Estimation of Biomechanical Parameters and Propulsive Efficiency of Rowing

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1. Introduction

Biomechanical methods of training improvement in rowing are extremely important today due to very strong rivalry in international regattas. Nobody is surprised when the difference between first and the places in a final is less than three seconds. This equates to about 1% difference in average boat velocity. It is definitely possible to gain this percent by means of increasing rowing efficiency. Thus, the main task of biomechanics as an applied science is to increase the mechanical efficiency of competitive sports.

If rowing is considered as the process of energy transformation from chemical substances in a human body to the entropy of the environment (4, 21), then it could be divided into two main parts: the inside and the outside of the human body. Energy applied to the oar handle is the dividing point for rowing. These two energy transformation processes are different by nature and their efficiencies are very different as well.

The internal or muscle efficiency is determined mainly by effectiveness of muscle contraction and is estimated for rowing in the range of 14-27% (2, 3, 4, 5, 8, 11, 13, 18). The external or propelling efficiency connected with hydrodynamics of the boat shell and oar blade and estimated in the range of 60-80% (1, 2, 3, 12, 16, 22). The propulsive efficiency of rowing will be the focus of this paper.

There are two main reasons for the energy waste that effect the propulsive efficiency of rowing. The first is connected with boat velocity fluctuation. The second is determined by characteristics of oar work.

It is clear that energy waste of boat velocity fluctuation is determined by the non-linear character of the velocity-resistance relationship during movements in liquids and gases. The only difference in some authors' opinions is the range of the waste. Some of them believe that it is significant (3, 12, 17) but others do not pay much attention to it (6, 15, 22).

Conversely, there is no common view on the reasons for energy waste in oar work. The oldest and simplest point is to explain energy waste by force decomposition into parallel and orthogonal components during oar rotation (10, 19). The most recent works define oar work efficiency as a function of hydrodynamic drag and lift forces (1, 7, 15, 16, 22).

Different approaches towards optimisation of rowing propulsive efficiency exist. Sanderson and Martindale (1986) suggest modifying the rower acceleration during recovery and enlargement of the oar blade. They found boat velocity efficiency in the range 93.5 – 95.5% for a single scull. Nolte (1991) recommends increasing of the stroke length and minimising displacement of the rower's centre of mass. Schwanitz (1991) believes that force emphasis on the first part of drive "…especially before the 90 degree position" could give some advantage.

An attempt will be made in this study towards the estimation of propulsive efficiency of rowing with the purpose of rowing technique optimisation.

2. Material and Methods

2.1. Apparatus

Measurement was conducted during on-water rowing in competitive boats using a radio telemetry system. Four parameters have been measured. The angle between oar and boat in the horizontal plane was measured using a servo potentiometer (4441, RS Components) mounted on the top of the pin. The force applied to the oar handle was measured by means of defining the oar bend using an inductive proximity sensor (9224 series, Honeywell). Boat shell acceleration along horizontal axis of boat movement was measured using a precise piezoelectric accelerometer (model 3052, EG&G IC Sensors). Boat velocity was measured by an electromagnetic sensor (Nielsen-Kellerman Co.). Average boat velocity during the stroke cycle was calculated from the readings of this sensor, but immediate velocity was derived by means of integration of acceleration data because of the very high time constant of the boat velocity sensor.

2.2. Subjects

Total of 71 rowers in 21 crews were measured. Table 1 shows that the crews were distributed quite evenly through rowers groups and boat types except the women's sweep boats, where only one crew was measured (Table 1).

Table 1. The distribution of the crews relative boat type and rowers group.

	1x	2x	4x	2-	4-	8+	**Total crews in group**
Men Heavy Weight	1	2	1		2	2	**8**
Men Light Weight	1			1	2		**4**
Women Heavy Weight	3		1			1	**5**
Women Light Weight		2	2				**4**
Total crews in boat type	**5**	**4**	**4**	**1**	**4**	**3**	**21**

The average height and weight of rowers were significantly different between heavy-weight and light-weight groups but they were practically the same in sweep and sculling groups (Table 2).

