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The impact of fluctuations in boat velocity during the rowing cycle on race time

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In competitive rowing, the fluctuations in boat velocity during the rowing cycle are associated with an increased water resistance of the boat as compared with a boat moving at a constant velocity. We aimed to quantify the influence of the increased water resistance on race time using a mathematical approximation, based on the increase in physiological power being proportional to the 2nd power of boat speed. Biomechanical data (oar force, rowing angle, boat velocity, and boat acceleration) were measured when eight elite coxless pair crews performed a rowing test with a stepwise increasing stroke rate (SR: 20, 24, 28, and 32 min^{-1}) that successively increased the mean boat speed. The results revealed a +4.59 s (SR 24.2) to +5.05 s (SR 31.5) 2000-m race-time difference compared with a boat hypothetically moving without velocity fluctuations. Velocity fluctuations were highly correlated with SR ($r = 0.93$) because the accelerations of the rowers' body mass and the mass of the counteracting boat increase with SR. The possibilities to reduce velocity fluctuations and therefore race time are limited. For elite rowers, race time may be slightly reduced by a moderate reduction in SR that is compensated by an increased force output for each stroke.

In competitive rowing, fluctuations in boat velocity during the rowing cycle increase the average water resistance of the boat compared with a boat hypothetically moving at a constant velocity (v). Water resistance should be approximately proportional to $v^{1.8}$ (Affeld et al., 1988a) or v^2 (Koerner & Schwanitz, 1985; Nolte, 1991; Brearley et al., 1998) – that is, water resistance is increased about four times when velocity is doubled. In detail, the increased water resistance in the phases of the rowing cycle when the boat velocity is larger than the mean velocity of a rowing cycle is only partially compensated by the decreased water resistance when the boat velocity is below the mean velocity. For this reason, it would be most effective to keep boat velocity constant. However, this is impossible because (i) the rowing cycle is divided into a propulsive (drive) phase and a recovery phase and (ii) the rower's center of gravity moves relative to the boat, toward the bow in the drive phase and toward the stern in the recovery phase. This enforces an acceleration of the boat in the opposite direction. As the rower's mass is several times larger than the mass of the boat, the acceleration of the boat is larger than the acceleration of the rower's mass.

To reduce velocity fluctuations, it was proposed to modify the rowing technique (e.g. Celentano et al., 1974; Sanderson & Martindale, 1986; Nolte, 1991; Smith & Loschner, 2002; Baudouin & Hawkins, 2004). Assessing the outcome of such changes in rowing technique directly in a field study is impossible because the measuring error, due to the variance of physiological and psychological factors between repeated measures (this means the comparison of rowing in a "good" and a "poor" technique), is too high. Some authors applied a mathematical model of the rowing movement to solve the problem (e.g. Celentano et al., 1974; Sanderson & Martindale, 1986; Affeld et al., 1988a, b; Brearley et al., 1998), but modelling such a complex movement is difficult and wrong assumptions and simplifications may lead to irrelevant conclusions.

A solution to quantify the effect of velocity fluctuations on race time is to model real data measured during on-water rowing by a less complex mathematical approximation. The approach was described by Nolte (1991) and applied in a case study in the single scull (Hill, 1997). This revealed for a 2000 m time of 7 min additional 4.6 s (when rowing with a symmetrical force pattern) to 5.05 s (catch-accentuated force pattern) when compared with a boat hypothetically moving at a constant velocity. Although the symmetrical force graphs were smoother, resulting in a smoother profile of boat acceleration and boat velocity, the larger time loss for the other condition was due to the higher stroke rate (SR) (37.1 vs 33.9 min^{-1}). This can be explained by the following model: to increase SR, the rower shortens the recovery phase by moving faster relative to the boat (toward the stern). This enlarges acceleration and deceleration of the body mass and the counteracting boat; the fluctuations in boat velocity increase. The drive phase will also be shortened when force output is maintained because the boat is moving faster, but this effect is small compared with the shortening of the recovery phase (e.g. Hill, 1995, 2002). This model was confirmed by additional data measured in different training runs in the single scull and the coxless pair (Hill, 1997). Data obtained from rowing with different SRs (from 19 to 37.1 min^{-1}) showed a strong correlation ($r = 0.92$) between SR and the fluctuations in boat acceleration.

Beyond the methodological limitations and the preliminary results of this single-case study, the present study aims to investigate the effect of velocity fluctuations in a larger sample, using a standardized protocol and extended and more accurate biomechanical measures (e.g. in the case study, the mean boat speed was computed from the boat acceleration data, which can be affected by offset inaccuracies). This approach allows a statistical analysis and potentially the detection of between-crew differences and their underlying factors. Furthermore, the test protocol enables the systematic investigation of the effect of SR on velocity fluctuations and the related race time differences, whereby the repeated measures design eliminates a confounding by different rowing styles.

Materials and methods

Subjects and procedure

Data were obtained from 15 male competition-experienced oarsmen from a local training group and two national squad teams who performed a rowing test for biomechanical diagnostics in the coxless pair (Fahrig et al., 2006). The mean age was 20.3 years (range 17–31 years), the mean body height was 1.89 m (range 1.83–1.94 m), and the mean body mass was 83.2 kg (individual range 70–90 kg, range of mean crew mass 70.5–90 kg). Ten measurement sessions were undertaken at three different dates and locations: two in November 2003 in Dortmund, four in November 2004 in Cologne, and four in April 2005 in Montpellier. One oarsman participated twice but with different crew partners, and two crews were measured twice (at different dates). Therefore, to avoid repetition effects, only one measure of these two crews was used for statistical analysis (the measurements that showed the larger deviation to the planned SRs of the rowing test were excluded).

