers, generated during the drive phase, at the drag factor settings of 100, 150 and 200 were 482W, 484W and 482W, respectively. The force-time curves shown represent impulses (area under the curves) for the drag factors 100, 150 and 200 of 258 N-s, 280 N-s and 314 N-s, respectively.



**Fig. 4** Relationship between stroke impulse and stroke rate, work and mean power at 3 different drag factors. The impulse generated by the participant was positively related to the drag factor at which he rowed. This relationship held over a range of stroke rate, mean power and work.

Previously, we demonstrated that at the LO drag factor, an increase in  $V_E$  that was related to stroke rate over the course of the same progressive rowing test used in the current study [14]. However, the previous study was conducted with participants in the preparatory period of training, before the spring competitive season had commenced. It has been mentioned that measurement of rowers' physiological capacity in the preparatory phase is not ideal [20]. In the current study, participants were tested immediately following the competitive racing season. Similar to previous research [14], a relationship between the  $V_{E\text{diff}}$  and  $SR_{\text{diff}}$  in the current study suggests that entrainment of breathing may link stroke resistance to  $V_E$  via  $SR$  (● Fig. 2). Ventilatory-locomotion coupling in rowing, whereby breathing frequency is entrained to  $SR$ , has been described previously in rowers of varying abilities and experience levels [14, 17, 18]. Entrainment of breathing in rowing has been reported to increase with experience and training level [17, 18]. Because the participants in the current study were tested immediately after the spring competitive season, we expected to find considerably stronger entrainment of breathing in these subjects. However, the  $V_{E\text{diff}}-SR_{\text{diff}}$  relationship in the current study was comparable to that of the previous study (i.e.,  $r=0.76$  [14] vs.  $r=0.74$ ; ● Fig. 2). Additional research examining the effects of resistance on the physiological response to rowing in elite rowers may further clarify how increasing the oar blade surface area, which has been the empirical trend, affects successful crews.

While the principle of specificity argues that rowers should increasingly train at resistances similar to those encountered in competition [3], the results of the current study suggest that rowing at a lower resistance may be more aerobically strenuous and preferable for certain aspects of overload training. A question therefore remains: if rowers may benefit from using higher resistances/increased oar blade surface area in competition, might they also benefit from lower resistances/decreased oar blade surface area during training?

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