Table 2. Average height and weight in different rowers' groups.

	Crews N	Rowers N	Height (m)	±SD	Weight (kg)	±SD
Men Heavy Weight	8	33	1.93	0.05	89.6	4.6
Men Light Weight	4	11	1.83	0.06	72.1	1.9
Women Heavy Weight	5	15	1.79	0.03	73.3	4.2
Women Light Weight	4	12	1.74	0.06	63.3	9.0
Total:	**21**	**71**				
Men Sculling	5	10	1.88	0.06	84.4	8.8
Men Sweep	7	34	1.90	0.07	83.3	9.6
Women Sculling	8	19	1.78	0.04	70.8	6.6
Women Sweep	1	8	1.80	0.03	73.5	3.1

2.3. Procedure

Every crew performed a set of three test trials of one minute duration, with unlimited recovery time:

- the first one at a training stroke rate 22-24 min^{-1},
- the second one at a higher intensity – 28-30 min^{-1} and
- the third one at a racing rate 34-36 min^{-1}.

Actual ratings were 23.3±1.9 min^{-1} in the first piece, 29.6±1.7 min^{-1} in the second one and 35.8±2.5 min^{-1} in the third one (mean±SD). The average stroke rate in three trials was 29.5±5.5 min^{-1} and it was distributed evenly in rowers' groups. This gave rise to the possibility of comparing the average figures of biomechanical parameters.

2.4. Data processing

The data was collected and stored in real time in a PC and then processed using special software. Typical *patterns* of biomechanical parameters of the athlete's cyclic movements were produced. Then the patterns of derived parameters and the average patterns of the crew were calculated and used for statistical analysis. The total number of 63 crew patterns (21 crews by 3 trials) and 213 individual rowing patterns (71 rowers by 3 trials) formed a database for subsequent analysis.

The seven independent variables were selected as follows:

- Rowers sex (gender),
- Rowers Weight (kg), indicating light-weight or heavy-weight rowers,
- Boat Type (sculling or sweep),
- Number of Rowers in the crew, indicating small or large boat,
- Rowing Rate (str/min),
- Drag coefficient per rower.

These independent variables were used for estimation of resulting biomechanical parameters.

2.5. Calculation of energy waste

The following three assumptions must be made:

- Rowers apply force to the middle of the handle (estimated error 0.5%);
- Resulting force of water drag and lift applied to the centre of the oar blade (estimated error 2-3%);
- Relationship between boat velocity (v) and drag force (Fdr) described by the equation

$$Fdr = k\,v^2$$

where k – drag coefficient dependent on boat type and environmental conditions (estimated error 1%).

Previous studies give reason to believe that these assumptions are close to the truth. Moreover, the validity of the last assumption was checked in this study. Thus, the total error of the method should not be higher than 5%.

The force applied to the oar blade was calculated using measured handle force. The drag coefficient k was calculated for each test trial using instantaneous blade force and boat velocity. Thus, waste power in boat shell velocity fluctuation was calculated

The track of oar blade during the stroke cycle was defined using oar angle and boat velocity data (Figure 1) and blade velocity in orthogonal to the blade direction was derived. The waste power in the blade slip through water was calculated.