Boats (Empacher, Eberbach, Germany) and carbon oars (Concept II, Morrisville, VT, USA) were equipped with the mobile measuring system MMS2000 (FES, Berlin, Germany, www.fes-sport.de; Böhmert & Mattes, 2003) to collect biomechanical data. This system was developed for biomechanical diagnostics and has been used in the German Rowing Association since 2000. Oar force was assessed with sensors fixed to the oars inboard near the point of rotation, which measured the flexion of the oar. For calibration, weights were attached at the transition between the shaft and the blade of the oars, which were fixed 5 cm from the end of the handle and propped up under the oarlock in the horizontal plane. The oar angle was measured with potentiometers mounted on the oar gate. Acceleration of the boat in its length-axis was measured with a 2 g sensor attached near the stretcher of the bowman. Boat velocity was measured with an impeller mounted underneath the boat. For the measurements in April 2005, boat velocity was measured with a high-resolution GPS system (Reinking & Härting, 2002) instead of an impeller. The accuracy of the GPS system (vector length of 3 mm between two samples) is high enough to measure horizontal (yawing) and vertical (pitching) boat movements (Fahrig et al., 2006; Wagner et al., in press). Data from the MMS2000 were digitized with a sample rate of 50 Hz and a resolution of 12 bits and stored on a hard disk. Data from the GPS system were digitized with a sample rate of 10 Hz, interpolated to 50 Hz, and synchronized offline with the data of the MMS2000 data based on the correlation between the acceleration data obtained from both measuring systems. Although a resolution of 10 Hz is very low for measuring rowing data on the single-stroke level, the GPS system allows measurement of mean boat velocity with sufficient accuracy for a longer time interval.

After warming up, each crew rowed about 100 strokes, divided into four intervals with a stepwise increase in SR (planned SRs 20/24/28/32 min^{-1}).

Data analysis

Data were analyzed offline using a custom-made software, as well as data analysis software DADiSP (http://www.dadisp.com). Details of the algorithms used for automatic stroke detection and force graph analysis are given in Hill (2002). A rowing cycle was defined from onset of stroke (drive phase) n to the last sample point before onset of stroke $n+1$. SR (min^{-1}) was defined as 60/(onset time stroke $n+1$ – onset time stroke n). For each stroke, the area under the force graph [impulse (per stroke)] (Fig. 1(a)), as well as factors for smoothness (Fig. 1(b)) and center of force graph were computed (Fig. 1(c)). As measures of the rowers' performance for the different SR intervals, the product impulse × SR and the mechanical power P_{mech} were computed. P_{mech} was calculated as follows: for each sample point, the force F at the handle of the oar was multiplied by the handle velocity $v = (\text{oar angle [sample]} \times 2\pi \times 1.1\,\text{m})/(360 \times \text{time [sample]})$. The average value of $F \times v$ for all samples was computed and divided by the duration of the rowing cycle. It should be noted that this calculation provides the rower's power applied to the oar (which is different from propulsive power) and it was not considered that the effective length of the oar handle changes during the drive phase (e.g. Schneider, 1980; Nolte, 1985; Affeld et al., 1988a). However, in order to compare different SRs in a within-subject design, this calculation is sufficient. The relations between impulse × SR and P_{mech} with mean boat speed were analyzed by means of power regressions. The computation of fluctuations in boat acceleration is described in Fig. 1(d). Fluctuations in boat velocity were computed accordingly.

Mean values for the different variables were computed for each of the four intervals with different SRs separately. Data were visually examined for to-be-excluded artifacts. Only those strokes were included in which SR, area of force graphs (impulse), and mean boat velocity were nearly constant, as indicated by the stroke-by-stroke course of these variables

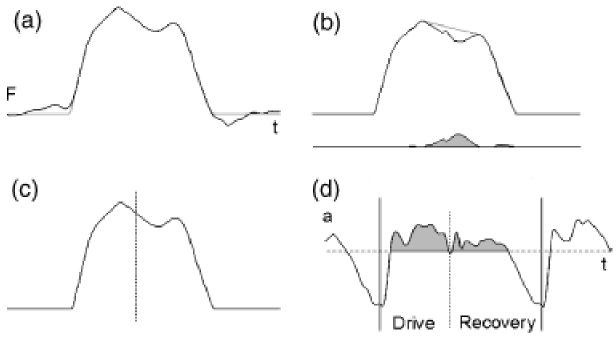

Fig. 1. Method of force graph analysis. (a) Detection of catch and finish by fitting tangents to the steepest slope and extrapolate them to the baseline; cutting of negative values. (b) Smoothness of force graph. To compute smoothness, a line (gray shaded) was drawn over the concave segments of the force graph. The algorithm checked for maxima and turning points and computed the area between the force graph and the interpolated line between two maxima or turning points. This area (gray shaded difference area at the bottom) was related to that of the force graph. In the given example the value for smoothness is 4%. (c) The center of force graph was computed to determine whether the force graph patterns could be assigned to a harder catch, a harder finish, or a pattern somewhere in between. The point (indicated by the dotted vertical line) at which the force graph was divided into two halves of equal areas was computed and related to the duration of the drive phase. Drive duration is set to 100%. In the example, the value for the center is 45.8%. (d) Computation of fluctuations in boat acceleration. The acceleration–time course for each rowing cycle (indicated by the two vertical lines marking the onset of the drive phases of stroke n and stroke $n+1$) was baseline corrected (mean value = 0) and the mean of the positive part (gray-shaded area) of the acceleration–time course was computed (the mean is independent of time whereas the area depends on the duration of the rowing cycle or the stroke rate, respectively).

(Fig. 2). Strokes forming the transition between two SR intervals were excluded from analysis.

