

## Effect of stroke rate on the distribution of net mechanical power in rowing

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### Abstract

The aim of this study was to assess the effect of manipulating stroke rate on the distribution of mechanical power in rowing. Two causes of inefficient mechanical energy expenditure were identified in rowing. The ratio between power not lost at the blades and generated mechanical power ( $\bar{P}_{\text{rower}}$ ) and the ratio between power not lost to velocity fluctuations and  $\bar{P}_{\text{rower}}$  were used to quantify efficiency ( $e_{\text{propelling}}$  and  $e_{\text{velocity}}$  respectively). Subsequently, the fraction of  $\bar{P}_{\text{rower}}$  that contributes to the average velocity ( $\bar{x}_{\text{boat}}$ ) was calculated ( $e_{\text{net}}$ ). For nine participants, stroke rate was manipulated between 20 and 36 strokes per minute to examine the effect on the power flow. The data were analysed using a repeated-measures analysis of variance. Results indicated that at higher stroke rates,  $\bar{P}_{\text{rower}}$ ,  $\bar{x}_{\text{boat}}$ ,  $e_{\text{propelling}}$ , and  $e_{\text{net}}$  increase, whereas  $e_{\text{velocity}}$  decreases ( $P < 0.0001$ ). The decrease in  $e_{\text{velocity}}$  can be explained by a larger impulse exchange between rower and boat. The increase in  $e_{\text{propelling}}$  can be explained because the work at the blades decreases, which in turn can be explained by a change in blade kinematics. The increase in  $e_{\text{net}}$  results because the increase in  $e_{\text{propelling}}$  is higher than the decrease in  $e_{\text{velocity}}$ . Our results show that the power equation is an adequate conceptual model with which to analyse rowing performance.

**Keywords:** Efficiency, mechanics, power distribution, rowing

### Introduction

Rowing is a very demanding sport, physically as well as technically. As in most endurance sports, a high mean velocity is the performance goal. This not only requires the rower to develop a high power output, but also requires good technical skills, so that most of this power contributes to mean boat velocity.

Rowing regattas are usually held on a 2000-m course. In a single scull it takes a male rower around 7 min to cover this distance. During a race, average values for mechanical power output of about 500 W are common (Celentano, Cortile, Di Prampero, & Caretelli, 1974; Dal Monte & Komor, 1989).

The rowing cycle can be divided into a stroke phase and a recovery phase. During the stroke phase, when the blades are in the water, the rower exerts a force on the oar handles and moves towards the bow. During the recovery phase, the blades are out of the water and the rower moves back towards the stern. Because the rower is about six times heavier than the boat, changes in velocity of the rower have marked

effects on instantaneous boat velocity (see Baudouin & Hawkins, 2004; Celentano *et al.*, 1974; Zatsiorsky & Yakunin, 1991).

Rowing performance is affected by three factors (Sanderson & Martindale, 1986). First, performance is affected by the power generated by the rower. Second, performance is affected by the power necessary to move the boat against drag forces. The possibilities for lowering the necessary power are limited, however, since boat designs are constricted by FISA regulations. Third, rowing performance is affected by the efficiency of power utilization; this efficiency may be affected by technique or rigging of the boat.

The mechanical power equation has been argued to provide an adequate theoretical framework for the study of high-intensity periodic movements like rowing, cycling, and skating (Van Ingen Schenau & Cavanagh, 1990). This approach allows us to analyse how the net mechanical power delivered by the athlete's muscles and the power loss to the environment together determine the performance.

Where steady-state rowing is concerned, there will be on average no change in the kinetic energy of the system, and the fraction of the average delivered net mechanical power not contributing to average velocity can be considered “a loss”. It is important in rowing to maximize the fraction of the net mechanical power of the rower that contributes to the average boat velocity. In steady-state rowing, two types of ineffective expenditure of mechanical power can be identified. First, a considerable amount of mechanical energy is spent on giving kinetic energy to water with the blades. The associated power loss is quantified in terms of the propelling efficiency, defined as the ratio of the power not lost to the movement of water and the net mechanical power generated by the rower (Van Ingen Schenau & Cavanagh, 1990). For rowing, a propelling efficiency of 0.7–0.8 has been reported (Affeld, Schichl, & Ziemann, 1993). Second, power is lost because within the rowing cycle the boat does not travel at a constant velocity. Because power lost due to drag is related to velocity cubed (Zatsiorsky & Yakunin, 1991), fluctuations around the mean velocity have negative effects on the total average cost to overcome drag, as argued by Sanderson and Martindale (1986). According to Sanderson and Martindale (1986), the percentage of the net mechanical power used to overcome the extra resistance caused by velocity fluctuations, which will be quantified in terms of velocity efficiency ( $e_{\text{velocity}}$ ) in this study, is in the order of 5–10%.

It should be kept in mind that we refer to the mechanical power delivered by the rower as the “net” mechanical power for good reasons: this term represents the sum of the positive and negative mechanical power delivered by all muscles involved (Aleshinsky, 1986). In a periodic movement like rowing, the kinetic energy, although constant from cycle to cycle, fluctuates within a cycle. Any increase in the kinetic energy is induced by concentric muscle contractions. In so far as the subsequent decrease in velocity is caused by eccentric contractions of muscle fibres, the kinetic energy released is converted into heat (negative muscle power), meaning that it is “lost” and has to be regenerated in the next stroke

cycle. Consequently, the net mechanical power as it appears in the mechanical power equation as used in this study is lower than the positive muscle power by an amount equalling the negative muscle power.