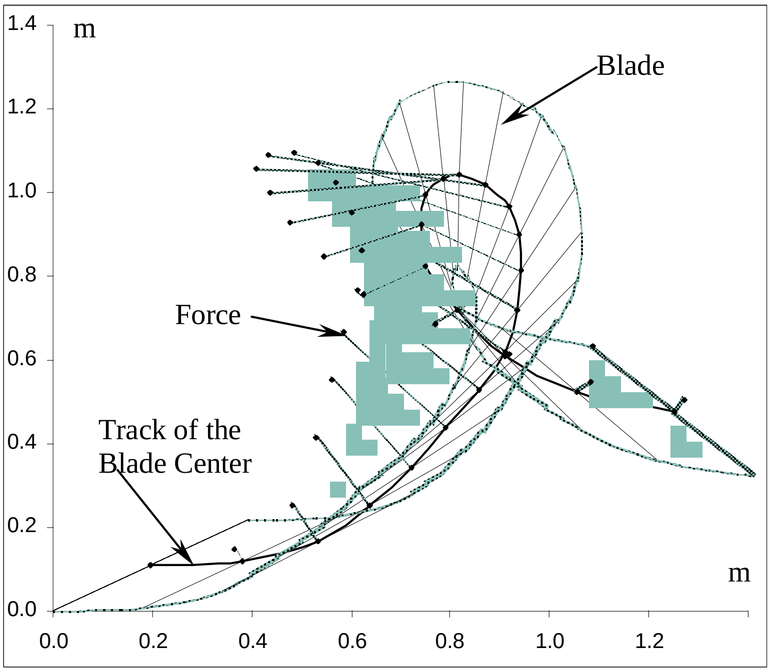


Figure 1. Oar Blade Track during drive phase of the stroke

Propulsive efficiency of the blade was derived as a ratio of the total power applied to the handle to the propulsive power. Efficiency of boat shell propulsion was calculated using propulsive power and its waste in shell velocity fluctuation. Overall mechanical efficiency of rowing propulsion was calculated as the product of blade and shell efficiencies.

Although it is useful information for researchers, mechanical efficiency says little from a practical point, because it does not show gain or loss of boat velocity. Therefore, another definition of efficiency was derived as a ratio of actual boat velocity to a maximal one that could be available in terms of whole produced power spent on boat propulsion. We call this parameter “Efficiency of Boat Velocity” or simple “Velocity Efficiency” and derived it for shell propulsion and for blade propulsion.

Overall velocity efficiency of rowing was calculated as a product of blade and shell velocity efficiencies. Velocity Efficiency could be directly applied for evaluation of gain or loss of boat velocity. For example, if a crew gains 1% of velocity efficiency then its result will be about 1% better, at the same rowing power.

3. Results and Discussion

The significance of dependencies of the 14 main biomechanical parameters was defined (Table 3) and equations of multiple regression were calculated for every biomechanical parameters using significant variables only. Then normalised deviations of every parameter for every rower from the regression trend were calculated and used for rowing technique evaluation. The directions toward better performance (Table 3) were used here as a result of expert analysis, which indicate positive or negative correlation of parameters with rowing

Table 3. Dependencies of the main biomechanical parameters on independent variables (x – significant dependence)

	Independent variables:	Sex	Weight	Boat Type	Rowers Num.	Rate	Drag	Direction toward better performance
	Biomechanical parameters							
1	Boat Velocity/Gold St.	x	x			x	x	+
2	Boat Efficiency (%)			x	x	x	x	+
3	Drive/Stroke (%)	x	x			x	x	-
4	Catch (dg)			x				-
5	Release (dg)			x			x	+
6	Length/Height (%)		x	x	x		x	+
7	Average Force (N)	x	x				x	+
8	Aver.F/Weight (N/kg)	x	x				x	+
9	Aver/Max Force (%)							+
10	Rowing Power (W)	x	x			x	x	+
11	P/Weight (W/kg)	x	x			x	x	+
12	Propulsive Power (W)	x	x	x		x	x	+
13	Waste Power (W)					x	x	-
14	Blade Efficiency (%)					x		+

3.1. The main relationships between biomechanical parameters

3.1.1. Average Boat Velocity

It is an obvious fact that boat velocity depends on stroke rate, but the characteristics of the dependence vary between boat types. When boat velocity is presented as a percentage of the Gold Standard velocity, a strong correlation with stroke rate is found (Figure 2a).