The variable $dT_{2000\,m}$, expressing the effect of velocity fluctuations on race time, was computed based on the integral of the boat acceleration data of the MMS2000 (Fig. 3) because (i) two different systems (either impeller or GPS) were used to measure boat velocity and (ii) the accuracy of an acceleration measure is better for detecting fast changes in velocity. As the acceleration-based measure is too inaccurate for computing the absolute boat velocity (e.g. due to offset inaccuracies), the integral of the acceleration time course was adjusted to the mean value obtained from the boat velocity measure. For comparison, $dT_{2000\,m}$ was computed for the original boat velocity data as well. These data were very similar to the acceleration-based data and strongly (and significantly) correlated ($r = 0.95$) with them. Furthermore, the comparison of the impeller-based (e.g. Fig. 3) as well as the GPS-based velocity time courses with the integral of the boat acceleration showed only marginal differences, demonstrating sufficient accuracy for both systems to measure boat velocity without producing a bias.

Physiological variables are the limiting factors for rowing performance and physical variables like P_{mech} are dependent variables. Therefore, the following calculations for $dT_{2000\,m}$ were based on a model assuming that physiological power, which is equivalent to oxygen uptake under submaximal physical load, is proportional to the 2nd power of boat speed. This factor is close to the literature data for measures in real rowing, in contrast to higher factors reported for the rowing ergometer data (which may depend on specific flywheel characteristics). For comparison, calculations based on the 2.5th and the 3rd power of speed are provided as well.

Definition of variable $dT_{2000\,m}$

For a better illustration of the effect of velocity fluctuations on race time, it was related to a 2000 m race time instead of a difference in mean boat speed. That is, the variable $dT_{2000\,m}$ reflects the additional time in seconds required for the 2000 m distance compared with a boat hypothetically moving at a constant velocity.

To illustrate the procedure for calculation of $dT_{2000\,m}$, it can be applied to a simplified model by Nolte (1991) in which a "rowing cycle" is divided into two phases of equal duration: one phase with a velocity of 4 m/s, and the other phase of 6 m/s (the mean velocity being 5 m/s, which corresponds to a 2000 m time of 6 min 40 s). The mean of the squared velocity $= (4^2+6^2)/2 = 26$. This 4% increase of drag ($25 \times 1.04 = 26$) would cost an additional 4% of physiological power (based on the used quadratic model). Therefore, when rowing with the same physiological power in a virtual boat with constant velocity, the virtual rowing speed would be $\sqrt{26} = 5.099$ m/s, or a 2000 m time of 6 min 32.2 s. For this hypothetical example, the increased water resistance due to velocity fluctuations would cost an additional 7.8 s in a 2000 m race.

Analyses proceeded in the following steps:

(i) For each SR interval, the measured and calibrated data for boat acceleration and boat velocity were selected. The interval was defined from the onset of the first stroke to the last sample point before the onset of the last stroke.
(ii) The acceleration data were corrected for offset drifts: The mean of the segment was calculated and subtracted from each sample point, resulting in a mean value of zero, so that positive and negative acceleration cancelled out one another.
(iii) The integrals i_{acc} (= velocity–time course) of the acceleration–time course were computed and baseline corrected again (cf. Fig. 2).
(iv) The mean of the velocity–time course (mean boat speed) obtained from the velocity measure (impeller or GPS) was computed. This value was added as an offset to adjust the velocity–time course obtained by integrating the acceleration data (i_{acc}) to the real boat speed (cf. Fig. 3).
(v) The velocity–time course (i_{acc}) was first squared sample by sample. Then the mean value of the squared velocity time course was computed. This mean value is proportional to the water resistance acting at the hull.
(vi) The square root of the result of (v) is equivalent to the virtual boat velocity without velocity fluctuations. The 2000 m times for the real (measured) boat velocity and for the virtual (computed) velocity, and the difference $dT_{2000\,m}$ between both values, were computed.

For statistical analysis, analyses of variance (ANOVA) were computed. The Newman–Keuls test was used for pairwise *post hoc* comparisons of significant ($P < 0.05$) main effects and interactions. To investigate correlations between variables, Pearson's r was computed. The software STATISTICA 5.1 (http://www.statsoft.com) was used for analysis, except for the power regressions, which were computed with STATVIEW 5.0 (http://www.statview.com).