Altering the stroke rate is likely to affect the mechanical power flow in rowing. Stroke rate is an important aspect of rowing technique and is not constant during a 2000-m race. Stroke rate is typically highest during the first and last 250 m. The rower’s average net mechanical power output over a single cycle is expected to increase with increasing stroke rate. We also expect stroke rate to influence power lost to velocity fluctuations. Accelerations of the rower in relation to the boat are expected to be higher at higher stroke rates, which will affect boat velocity because of larger impulse exchanges between rower and boat. The results of previous research on this subject are inconsistent. Celentano *et al.* (1974) reported a reduction in fluctuations, whereas Kleshnev (1999) and Sanderson and Martindale (1986) reported an increase in fluctuations at higher stroke rates. Regarding the power loss at the blades, Kleshnev (1999) reported a higher propelling efficiency at higher boat velocities. However, this finding appears to be inconsistent with the observation that more splashing and “foam” at the blades occur at higher stroke rates. One would expect this larger disturbance of water to lead to a greater loss in power, and thus a lower propelling efficiency. In this study, we examine how the net mechanical power output of the rower, the fraction of this power contributing to the average velocity, and power losses quantified by propelling efficiency and velocity efficiency are affected by stroke rate.

## Methods

### *Participants and protocol*

Nine athletes (6 males, 3 females) participated in this study. All participants were experienced rowers in the single scull. The relevant characteristics of the rowers are displayed in Table I. Participants were instructed to row at rates of 20, 24, 28, 32, and 36 strokes per minute. This range represents the range

Table II. Results for average velocity, the rower’s average power, propelling efficiency, velocity efficiency, and total efficiency at the five different stroke rates (mean  $\pm$  s).

Stroke rate	$\bar{x}_{\text{boat}}$ ( $\text{m} \cdot \text{s}^{-1}$ )	$P_{\text{rower}}$ (W)	$e_{\text{propelling}}$	$e_{\text{velocity}}$	$e_{\text{net}}$
20	$3.84 \pm 0.32$	$277 \pm 74.0$	$0.785 \pm 0.019$	$0.955 \pm 0.0062$	$0.740 \pm 0.021$
24	$4.07 \pm 0.29$	$328 \pm 77.6$	$0.797 \pm 0.019$	$0.954 \pm 0.0068$	$0.751 \pm 0.022$
28	$4.33 \pm 0.37$	$389 \pm 95.8$	$0.812 \pm 0.019$	$0.953 \pm 0.0070$	$0.765 \pm 0.020$
32	$4.52 \pm 0.30$	$441 \pm 98.1$	$0.821 \pm 0.019$	$0.950 \pm 0.0067$	$0.770 \pm 0.021$
36	$4.76 \pm 0.76$	$505 \pm 118$	$0.830 \pm 0.017$	$0.947 \pm 0.0074$	$0.777 \pm 0.019$

Note: The standard deviations concern inter-subject variability and do not influence the ANOVA results.

Table I. Height, body mass, age, years of rowing experience, and preferred stroke rate during a 2000-m ( $n = 9$ ).

	Height (m)	Body mass (kg)	Age (years)	Rowing experience (years)	Preferred race stroke rate (strokes $\cdot$ min $^{-1}$ )
Mean $\pm$ s	1.86 $\pm$ 0.09	77.8 $\pm$ 11.7	22.9 $\pm$ 3.0	5.8 $\pm$ 3.6	32.6 $\pm$ 1.13
Minimum	1.73	59	19	2	30
Maximum	1.97	97	26	12	34

of stroke rates typical for training and competition. They rowed five trials at each prescribed stroke rate, giving a total of 25 trials. The trials were randomized. The participants were instructed to row as fast as possible for approximately 20 strokes, respecting the requested rating. Some of the participants were also asked to participate in several "resistance trials" (described below) following the 25 initial trials. All trials were performed in the same month, under similar calm weather conditions with no apparent water current. The participants signed an informed consent before the study began.

#### Equipment and data processing

A single scull (Euro Racing Boats, Australia) was equipped with the ROWSYS measurement and telemetry system, which was developed and built by the University of Sydney and the New South Wales Institute of Sports (Smith & Loschner, 2002). Forces on the pin were measured using three-dimensional piezoelectric transducers (Kistler, Switzerland) mounted on each pin. Oar angles in the horizontal plane were measured using servo-potentiometers (Radiospares 173-580), which were attached to both oars using a plastic rod. The oars (Croker S2 Slick, Australia) were allowed to move freely around the two axes. Boat velocity was measured using a trailing turbine (Nielsen Kellermann) with embedded magnets, mounted underneath the hull of the boat. The location of the sliding seat in relation to the boat was measured using a cable and drum potentiometer (Aerospace Technologies).

All data were sampled at 100 Hz. Raw data were transmitted to the shore in real-time using a wireless transmitter (PocketLAB, Digital effects) and stored in digital form. Before further processing, all data were filtered with a cut-off frequency of 10 Hz, using a third-order Butterworth filter. All subsequent calculations were carried out using MatLab (The MathWorks, USA).

For all variables of interest, the average over an entire rowing cycle was calculated. For each of the five trials in each condition, 10 consistent rowing cycles were selected on the basis of visual inspection, so for each condition the average of 50 rowing cycles was calculated. From each trial, the first five strokes were discarded, as well as strokes showing disturbances (noise) in the data. Stroke

consistency was checked by examining force-time and velocity-time profiles. At the beginning of each stroke, boat velocity together with oar angle of the port and starboard oars were calculated. The differences in these values between each subsequent stroke were determined to provide an indication of periodicity.