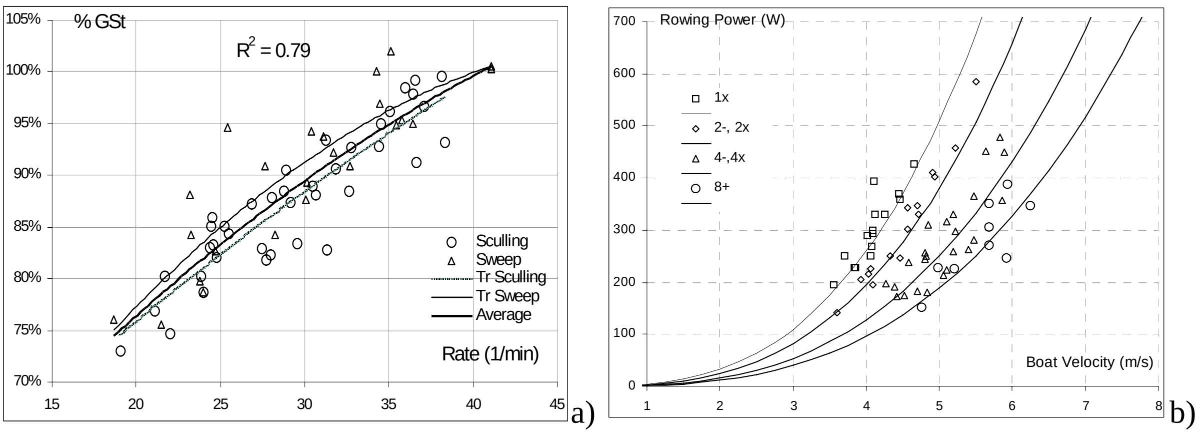


Figure 2. Relationships between average boat velocity (in percentage to the Gold Standard) and strokes rate (a) and between rowing power and boat velocity for different types of boat (b).

This graph could be useful for definition of the target strokes rate for achievement of the Gold Standard boat velocity. It shows that 100% of GSt corresponds to 40 str/min rate, 95% - to 35 str/min and so on.

Relationships between rowing power and boat velocity are significantly different for different types of boat (Figure 2b). This graph shows good implementation of power-velocity equation $P=kV^3$. Correlation coefficients between actual and trend data were in range 0.8-0.9.

3.1.2. Variation and Efficiency of the Boat Velocity

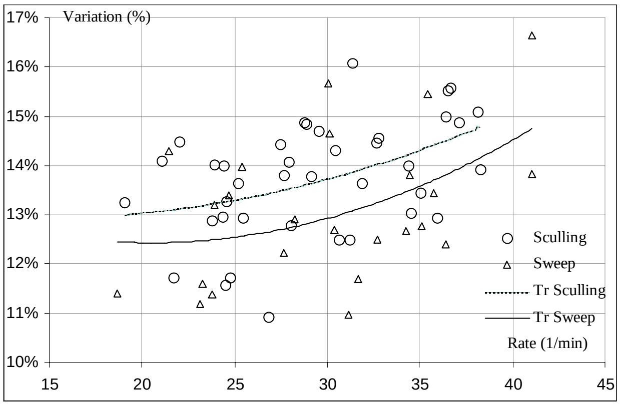
The Variation of the boat velocity was calculated as a standard deviation of velocity during stroke cycle divided on average velocity. The Efficiency was derived as a ratio of actual fluctuated velocity to a calculated constant velocity at the same propulsive power and drag coefficient applied. In other words, the efficiency of boat velocity shows absolute loss of velocity because of its fluctuation.

Statistical analysis did not show significant differences of both parameters in different rowers' groups (Table 4).