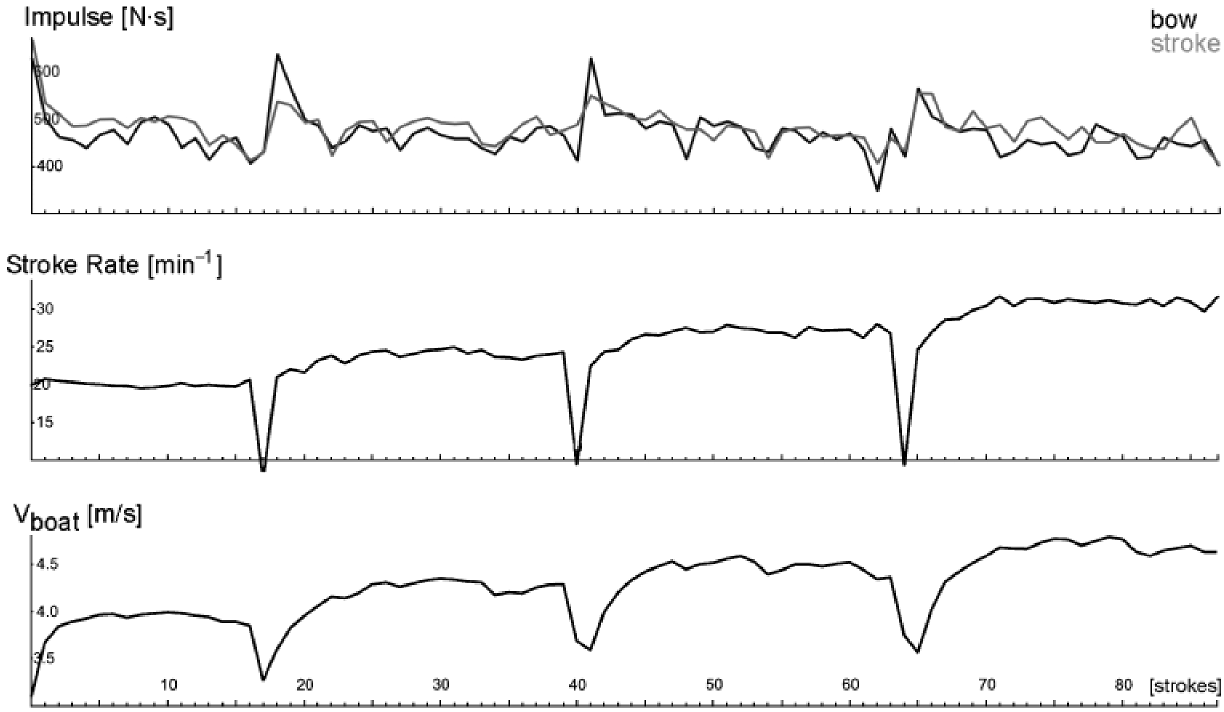

Fig. 2. Selected variables derived from the analysis of the measured biomechanical data of one coxless pair crew. Course of area under the force graph [impulse (per stroke), upper trace], stroke rate (middle), and mean boat velocity (below) for all four stroke rate intervals (90 rowing cycles total). Stroke rate and mean boat velocity increase from interval to interval. The breaks between the intervals are clearly indicated by the reduced velocity and the increased impulses at the beginning of the next interval (because boat velocity is smaller the drive duration is longer and, hence, the impulse larger).

Results

The mean values of the analyzed variables for each of the four SR intervals separately are presented in Table 1. Separate ANOVAs for each of these dependent variables were computed with SR interval as the repeated measures factor. F and P values for the main effect interval are given in Table 1 as well. For the variables impulse and drive duration (T_{drive}), a second repeated measures factor for seat position (bow, stroke) was included.

The variables SR, impulse $\times$ SR, mechanical power (P_{mech}), and mean boat velocity (v_b) increased significantly from interval to interval and consequently the drive duration and the virtual 2000 m time decreased. *Post hoc* tests revealed significant differences between all intervals for these variables. For P_{mech} as well as for drive duration no main effect or interaction with seat position was found. No statistical difference was found for the variable impulse. $\mathrm{d}T_{2000\,\mathrm{m}}$ was the lowest for SR 24 (interval 2) and the largest for SR 32 (interval 4). For $\mathrm{d}T_{2000\,\mathrm{m},}$ a significant main effect was found; the *post hoc* analysis revealed significant differences between interval 4 and all other intervals. The models calculated for comparison with the assumption that physiological power is proportional to the 2.5th (3rd) power of speed instead of the 2nd power revealed mean values of 6.87 s (8.89 s), which is 1.43 (1.85) times the mean of $\mathrm{d}T_{2000\,\mathrm{m}}$ (4.8 s).

Considering the mean values of $\mathrm{d}T_{2000\,\mathrm{m}}$ (4.59–5.05 s), the variance between crews was remarkably high. The largest difference was found for interval 3 ($\mathrm{d}T_{2000\,\mathrm{m}}$: range 3.59–6.53 s), which could indicate a potential effect of rowing technique on velocity fluctuations. Therefore, for each SR interval separately, $\mathrm{d}T_{2000\,\mathrm{m}}$ was correlated with several variables derived from force graph analysis and oar angle measurement. The variables impulse, smoothness of force graph, center of gravity of force graph, oar angles at catch and finish, total oar angle, as well as the within-crew variables impulse difference between force graphs, and time differences in onset (catch) and offset (finish) of force graphs did not show any significant correlations with $\mathrm{d}T_{2000\,\mathrm{m}}$. The only variable that showed a significant negative correlation with $\mathrm{d}T_{2000\,\mathrm{m}}$ was mean boat velocity (Fig. 4), that is, $\mathrm{d}T_{2000\,\mathrm{m}}$ decreased with increasing boat speed (r values for SR intervals 1–4 separately: -0.92, -0.92, -0.9, -0.88; $n=8$, all $P<0.05$). This negative correlation reflects a second mechanism for the relation between boat speed and velocity fluctuations, based on a between-crew effect, in contrast to the within-crew effect with stroke-rate-dependent enlarged velocity fluctuations when boat speed increases (cf. Table 1).

The analysis of the relationship between SR and the fluctuations in boat acceleration/boat velocity revealed significant strong correlations between SR and fluctuations in acceleration ($r=0.98$, $n=8$,