Statistical analysis was performed using a repeated-measures analysis of variance (ANOVA). Since in this design only the within-subject effects were investigated, there was no need to differentiate between male and female rowers. Following the repeated-measures ANOVA, Student's *t*-tests were performed to evaluate differences between conditions for all dependent variables. Pearson's correlation coefficient between stroke rate and the dependent variables was calculated. Statistical significance was set at  $P = 0.05$  for all tests.

#### Determination of the mechanical variables

All calculations were performed in two dimensions. A complete definition of the frame of reference used for the boat ( $x, y$ ) and port-side oar ( $x', y'$ ) is given in Figure 1. Lateral and vertical displacements of the boat were assumed to be negligible. Although variables were determined for both oars separately, only the calculations for one oar are given. A full rowing cycle was assumed to be periodic. The stroke phase was assumed to commence at minimum oar angle and to end at maximum oar angle. The recovery phase was assumed to commence at maximum oar angle and end at minimum oar angle. Oar angle ( $\phi_{\text{oar}}$ ) was zero when the oar was perpendicular to the shell. Stroke length ( $\phi_{\text{stroke}}$ ) and stroke duration ( $T_{\text{stroke}}$ ) were defined as the change in  $\phi_{\text{oar}}$  and time between catch and finish. The location of the centre of mass of the rower was assumed to be equal to the location of the sliding seat. Forces on the seat in the  $x$ -direction were assumed to be negligible.

Forces on the blade were assumed to act only perpendicular to the blade (Affeld *et al.*, 1993) and to apply at the centre of the blade. Pin force perpendicular to the blade ( $F_{\text{pin}}^{x'}$ ) was derived from directly measured pin forces in the  $x$  and  $y$  directions and oar angle. Neglecting oar mass, the forces perpendicular to the handle ( $F_{\text{hands}}^{x'}$ , assumed to act at 0.04 m from the inboard end of the oar) and blade

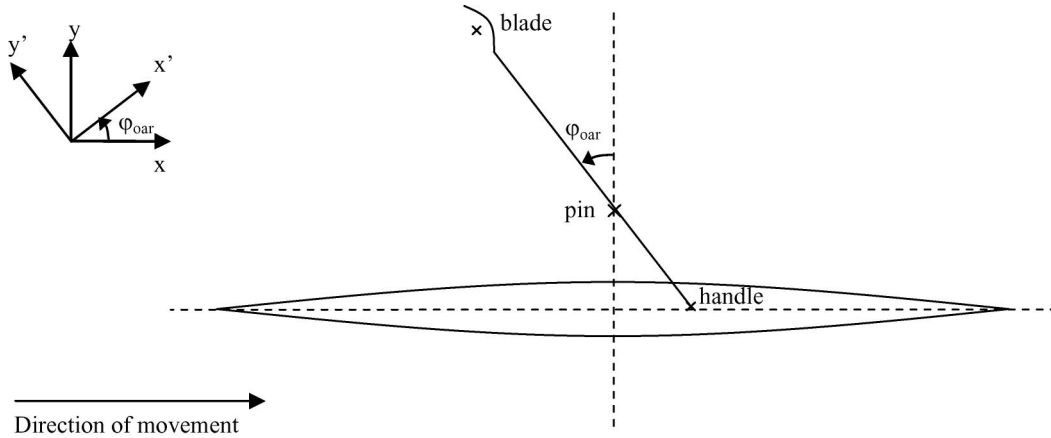


Figure 1. The shore-based frames of reference used in this study. The positive x-direction is in the direction of boat motion; the orientation of the  $x'$ - $y'$  system is defined by the orientation of the oar such that positive  $y'$  is in the direction of the vector from pin to handle. Oar angle ( $\phi_{oar}$ ) is considered positive in the direction of the release of the blades and zero when the oar is perpendicular to the boat. Points of application of handle, pin, and blade forces ( $F_{hands}$ ,  $F_{pin}$ , and  $F_{blade}$  respectively) are denoted by handle, pin, and blade.

( $F_{blade}^{x'}$ ) can be derived using the equations of motion for the oar:

$$F_{hands}^{x'} + F_{pin}^{x'} + F_{blade}^{x'} = 0 \quad (1a)$$

$$-F_{hands}^{x'} \cdot (y'_{handle} - y'_{pin}) - F_{blade}^{x'} \cdot (y'_{blade} - y'_{pin}) = 0 \quad (1b)$$

where  $y'_{handle}$ ,  $y'_{pin}$ , and  $y'_{blade}$  are the  $y'$  coordinates of the points of application of the forces on the handle, pin, and blade respectively in the  $x'$ ,  $y'$  frame of reference. With two equations that are linear in the two unknowns, this system can be solved for  $F_{hands}^{x'}$  and  $F_{blade}^{x'}$ .