Table 4. Boat velocity variation and velocity efficiency in different groups of rowers

Group	Men	Women	Sculling	Sweep	Heavy-Weight	Light-Weight	Senior A	Senior B & Junior
n	36	27	39	24	45	18	33	30
Variation (%) ±SD	13.5% 1.49%	13.4% 1.09%	13.7% 1.16%	13.1% 1.49%	13.5% 1.29%	13.6% 1.44%	13.4% 1.54%	13.6% 1.06%
Boat Efficiency (%) ±SD	98.11% 0.39%	98.09% 0.31%	98.04% 0.32%	98.21% 0.38%	98.09% 0.35%	98.13% 0.37%	98.14% 0.40%	98.06% 0.30%

Increasing of the stroke rate resulted on increase of velocity variation and loss of efficiency in every crew (Figure 3). On average, about 1.4% of velocity was lost at 20 str/min because of this factor and about 2.4% at 40 str/min. However, variation of these parameters between crews was significant and some of the reasons for this finding will be discussed below.



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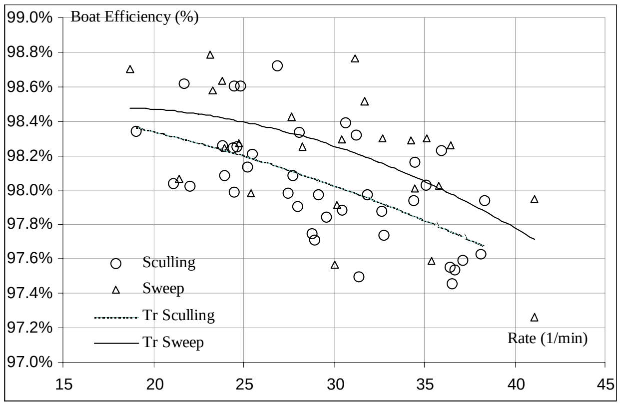

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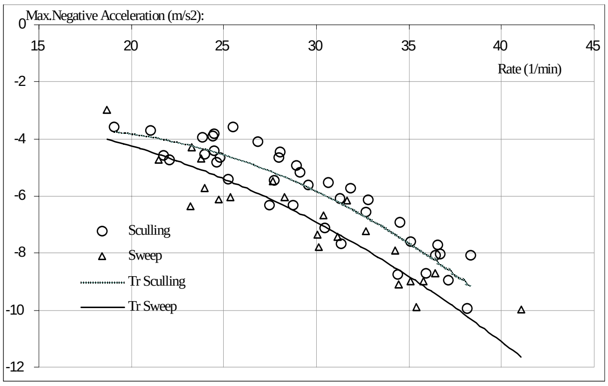
Figure 3. Dependence of boat velocity variation (a) and efficiency (b) on stroke rate.

3.1.3. Boat Acceleration

Discussion of the boat acceleration parameters has mainly descriptive character as no significant correlations were found with efficiency criteria. For example, Maximal Negative Acceleration of boat (at the catch) correlates very strongly (r = -0.88) with stroke rate (Figure 4a). Even though the Pearson correlation coefficient between this parameter and efficiency of boat velocity was quite significant (r = 0.54), there is no significant relationship between them as both depend on stroke rate.



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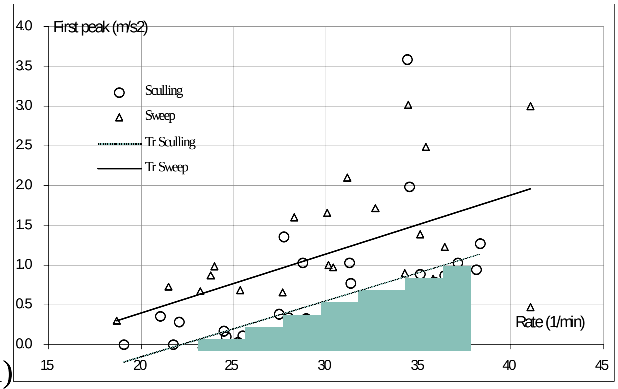

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Figure 4. Dependence of Maximal Negative Acceleration (a) and its First Positive Peak (b) on stroke rate.

The average figures of Maximal Negative Acceleration are shown in Table 5. It is noticeable that this parameter was significantly higher in men than in women and in the sweep group than in the sculling group.

Table 5. Maximal Negative Acceleration and its First Positive Peak in different rowers' groups.