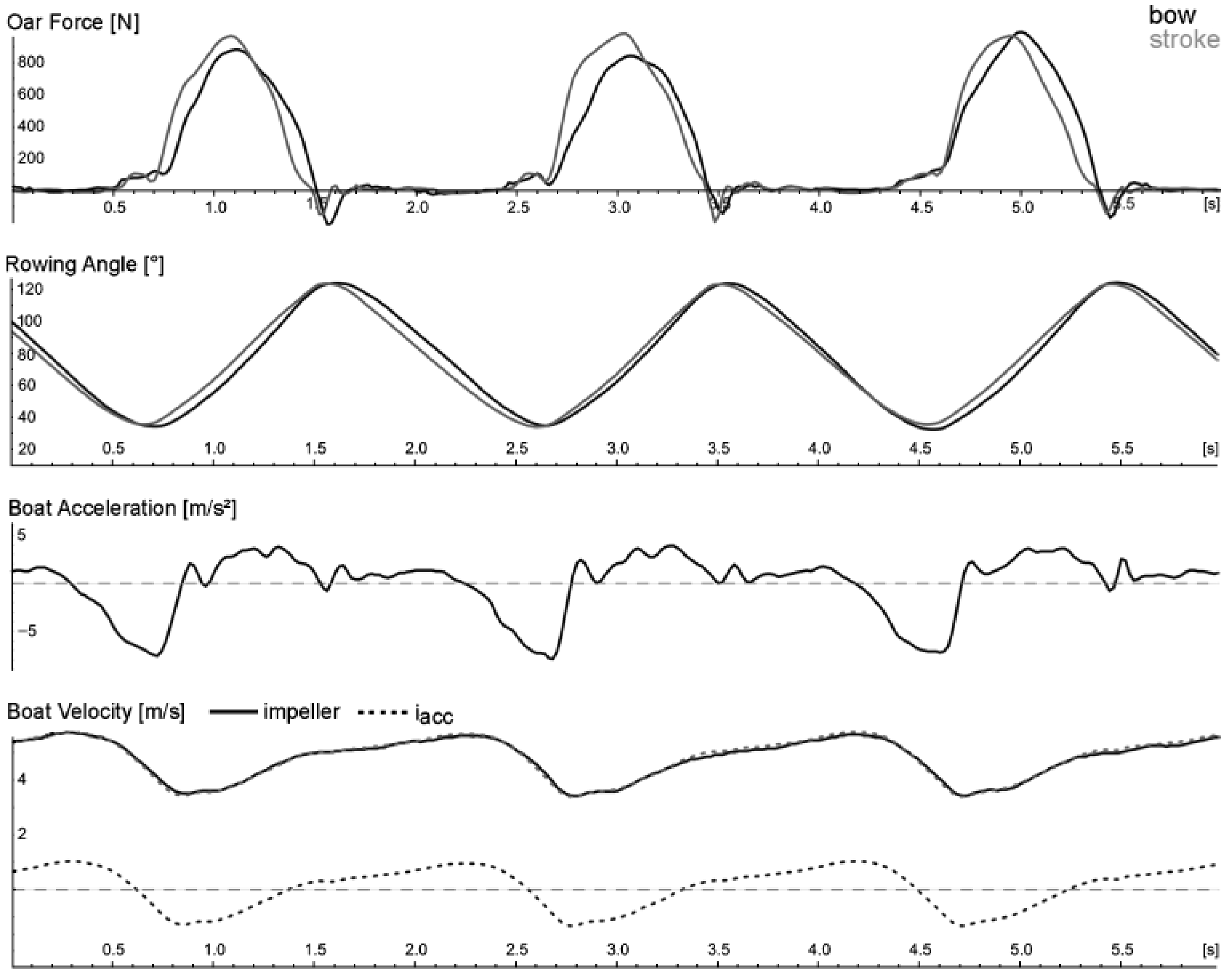

Fig. 3. Measured raw data (oar force, oar angle, boat acceleration, and boat velocity) of three rowing cycles of interval 4 (stroke rate 31 min^{-1}). The lowest trace displays the boat velocity after integrating the acceleration (i_{acc}, mean = 0). In the second trace from below the impeller-based (dashed line) and acceleration-based (i_{acc}, dotted line) velocity measure (after adding the mean boat speed of 4.7 m/s obtained from the impeller-based velocity measure to i_{acc}) are overlayed, which shows the congruency of both velocity–time profiles very well.

Table 1. Mean values and standard deviations for the four stroke rate intervals (planned stroke rates 20–24–28–32 min^{-1}) of the analyzed variables as well as *F* and *P* values for the main effect "interval" (df 3, 21)

Stroke rates (planned)	20 (interval 1)	24 (interval 2)	28 (interval 3)	32 (interval 4)	*F*	*P*
n strokes	17.4 ± 4.5	17.1 ± 2.9	15.6 ± 3.9	16.6 ± 3.8	0.41	0.75
SR (min^{-1})	20.6 ± 0.61	24.2 ± 0.53	27.7 ± 1.08	31.5 ± 0.68	463	< 0.001
Impulse 1	442 ± 29	448 ± 27	450 ± 23	445 ± 19	0.14	0.93
Impulse 2 ($N \times$ s)	449 ± 42	447 ± 34	442 ± 39	444 ± 36		
Impulse × SR	9186 ± 503	10 831 ± 486	12 355 ± 638	14 001 ± 589	623	< 0.001
P_{mech} 1 (W)	287 ± 21	362 ± 27	436 ± 19	507 ± 22	636	< 0.001
P_{mech} 2	290 ± 31	358 ± 37	422 ± 44	500 ± 48		
T_{drive} 1	862 ± 26	810 ± 34	779 ± 28	752 ± 30	143	< 0.001
T_{drive} 2 (ms)	868 ± 49	821 ± 45	788 ± 45	757 ± 31		
v_b (m/s)	3.89 ± 0.22	4.22 ± 0.24	4.47 ± 0.25	4.7 ± 0.26	300	< 0.001
$T_{2000\,m}$ (min:s)	8:36 ± 30	7:54.9 ± 26	7:28.6 ± 25	7:06.4 ± 23	274	< 0.001
$dT_{2000\,m}$ (s)	4.79 ± 0.8	4.59 ± 0.6	4.78 ± 0.8	5.05 ± 0.7	7.38	< 0.01

n strokes, number of strokes included in each interval; SR, stroke rate; impulse 1, bow position; impulse 2, stroke position; P_{mech}, mechanical power (1 bow, 2 stroke); T_{drive}: duration of drive phase; v_b, mean boat velocity; $T_{2000\,m}$, virtual 2000 m race time; $dT_{2000\,m}$, time loss resulting from velocity fluctuations for a virtual 2000 m time.