Oar angular velocity ( $\omega_{oar}$ ) was calculated by taking the 5-point numerical time derivative of  $\phi_{oar}$ . The velocity in the  $x'$ -direction of the blade ( $\dot{x}'_{blade}$ ) in relation to the shore was calculated from the boat velocity signal ( $\dot{x}_{boat}$ ) and  $\omega_{oar}$ :

$$\dot{x}'_{blade} = \dot{x}_{boat} - \omega_{oar} \cdot (y'_{blade} - y'_{pin}) \quad (2a)$$

where  $\dot{x}_{boat}$  is the component of boat velocity in the  $x'$ -direction:

$$\dot{x}_{boat} = \dot{x}_{boat} \cdot \cos(\phi_{oar}) \quad (2b)$$

In its general form, the power equation for a linkage of rigid bodies connected in hinge joints can be written as:

$$\sum \mathbf{F}_e \cdot \mathbf{v}_e + \sum \mathbf{M}_e \cdot \dot{\phi}_e + \sum \mathbf{M}_j \cdot \dot{\phi}_j = \sum \frac{dE_{kinetic}}{dt} \quad (3)$$

(e.g. Van Ingen Schenau & Cavanagh, 1990; Zatsiorsky, 2002). The first term describes the power

exchange with the environment due to external forces, the second term the power exchange with the environment due to external moments (negligible in the case of rowing), and the third term the power inflow from the joint torques (i.e. net mechanical power production). The right-hand side of the equation describes the time derivative of kinetic energy of all the segments.

Neglecting seat forces, the instantaneous net mechanical power equation applied to the rower can be written as:

$$P_{rower} + F_{handle}^x \cdot \dot{x}_{handle} + F_{handle}^y \cdot \dot{y}_{handle} + F_{stretcher}^x \cdot \dot{x}_{boat} = \frac{dE_{kinetic}}{dt} \quad (4a)$$

(e.g. Zatsiorsky & Yakunin, 1991). Averaging this equation over one cycle during steady-state rowing with period time  $T$  yields the following expression for the average net mechanical power delivered by the rower ( $\bar{P}_{rower}$ ):

$$\bar{P}_{rower} = -\frac{1}{T} \int_{t_0}^{t_0+T} (F_{handle}^x \cdot \dot{x}_{handle} + F_{handle}^y \cdot \dot{y}_{handle}) dt + \frac{1}{T} \int_{t_0}^{t_0+T} (F_{stretcher}^x \cdot \dot{x}_{boat}) dt \quad (4b)$$

where  $F_{stretcher}^x$  is the force from the stretcher on the feet in the x-direction,  $F_{handle}^x$  is the force from the handle on the hands, and  $\dot{x}_{handle}$  and  $\dot{y}_{handle}$  are the velocity of the handle in the x- and y-direction respectively. As seen from this equation,  $\bar{P}_{rower}$  is not affected by changes in the kinetic energy of the rower, because for any periodic movement the time derivative of  $E_{kinetic}$ , averaged over one full cycle, equals zero.

Neglecting the horizontal seat force, it follows from the equation of motion of the rower that:

$$F_{\text{stretcher}}^x = m_{\text{rower}} \cdot \ddot{x}_{\text{rower}} - F_{\text{handle}}^x \quad (4c)$$

where  $m_{\text{rower}}$  is the mass of the rower and  $\ddot{x}_{\text{rower}}$  is the acceleration of the rower in the x-direction (approximated by the acceleration of the sliding seat). Substituting equation (4c) into equation (4b) yields:

$$\begin{aligned} \bar{P}_{\text{rower}} = & -\frac{1}{T} \int_{t_0}^{t_0+T} (F_{\text{handle}}^x \cdot (\dot{x}_{\text{handle}} - \dot{x}_{\text{boat}}) \\ & + F_{\text{handle}}^y \cdot \dot{y}_{\text{handle}}) dt + \\ & -\frac{1}{T} \int_{t_0}^{t_0+T} (m_{\text{rower}} \cdot \ddot{x}_{\text{rower}} \cdot \dot{x}_{\text{boat}}) dt \end{aligned} \quad (4d)$$

This can be rewritten as:

$$\begin{aligned} \bar{P}_{\text{rower}} = & -\frac{1}{T} \cdot \int_{t_0}^{t_0+T} (F_{\text{handle}}^{x'} \cdot (y'_{\text{handle}} - y'_{\text{pin}}) \cdot \omega_{\text{oar}}) dt + \\ & -\frac{1}{T} \cdot \int_{t_0}^{t_0+T} (m_{\text{rower}} \cdot \ddot{x}_{\text{rower}} \cdot \dot{x}_{\text{boat}}) dt \end{aligned} \quad (4e)$$

with  $F_{\text{hands}}^{x'}$  equal to  $-F_{\text{handle}}^{x'}$  as defined in equation (1a). The average power lost at the blades ( $\bar{P}_{\text{blade}}$ ) was calculated by taking the average over a rowing cycle of the dot product of  $\dot{x}'_{\text{blade}}$  and  $F_{\text{blade}}^{x'}$  for both handles:

$$\bar{P}_{\text{blade}} = \frac{1}{T} \cdot \int_{t_0}^{t_0+T} (F_{\text{blade}}^{x'} \cdot \dot{x}'_{\text{blade}}) dt \quad (5)$$

In line with previous research (e.g. Baudouin & Hawkins, 2004; Sanderson & Martindale, 1986), instantaneous drag power ( $P_{\text{drag}}$ ) was assumed to be proportional to frontal area, to a dimensionless drag constant  $C_d$  (both assumed to be constant throughout the rowing cycle), to density of water, and to velocity to the power of  $n$ . Combining the parameters,  $P_{\text{drag}}$  can then be calculated as:

$$P_{\text{drag}} = -k \cdot \dot{x}_{\text{boat}}^n \quad (6)$$

Constants  $k$  and  $n$  were determined from trials where participants were asked to build up speed and to subsequently keep the blades from touching the water as long as possible while sitting still. During these “resistance trials”, the drag force is the only horizontal force acting on the system and the acceleration of the total centre of mass is equal to the boat acceleration. This means that the equation of motion for the boat, rower, and oars system can be written as:

$$m_{\text{total}} \cdot \ddot{x}_{\text{boat}} = -k \cdot \dot{x}_{\text{boat}}^{n-1} \quad (7a)$$