Group	Men	Women	Sculling	Sweep	Heavy-Weight	Light-Weight	Senior A	Senior B & Junior
Max.Negative Accel.(m/s2): ±SD	-6.9* 2.2	-5.8* 1.7	-5.9* 1.7	-7.2* 2.3	-6.3 2.2	-6.7 1.8	-6.8 2.2	-5.9 1.7
First peak (m/s2) ±SD	0.9 0.8	0.6 0.8	0.5** 0.7	1.1** 0.9	0.6* 0.7	1.1* 0.9	0.8 0.8	0.7 0.8

Significance of differences: * $p < 0.05$, ** $p < 0.01$

Height of the First Positive Peak of acceleration is also shown in Table 5, as some coaches pay attention to this parameter. This parameter also depends on stroke rate (Figure 4b) and all crews display this peak at rate higher 32 st/min. The average values of this parameter were significantly higher in sweep rowers than in scullers and higher in lightweight than in heavyweight.

3.1.4. Time parameters

Drive Time and Recovery Time are both very dependent on stroke rate (Figure 5). However, the nature of the dependence is differs. Correlation of Drive Time with stroke rate is high ($r = 0.90$) and dependence is practically linear. Recovery Time has extremely strong correlation with rate ($r = 0.99$) with determination coefficient $R^2 = 0.977$. This means that 97.7% of variation of this parameter is explained by stroke rate variation. The trend of dependence is curve-linear and its extrapolation above rates of 40 str/min results in no decrease of Recovery Time. Put simply, at higher stroke rates attempts to increase it will be more productive if emphasis is placed on reducing drive time.

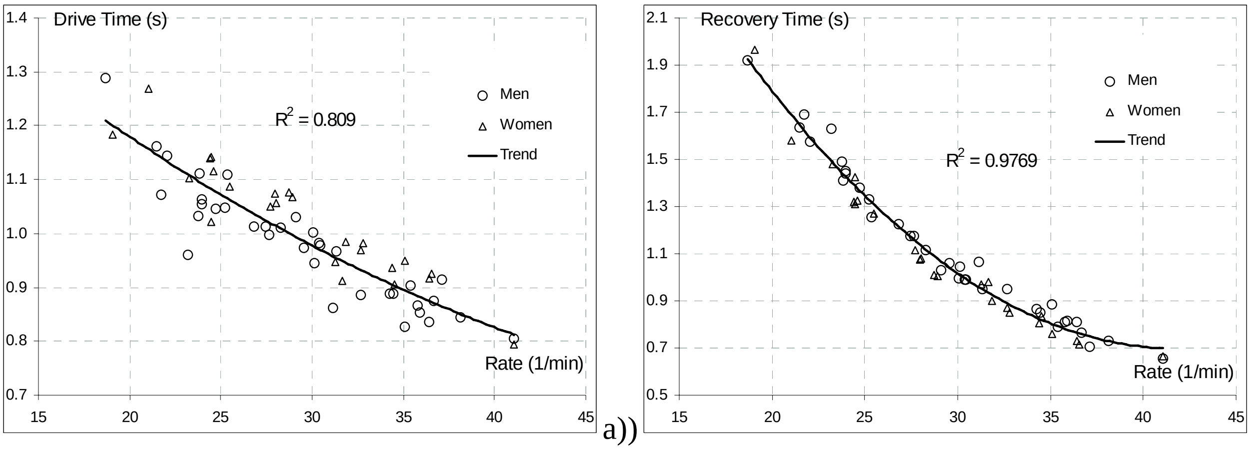


Figure 5. Dependence of Drive Time and Recovery Time on strokes Rate.