Fig. 5) and between SR and velocity fluctuations ($r = 0.93$). The fluctuations in boat acceleration and boat velocity, consequently, showed a strong correlation as well ($r = 0.96$). Furthermore, the mean boat speed exhibited significant correlations with fluctuations of acceleration ($r = 0.76$) and velocity

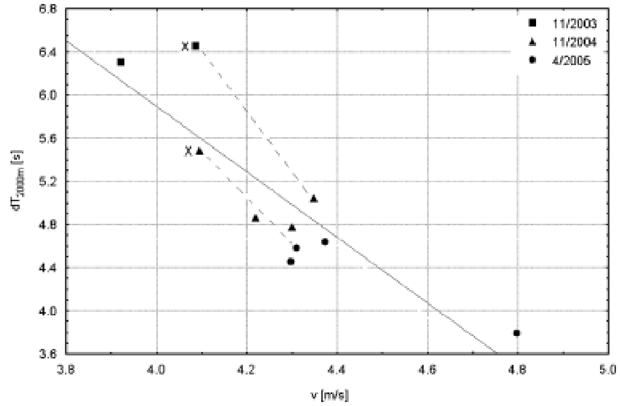

Fig. 4. Relation between mean boat speed v and $dT_{2000\,m}$ (between crew effect). Data of all four stroke rate intervals averaged. Data of the three measuring dates are marked by different symbols. The values of the second dataset (x, not included in the other analysis) of the two crews measured twice are included in this figure to show the variation between measuring dates (indicated by the broken lines). Pearson's $r = -0.87$; $dT_{2000\,m} = 18.288–3.1 \times v$.

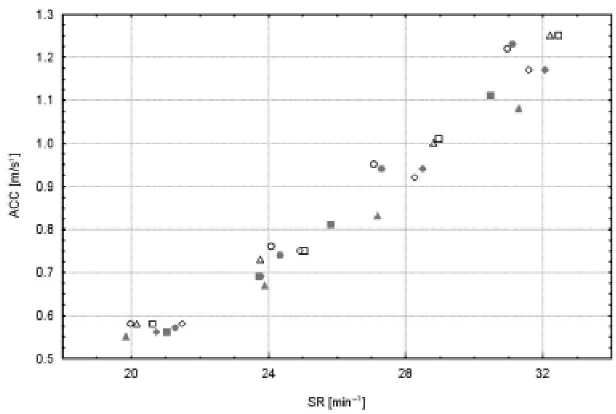

Fig. 5. Relation between stroke rate (SR) and acceleration fluctuations (acc, average of the positive acceleration values for each rowing cycle) of the boat. Mean values for each of the four stroke rate intervals for each of the eight crews (marked with different symbols). Pearson's $r = 0.98$; $acc = -0.6145+0.05629 \times SR$.

fluctuations ($r = 0.84$, all $P<0.05$) because boat speed increased with SR (cf. Table 1).

The relation between mean boat speed and physical power as well as force output was analyzed with power regressions, revealing that P_{mech} is proportional to $v_b^{2.92}$ (range of the exponents for the individual crew values, $n = 8$, 2.63–3.2) and impulse $\times$ SR is proportional to $v_b^{2.21}$ (range of the exponents 1.94–2.43), (Fig. 6).

Discussion

Owing to the biomechanical requirements of rowing, fluctuations in boat velocity cannot be avoided but a reduction of velocity fluctuations is still regarded as an important approach to increase efficiency in competitive rowing. The present study aimed to quantify the decrease in rowing speed caused by velocity fluctuations. The analysis was based on data obtained from eight coxless-pair crews during on-water rowing and a mathematical approximation. Compared with a boat hypothetically moving at a constant velocity, an average time loss $dT_{2000\,m}$ between 4.59 s (SR 24 min^{-1}) and 5.05 s (SR 32 min^{-1}) for the 2000 m race distance resulting from velocity fluctuations was found. This result is comparable with data obtained from single scull rowing in a previous case study (Hill, 1997). Further studies may be useful to investigate the relations between velocity fluctuations and boat class as well as crew weight.

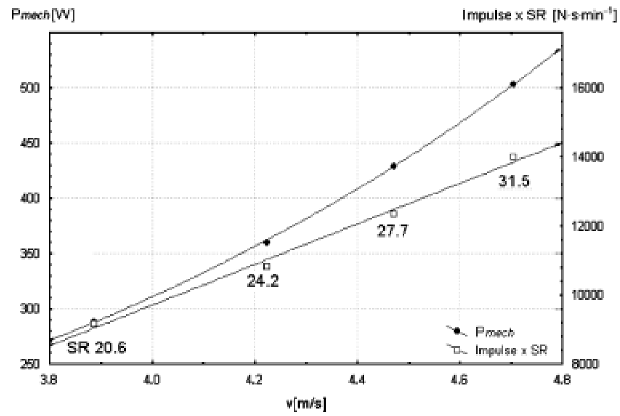

Fig. 6. Relationship between v_b and P_{mech} (full circles, left y-axis), and v_b and impulse $\times$ stroke rate (open squares, right y-axis) for the four stroke rate intervals (mean values of the eight crews). The power regressions are $P_{mech} = 5.46 \times v_b^{2.92}$, and impulse $\times$ SR $= 455.9 \times v_b^{2.21}$.

The critical question when deciding which model to use to quantify the effect of velocity fluctuations on race time ($dT_{2000\,m}$) is whether to relate velocity fluctuations to physical or physiological variables. Theoretically, mechanical power is proportional to the 3rd power of boat speed and impulse $\times$ SR is proportional to the 2nd power of boat speed, and our measured data are close to these values. Sanderson and Martindale (1986), and recently Hofmijster et al. (2007), modeled velocity fluctuations based on the 3rd power of boat speed. Their results were similar to our values if, for comparison, related to the 3rd power of speed. In rowing practice, however, the physiological variables are the limiting factors for rowing performance. Shephard (1998) wrote in his review: "Paradoxically, the oxygen cost of rowing is proportional to the 2.24th power of speed rather than the 3rd power, as might be predicted from drag force calculations." If the physical load (e.g. boat speed in rowing) is submaximal, muscle energy is provided by aerobic metabolic processes that are equivalent to oxygen uptake [absolute VO_2