This is a first-order non-linear ordinary differential equation, which has the following solution:

$$\dot{x}_{\text{boat}}(t) = \left( \left( -\frac{k}{m_{\text{total}}} \cdot t + C \right) \cdot (2-n) \right)^{\frac{1}{2-n}}$$

With:

$$C = \frac{\dot{x}_0^{2-n}}{2-n} \quad (7b)$$

where  $\dot{x}_{\text{boat}}(t)$  is the boat velocity as a function of time ( $t$ ),  $\dot{x}_0$  is the initial velocity at  $t=0$ , and  $m_{\text{total}}$  is the total mass of the system. Constant  $k$  can be scaled to the total mass since the boat frontal area, and thus  $k$ , is expected to increase linearly with increasing mass. By fitting this model to the experimental data using the least squares method, values for  $k$  and  $n$  were obtained.  $\bar{P}_{\text{drag}}$  was calculated as the average over a full rowing cycle of  $P_{\text{drag}}$ .

#### Determination of the efficiency terms

To calculate the efficiency terms described below, the assumption was made that rowing is perfectly periodic, hence the average time derivative of all kinetic energy terms equals zero. Consequently, the average sum of all power terms should equal zero:

$$\bar{P}_{\text{rower}} + \bar{P}_{\text{blade}} + \bar{P}_{\text{drag}} = 0 \quad (8)$$

Propelling efficiency ( $e_{\text{propelling}}$ ), which describes the fraction of  $\bar{P}_{\text{rower}}$  not lost at the blades, was calculated as:

$$e_{\text{propelling}} = 1 - \frac{\bar{P}_{\text{blade}}}{\bar{P}_{\text{rower}}} \quad (9a)$$

This can also be written as:

$$e_{\text{propelling}} = 1 - \frac{W_{\text{blade,cycle}}}{W_{\text{rower,cycle}}} \quad (9b)$$

$W_{\text{blade,cycle}}$  represents the work performed at the blades and  $W_{\text{rower,cycle}}$  the net mechanical work performed by the rower during one complete rowing cycle.

To quantify the power loss caused by fluctuations in velocity, we introduce the term velocity efficiency ( $e_{\text{velocity}}$ ). The difference between actual drag and hypothetical drag if the boat speed were constant was calculated. Hypothetical drag at constant boat velocity was calculated using equation (6), but with average velocity of the rowing cycle ( $\bar{\dot{x}}_{\text{boat}}$ ) as input. The fraction of  $\bar{P}_{\text{rower}}$  that was not lost to velocity fluctuations,  $e_{\text{velocity}}$ , was calculated as follows:

$$e_{\text{velocity}} = 1 - \frac{\bar{P}_{\text{drag}} - k \cdot \bar{\dot{x}}_{\text{boat}}^n}{\bar{P}_{\text{rower}}} \quad (10)$$

The fraction of  $\bar{P}_{\text{rower}}$  that contributes to the average velocity was expressed as net efficiency ( $e_{\text{net}}$ ), which was calculated as:

$$e_{\text{net}} = \frac{\bar{P}_{\text{rower}} - (1 - e_{\text{propelling}}) \cdot \bar{P}_{\text{rower}} - (1 - e_{\text{velocity}}) \cdot \bar{P}_{\text{rower}}}{\bar{P}_{\text{rower}}} \\ = e_{\text{propelling}} + e_{\text{velocity}} - 1 \quad (11)$$

## Results

### Drag

The constants  $k$  and  $n$  in equations (6), (7a), and (7b) were experimentally determined at 0.054 times the mass of the rower, boat, and oars for  $k$  and 2.7 for  $n$ . Figure 2 shows the relationship between the actual and the predicted velocity during the resistance trials. The correlation between actual and predicted velocity was significant at  $r=0.99$  ( $P < 0.05$ ). Although because of the nature of the measurements, most data points were obtained below the range of shell velocity during the other experiments, the data show there is no reason to expect different drag behaviour at higher velocities.

### Accuracy of the calculated powers and indication of periodicity

In steady-state rowing,  $\bar{P}_{\text{rower}}$  should equal the absolute sum of  $\bar{P}_{\text{blade}}$  and  $\bar{P}_{\text{drag}}$  (equation 8). A comparison of the calculated values for the power terms provides an indication of the accuracy of the calculation of the separate terms. In this study, the sum of  $\bar{P}_{\text{blade}}$  and  $\bar{P}_{\text{drag}}$  had an average absolute deviation of 7% of  $\bar{P}_{\text{rower}}$  (26.3 W) for all trials.

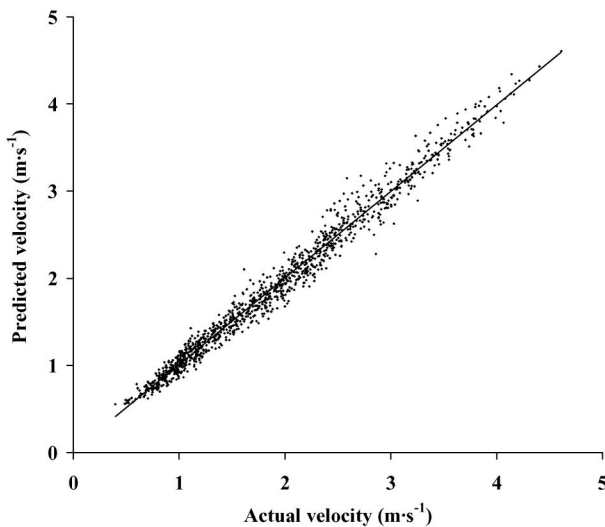


Figure 2. Relationship between the predicted velocity and the actual velocity during the “resistance trials”. Note that data are taken from several participants.