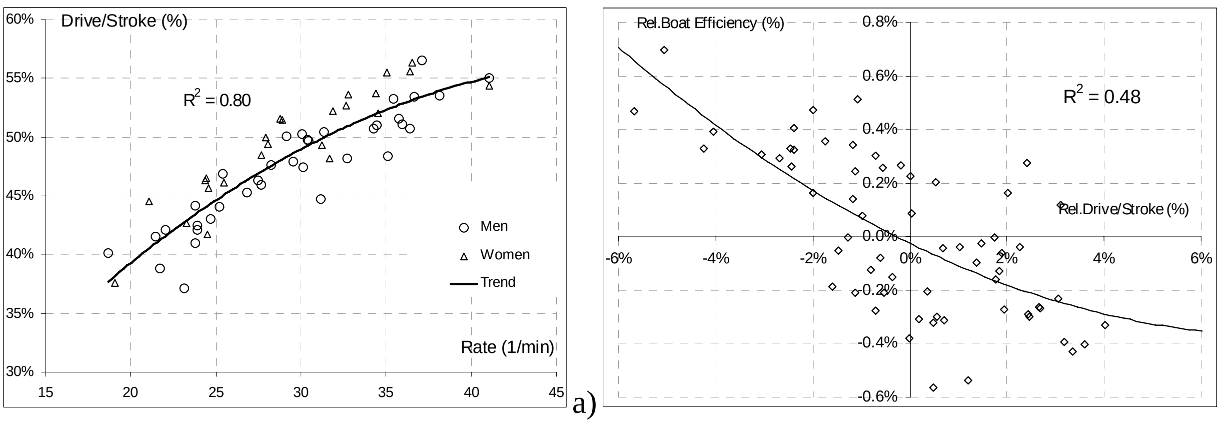


Figure 6. Dependence of Drive/Stroke Ratio on Strokes Rate (a) and Dependence of Boat Efficiency on Drive/Stroke Ratio without influence of the rate (b)

The ratio of Drive Time to Stroke Time Ratio incorporates characteristics of both parameters and is also very rate-dependent (Figure 6a). This parameter correlates with Efficiency of Boat Velocity as well (r = -0.73), this could be partially explained by rate influence.

The most important result shows the comparison of deviations of both Drive/Stroke Ratio and Boat Efficiency from their rate-based trends (Figure 6b). This gives a good correlation (r = -0.69) which results in a gain of Boat Efficiency at decreasing of Drive/Stroke Ratio.

Analysis of the figures shows that it is possible to gain 1% of Boat Velocity by means of decreasing Drive/Stroke Ratio by 10%. This means, for example, that at rate 36 str/min it is necessary to decrease drive time from 0.93 s (56%) down to 0.77 s (46%) at the same stroke length. This is quite close to the reality if we look on Figure 6a again.

3.1.5. Angle and Length parameters,

None of parameters in this section depend upon stroke rate (Table 3) or boat velocity, making their comparison easier. Moderate correlation was found between relative stroke length and rowing performance, which was defined as a place at international competitions (r = 0.41).

Obviously, Catch, Release and Amplitude angles were significantly larger in sculling than in sweep rowing (Table 6). The largest difference was in release angle that was 11-12% larger in sculling.

Table 6. Average Angle and Length parameters in different rowers' groups.

Group	Men Sculling	Men Sweep	Women Sculling	Women Sweep
Catch (dg)	-63.8**	-59.0**	-64.3**	-57.6**
±SD	2.6	5.4	3.5	0.7
Release (dg)	42.3**	31.0**	39.8**	27.2**
±SD	3.7	4.5	3.2	1.4
Amplitude (dg)	106.1**	90.0**	104.1**	84.8**
±SD	4.0	3.8	4.0	1.7
Length/Height (%)	81.7%**	78.4%**	84.8%**	78.1%**
±SD	2.9%	2.6%	3.1%	1.6%

Longitudinal stroke length and its ratio to rowers' height were higher in sculling as well. But this is true only if we assume a point of force application in the middle of the oar grip. If the total length of inboard lever was taken, then the opposite result could be received.