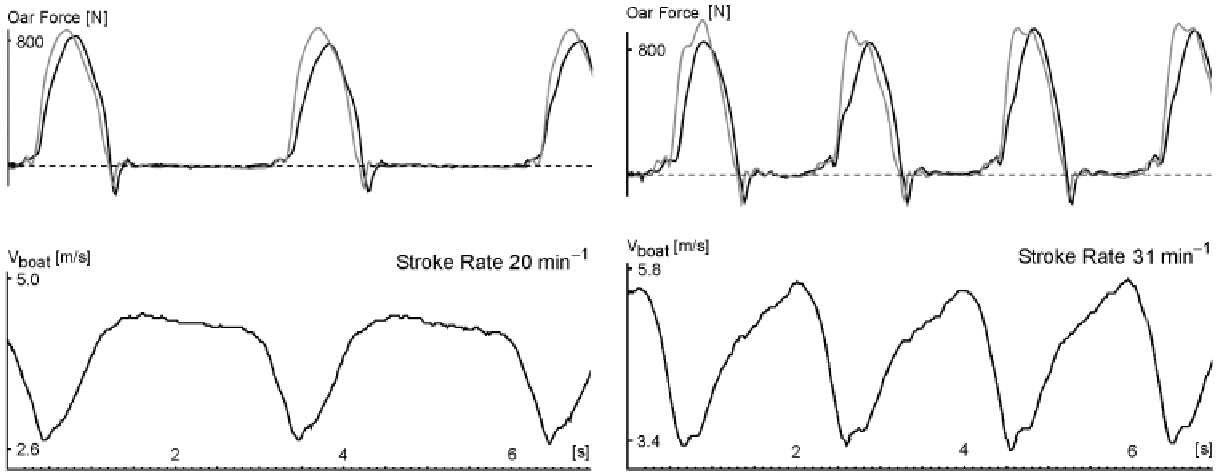

Fig. 7. Typical examples of force graphs and velocity time courses for different stroke rates (SR). When SR is low ($20\,\text{min}^{-1}$, left), boat speed decreases visibly during the recovery phase of the rowing cycle due to the dominating drag. In higher SRs ($31\,\text{min}^{-1}$, right), the faster body movements of the rowers result in an increase of speed of the counteracting boat in the first part of the recovery phase and decelerate the boat stronger around the catch.

($\text{l} \times \text{min}^{-1}$) or relative VO_2 ($\text{l} \times \text{min}^{-1} \times \text{kg}^{-1}$)]. If load is maximal, or if load increases in the initial stage, energy is in part provided by anaerobic metabolic processes. The literature data show that oxygen uptake in submaximal tests is proportional to about the 2nd to the 2.2th power of speed for real rowing (Secher, 1983; Pendergast et al., 2003) and cycling ergometry (Hollmann & Hettinger, 2000), and proportional to about the 2.2th to the 2.4th power of speed for rowing ergometry (Lakomy & Lakomy, 1993; Mahony et al., 1999). We based our analysis on a model assuming that physiological power is proportional to the 2nd power of boat speed. This exponent reflects the lower boundary of the values reported in the literature for ergometer and on-water rowing and the calculations for $dT_{2000\,\text{m}}$ may have been underestimated by several percent. To achieve a higher accuracy, it would be desirable to measure oxygen uptake in addition to biomechanical measures. This would allow for the use of the relationship between oxygen uptake and boat velocity as a measure of rowing efficiency and relate it to the biomechanical data in order to analyze limiting factors of individual rowing technique. Furthermore, it could be tested whether VO_2 and impulse × SR are strongly correlated, as this is indicated by the comparison of our data and the literature data.

The effect of velocity fluctuations on race time ($dT_{2000\,\text{m}}$) may depend on several factors. There are constant factors like the boat class or the body weight of the rowers and variable factors like rowing technique, power output, SR, and environmental factors. Like in the previous study (Hill, 1997), the present data showed a very strong positive correlation between SR and fluctuations in boat acceleration and velocity fluctuations during the rowing cycle. Martin and Bernfield (1980) found – contrary to their hypothesis – a positive but weaker ($r = 0.34$) correlation between SR and velocity fluctuation in a single case study of an eight. This weaker correlation may be due to their more inaccurate method (video analysis, no control of the rowers' force output, and, in particular, analyzing only the difference between the maximum and minimum of the velocity time course) and their small range in the SRs investigated (37–41).

We found no linearity between SR and $dT_{2000\,\text{m}}$ (similar to Sanderson & Martindale, 1986) because a second mechanism accounts for an inverse relationship between velocity fluctuations and SR: to reduce SR while maintaining force output and oar angle, a rower has to prolong the recovery phase of the rowing cycle. In this case, body movements are slower and the acceleration of the counteracting boat is smaller. As a consequence, the drag effect dominates and reduces boat speed, thereby enlarging velocity fluctuations (Fig. 7). For this reason, SR and $dT_{2000\,\text{m}}$ are only positively correlated when higher SRs (e.g. about >24 strokes/min in this study) are regarded. When low SRs are also included, both variables may tend to form a u-shaped relationship (cf. Table 1).

Together with mean boat speed, $dT_{2000\,\text{m}}$ showed a high variance. This can be explained by the different environmental factors, mainly the differences in wind direction and wind speed between the measures, which have a strong impact on mean boat speed (a calibration error for the measures of boat velocity and acceleration could be excluded). The high variance in $dT_{2000\,\text{m}}$ and the negative correlation with mean boat speed (Fig. 4) should be based on the same process: under different environmental (especially wind) conditions, the velocity fluctuations for a