The mean absolute difference in  $\phi_{\text{oar}}$  of the port and starboard side oar and  $\dot{x}_{\text{boat}}$  at the beginning of the stroke between each subsequent stroke was  $1.16^\circ$  ( $s=4.40$ ),  $1.14^\circ$  ( $s=4.92$ ), and  $0.13 \text{ m} \cdot \text{s}^{-1}$  ( $s=0.14$ ) respectively. This indicates that the behaviour was sufficiently close to being periodic, as intended.

### Effect of Stroke rate on $\bar{P}_{\text{rower}}$ , $e_{\text{propelling}}$ , $e_{\text{velocity}}$ , and $e_{\text{net}}$

The repeated-measures ANOVA demonstrated a significant main effect of stroke rate for  $\dot{x}_{\text{boat}}$  ( $P < 0.0001$ ),  $\bar{P}_{\text{rower}}$  ( $P < 0.0001$ ),  $e_{\text{propelling}}$  ( $P < 0.0001$ ),  $e_{\text{velocity}}$  ( $P < 0.0001$ ), and  $e_{\text{net}}$  ( $P < 0.0001$ ). The variables  $\dot{x}_{\text{boat}}$ ,  $\bar{P}_{\text{rower}}$ , and  $e_{\text{propelling}}$  all increased monotonically as stroke rate increased, whereas  $e_{\text{velocity}}$  decreased with increasing stroke rate. The correlation coefficient between stroke rate and  $\dot{x}_{\text{boat}}$ ,  $\bar{P}_{\text{rower}}$ ,  $e_{\text{propelling}}$ ,  $e_{\text{velocity}}$ , and  $e_{\text{net}}$  averaged over participants was 0.96, 0.98, 0.82,  $-0.72$ , and 0.73 respectively, indicating a strong linear relationship between stroke rate and these dependent variables ( $P < 0.05$  for all comparisons).

The average values and standard deviations for  $\dot{x}_{\text{boat}}$ ,  $\bar{P}_{\text{rower}}$ ,  $e_{\text{propelling}}$ ,  $e_{\text{velocity}}$ , and  $e_{\text{net}}$  at the five stroke rates are presented in Table II. Figure 3a provides a graphical representation of the average values for  $e_{\text{propelling}}$ ,  $e_{\text{velocity}}$ , and  $e_{\text{net}}$ .

The increase in  $\bar{P}_{\text{rower}}$  was mainly due to the increasing stroke rate, since  $W_{\text{rower,cycle}}$  did not differ significantly between stroke rates for each participant. Propelling efficiency increased at increasing stroke rate despite an increase in  $\bar{P}_{\text{blade}}$ , because  $\bar{P}_{\text{rower}}$  increased more than  $\bar{P}_{\text{blade}}$ . Velocity efficiency decreased at increasing stroke rate because  $\bar{P}_{\text{rower}}$  increased less than the power lost due to velocity fluctuations. Net efficiency increased at increasing stroke rate because the increase in  $e_{\text{propelling}}$  was higher than the decrease in  $e_{\text{velocity}}$ . Figure 3b provides a graphical representation of the average values for  $\bar{P}_{\text{rower}}$ ,  $\bar{P}_{\text{drag}}$ , and  $\bar{P}_{\text{blade}}$ . The values for  $T_{\text{stroke}}$ ,  $\phi_{\text{stroke}}$ ,  $W_{\text{rower,stroke}}$ , and  $W_{\text{blade,stroke}}$  are presented in Table III.

## Discussion

The values for  $e_{\text{propelling}}$  and  $e_{\text{velocity}}$  in this study are in the same range as those reported previously. Although using different methods of calculation, Kleshnev (1999) reported values of 0.785 for  $e_{\text{propelling}}$  and 0.938 for  $e_{\text{velocity}}$  (in his study, called “blade efficiency” and “boat efficiency” respectively). Kleshnev concluded that the greatest improvements in performance could be expected when increasing  $e_{\text{propelling}}$ , because the amount of power that is lost to blade slip is considerably greater than the amount of power lost to boat speed