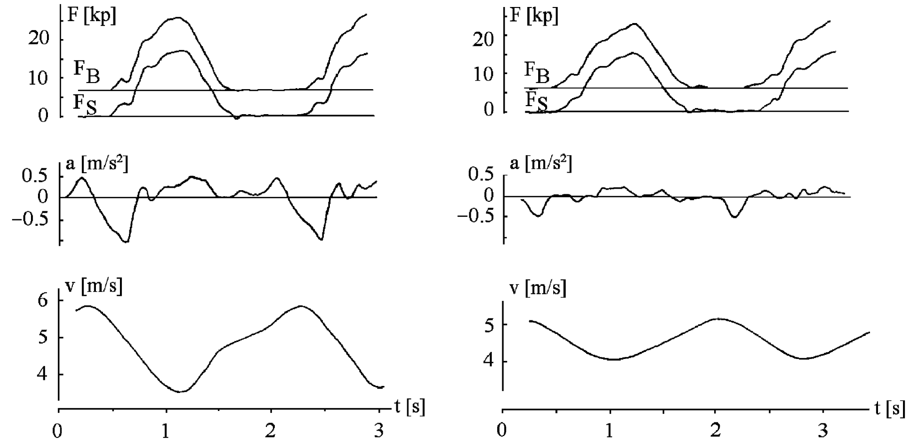

Fig. 8. Comparison of sliding-seat (left) and sliding-rigger single scull (right). Force graphs (upper traces), acceleration (middle), and velocity (below) of the boat. Fluctuations in acceleration and velocity during the rowing cycle are considerably smaller for the sliding-rigger (from Angst, 1982, modified, with permission of the author).

given SR and impulse should be similar, but the mean boat speed will be different. In this case, the time and number of rowing cycles for the 2000 m distance will be different as well. Generally, with a decrease in race time, the time in which the negative impact of velocity fluctuations could work is shortened as well. In summary, below race pace, the relation between $\mathrm{d}T_{2000\,\mathrm{m}}$ and boat speed is modulated by two different and contradictory mechanisms: (i) velocity fluctuations and $\mathrm{d}T_{2000\,\mathrm{m}}$ increase with boat speed when higher SRs are used to increase boat speed, by maintaining force output. (ii) $\mathrm{d}T_{2000\,\mathrm{m}}$ decreases with increasing boat speed when force output per stroke is increased by maintaining SR, or when environmental factors improve (e.g. a reduced wind resistance or a higher water temperature). When rowing with maximal power, the negative effect of velocity fluctuations will be larger if a higher SR is used, which, in turn, must be compensated by a reduced force output per stroke.

Considering that $\mathrm{d}T_{2000\,\mathrm{m}}$ equals about 5 s for a 2000 m race and depends mainly on rowing biomechanics, it remains unclear how large the benefit of an optimized rowing technique could be. A comparison with the sliding-rigger skiff, which was very successful in competitive rowing from 1981 to 1983 (until its prohibition by the FISA), may help to answer this question. Owing to its different boat technology, the fluctuations in velocity of the sliding-rigger are considerably smaller compared with the sliding-seat boat (Nolte, 1981, 1982; Angst, 1982; Beikert et al., 1982; Fig. 8). Affeld et al. (1988a, b) used mathematical modelling and estimated the sliding-rigger to be about 2.3–2.6 s faster in a 2000 m race. Nolte (1981, 1985) and Angst (1982) performed measurements where an athlete rowed in both boat types. Applying the analysis method of the present study to these data (after digitizing the plotted graphs of the published figures), a benefit of 2.1 s for the 2000 m distance for the sliding-rigger was calculated for the data presented by Nolte (1985; $\mathrm{d}T_{2000\,\mathrm{m}}$ 3.6 vs 1.54 s), and of about 3.6 s for the data presented by Angst (1982; $\mathrm{d}T_{2000\,\mathrm{m}}$ 4.4 vs 0.8 s). Although the accuracy of these data is limited, the comparison with the sliding-rigger helps to interpret the results of the present study: to reduce $\mathrm{d}T_{2000\,\mathrm{m}}$ by about 2–3 s in a 2000 m race a very different boat technology and rowing technique is required. This implies that with the conventional rowing technique, an achievable improvement must be marginal or at least considerably smaller. Smith and Loschner (2002) reported one potential approach for reducing velocity fluctuations. They presented examples of two single scullers with different recovery styles where one generated an optimized boat-velocity pattern by modulating the speed of body movement. However, this effect was not quantified, no information about SR and stroke duration was provided, and boat speeds were very different (about 4.2 vs 3.3 m/s). This indicates that the larger velocity fluctuations shown by the faster rower were due to a higher SR. Nevertheless, it would be of interest to investigate whether rowers are able to optimize their recovery style. A critical question is, how this effect depends on SR, that is, whether in higher SRs (e.g. at race pace) there are enough degrees of freedom in movement execution to modulate the recovery phase.

Some rowers and coaches would reason that it is justifiable to work on rowing technique to reduce velocity fluctuations, even if the benefit is only a few 100 ms, because the time differences at the finish line are often even smaller in competition. However, according to Fritsch (1990), it has to be noticed that an extended training of rowing technique may lead to a neglect of other important elements of rowing training. For the rowing practice of athletes with excellent movement skills, it may be useful to reduce SR moderately and compensate this by an increased force output for each stroke. This should result in a reduction of the work necessary for movement of the masses of body and boat within the rowing cycle, which is the main cause of velocity fluctuations. In addition, the total number of rowing cycles in a race and, hence, the work necessary to move the masses would decrease. This model needs to be confirmed in a further experiment because other variables (e.g. the slip of the blade) may be affected.

In summary, we conclude from the comparison of (i) real rowing, (ii) a boat moving hypothetically with a constant velocity, and (iii) sliding-rigger boat that velocity fluctuations cannot be reduced substantially in the sliding-seat boat.

Perspectives

The present study estimated the effect of velocity fluctuations on race time ($dT_{2000\,m}$) based on biomechanical measures in the coxless pair. It was found that these fluctuations, which increase with SR and are mainly an inevitable biomechanical consequence of the rowing technique, would cost about additional 5 s in a 2000 m race compared with a boat moving hypothetically with constant velocity. In rowing practice, a slight reduction of velocity fluctuations may be achieved by a moderate reduction of SR compensated by an increased force output for each stroke. These conclusions are restricted to elite rowing crews with an excellent rowing technique. For novice rowers, several factors of the complex movement of rowing will benefit from an improved technique (e.g. a reduction of boat movements around its three axes) and increase efficiency.

Key words: acceleration, biomechanics, boat speed, efficiency, elite rowing, stroke rate.

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