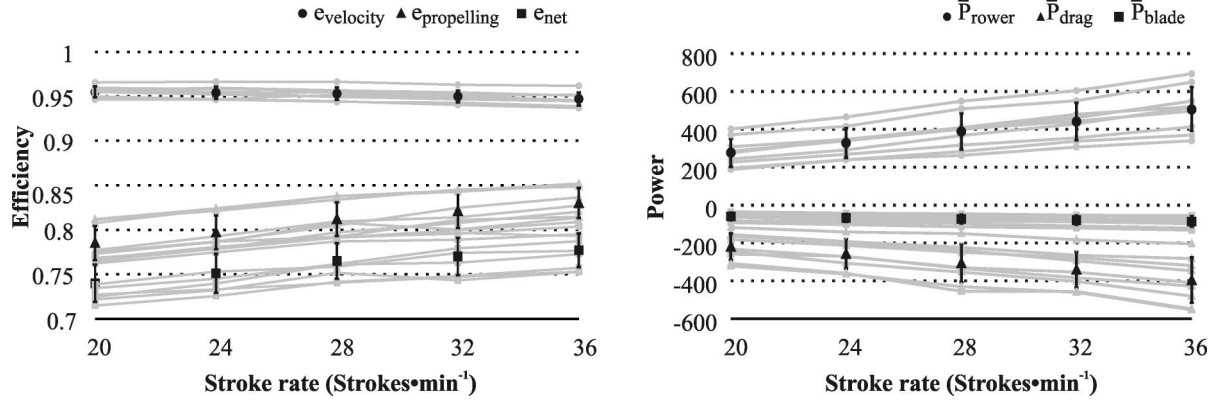


Figure 3. (a) Values and inter-subject standard deviations of  $e_{\text{propelling}}$ ,  $e_{\text{velocity}}$ , and  $e_{\text{net}}$  as a function of stroke rate. (b) Values and inter-subject standard deviations of  $\bar{P}_{\text{rower}}$ ,  $\bar{P}_{\text{drag}}$ , and  $\bar{P}_{\text{blade}}$  as a function of stroke rate. Average values are indicated by solid symbols. Open symbols indicate individual values. Note that the standard deviations concern inter-subject variability and do not influence the ANOVA results.

Table III. Stroke time, stroke length, work rate of the rower per stroke, and work at the blades per stroke (mean  $\pm$  s).

Stroke rate	$T_{\text{stroke}}$ (s)	$\phi_{\text{stroke}}$ (°)	$W_{\text{rower,stroke}}$	$W_{\text{blade,stroke}}$
20	$1.12 \pm 0.059$	$105.4 \pm 5.83$	$799.1 \pm 211$	$173.4 \pm 54.4$
24	$1.06 \pm 0.044$	$104.5 \pm 5.33$	$799.5 \pm 194$	$163.6 \pm 49.7$
28	$1.00 \pm 0.044$	$103.4 \pm 5.72$	$809.0 \pm 195$	$153.1 \pm 45.8$
32	$0.94 \pm 0.039$	$102.3 \pm 5.32$	$813.9 \pm 187$	$147.3 \pm 45.5$
36	$0.89 \pm 0.037$	$100.1 \pm 5.46$	$827.6 \pm 188$	$141.8 \pm 42.5$

Note: The standard deviations concern inter-subject variability and do not influence the ANOVA results.

fluctuations. However, it is currently unclear how net efficiency can be improved by the rower. Overall, rowing appears to become more efficient at higher stroke rates.

Our results clearly demonstrate that at higher stroke rates the rower is able to generate a higher net mechanical power output, resulting in a higher average velocity. This is in line with results reported previously (Martin & Bernfield, 1980). However, it must be noted that it is unlikely that rowers are able to maintain the  $\bar{P}_{\text{rower}}$  found at the highest stroke rates during a 2000-m race, if only because the preferred racing stroke rate reported by the participants was considerably lower than 36.

Velocity efficiency is reduced when the stroke rate increases. This is most likely because at higher stroke rates there is greater impulse exchange between the rower and the boat, since the accelerations of the rower relative to the boat must be higher when stroke length remains constant (see Table III). This is in accordance with the results of Loschner and Smith (1999), who previously reported the relationship between movement of the rower (represented by seat movement) and boat acceleration. Higher accelerations of the rower will result in larger fluctuations of the velocity of the rowing boat, which in turn will result to a higher relative power loss.

Although average  $e_{\text{velocity}}$  differed less than 1% between the lowest and the highest stroke rate, the

differences between all stroke rates were significant. However small, these differences are important. This becomes clear when the outcome on a 2000-m race is predicted. With all other variables remaining constant, a rower with an  $e_{\text{propelling}}$  of 0.8 and an  $e_{\text{velocity}}$  of 0.950 finishes the 2000-m race 5 m ahead (almost a boat length in a single scull) of an otherwise identical rower with an  $e_{\text{velocity}}$  of 0.945, as calculated from equations (6) and (8) through (10).

As mentioned in the Introduction, analysis of our data in the context of the mechanical power equation does not allow separation of the rower's net mechanical power output into positive and negative muscle contributions. Internal dissipation of mechanical energy (negative muscle power) is associated with deceleration of the body (reduction of the kinetic energy) through eccentric muscle contractions. At higher stroke rates, the fluctuations in kinetic energy are larger, suggesting that the internal dissipation of mechanical energy increases with stroke rate. An indirect way of investigating the magnitude of the negative muscle power is by considering metabolic energy expenditure. As both the dissipation of mechanical energy and the subsequent regeneration thereof involve metabolic energy expenditure, gross mechanical efficiency could be expected to deteriorate with increasing stroke rate if negative muscle power is substantial. From this it follows that minimization of negative

muscle power could be an important aspect of intermuscular coordination in rowing. As no data are known to us on the relation between stroke rate and gross mechanical efficiency or the amount of internal dissipation of mechanical energy in rowing, this is an area for future research.

The calculation of drag forces is based on relaxation measurements during which the rower does not move relative to the boat and during which the boat decelerates monotonically. Determining drag forces during passive motion in water is a common practice in this type of research (e.g. Zatsiorsky & Yakunin, 1991). This is a topic for future research, however, since during rowing competition the orientation and depth of immersion of the boat vary (Wagner, Bartmus, & Marees, 1993) and boat acceleration is non-zero during a rowing cycle. These variations must affect the drag forces. Lazauskas (1997) has proposed a more extensive model for calculating drag. However, actual measurements of drag during rowing are also necessary to obtain reliable values.

Intuitively, the positive correlation between stroke rate and  $e_{\text{propelling}}$  is unexpected, because at higher stroke rates more splashing and foam at the blades are typically observed, which could indicate a higher  $\bar{P}_{\text{blade}}$ . In fact, both  $\bar{P}_{\text{rower}}$  and  $\bar{P}_{\text{blade}}$  increase when the stroke rate increases. However, the relative increase in  $\bar{P}_{\text{blade}}$  is smaller, causing an increase of

$e_{\text{propelling}}$ , as also reported by Kleshnev (1999). During the recovery almost no mechanical work is done by the rower (data not shown here) and by definition no work is done by the blades. Thus it can be stated that as  $W_{\text{rower,cycle}}$  does not vary between different stroke rates (see Table II), the relatively small increase in  $\bar{P}_{\text{blade}}$  in relation to the increase in  $\bar{P}_{\text{rower}}$  is caused by a decrease in  $W_{\text{blade,stroke}}$  (equation 9b).

Figure 4 illustrates the path of the blade through the water at stroke rates of 20 and 36 strokes per minute. Although at both stroke rates the distance between blade insertion and retraction is about the same, at a stroke rate of 20 the blade moves over a considerably greater distance in the direction opposite to the direction of movement during the middle part of the stroke. In this phase of the stroke the greatest amount of work at the blades is performed, since the blade is almost perpendicular to its path and a large mass of water is being moved. This may explain why at higher stroke rates, when the blade moves less in the opposite direction, less work is performed at the blades.

The exact mechanisms of the way  $\bar{P}_{\text{blade}}$  is generated remain unclear. From investigation of calculated blade kinematics, it would appear that lift forces contribute to the propulsion. This has also been reported by several other authors (Affeld *et al.*, 1993; Baudouin & Hawkins, 2002). Figure 4 clearly

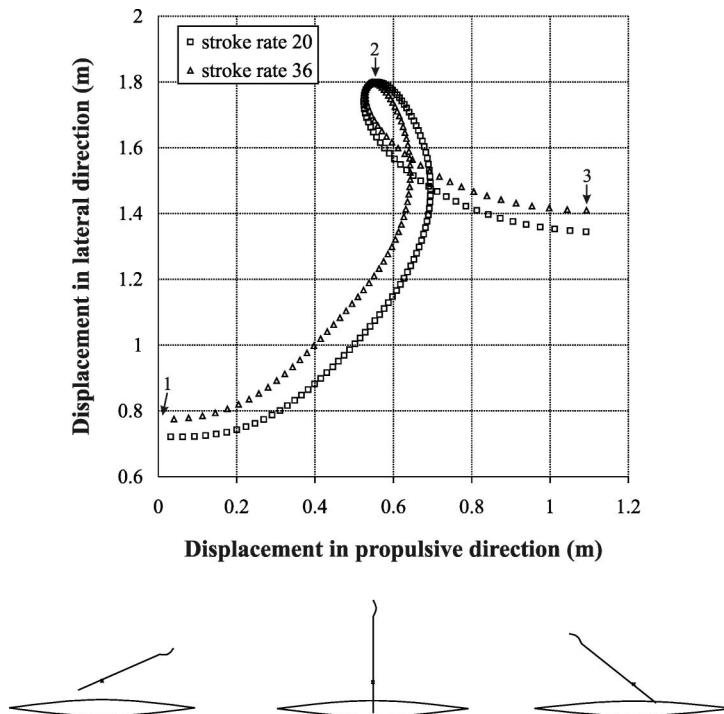


Figure 4. Example of the trajectory of the blade through the water during the stroke phase at stroke rates of 20 and 36 strokes per minute. The entry of the blade is plotted at the left-hand side of the graph. The curves are obtained from a 10 stroke average of a typical participant. The time interval between data points is 0.01 s. 1, 2, and 3 indicate the oar orientation at the beginning, middle, and end of the stroke.



shows that the displacement of the blade in propulsive direction is mainly in the direction of movement. Because the direction of drag forces is opposite to the direction of movement, lift forces on the blade are necessary to create a propulsive force on the boat during the stroke phase. This poses blade developers with a challenge, since, for optimal functionality, lift forces should be maximal during the first part of the stroke, whereas drag forces should be maximal during the middle part (Dreissigacker & Dreissigacker, 2000).

The flow of water around the blade will be very turbulent, causing the hydrodynamics around the blade to be complex (see also Barré & Kobus, 1998). The best way to obtain the kinetics of the blade would be to measure the forces directly. Future research on blade hydrodynamics, as well as the development of equipment allowing measurement of the force distribution over the blade, might provide answers to what actually happens around the blades.

In conclusion, this study has outlined the effect of stroke rate on the power flow in short-duration maximum-effort rowing. As the average net mechanical power output generated at the highest stroke rates investigated is unlikely to be sustainable over a 2000-m race, future research should address the possible changes in power flow during a longer period of exertion.

We have shown that the power equation is an adequate conceptual model to analyse rowing performance. The results indicate that stroke rate not only affects the net mechanical power output of the rower, but also affects the power loss at the blades and the power loss associated with velocity fluctuations. When similar data become available on the effects of other technique-related factors, it may become possible to understand the optimal technique as the optimal compromise between generation of power by the rower and power loss to variables not contributing to average velocity.

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