Table 7. Average Length/Height Ratio calculated with total length of inboard lever

Group	Men Sculling	Men Sweep	Women Sculling	Women Sweep
Length/Height (%)	85.6%*	95.0%*	88.9%*	94.6%*
±SD	3.0%	3.2%	3.2%	1.9%

It seems to be that point of force application is situated about one third of grip length from its top. This point demands further investigation, as the Length/Height Ratio is extremely important parameter for evaluation of the force-velocity relationship and for comparison of sculling, sweep and ergometer rowing.

3.1.6. Force parameters

Force parameters were non-dependent on stroke rate and angle parameters (Table 3). This feature looks surprising and could be explained by conditions of measurements. Only stroke rate was regimented and rowers intended to apply as much force as possible during any intensity of rowing. But this should not effect average data in rowers' groups (Table 8).

Table 8. Average data on Force Parameters in rowers' groups.

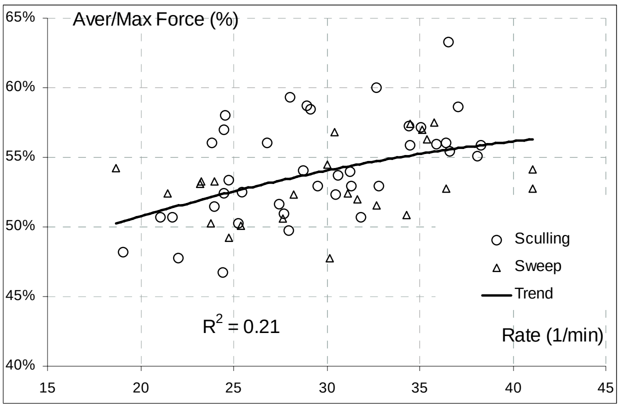
Group	Men	Women	Sculling	Sweep	Heavy-Weight	Light-Weight	Senior A	Senior B & Junior
Max. Force (N)	695**	535**	624	630	635	604	674**	574**
±SD	105	46	124	106	121	105	113	97
Average Force (N)	378**	290**	337	345	341	337	366**	312**
±SD	77	36	68	89	67	97	82	58
Aver.F/Weight (N/kg)	4.40	4.21	4.46*	4.08*	4.14**	4.77**	4.44	4.19
±SD	0.75	0.63	0.65	0.73	0.58	0.78	0.74	0.64

Men applied significantly higher force than women in absolute values, but there were significant differences between them in relation to body weight. The same relationship was found between

"Senior A" and "Senior B & Juniors" groups. This means that men and Senior A applied higher force in proportion with higher body weight only.

Conversely, relative force values were significantly higher in scullers than in sweep rowers and in light-weight than in heavyweight rowers. Absolute values were practically the same in this four groups.

The *Ratio of Average to Maximal Forces* (RAMF) was slightly dependent on stroke rate (Figure 7a) and did not depend on rowers sex, weight or boat type. The average value of this parameter for whole sample was 53.8±3.3%.



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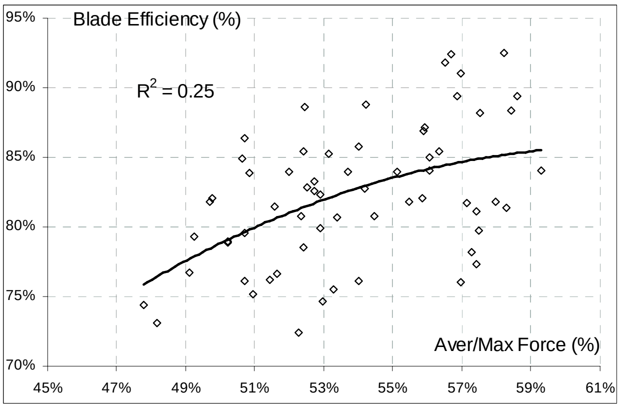

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Figure 7. Dependence of RAMF on rate (a) and relationship between RAMF and Blade Efficiency (b)

A sufficiently significant relationship between this parameter and Blade Efficiency was found (r = 0.48, Figure 7b) to treat this parameter as important one for rowers technique evaluation.

With the purpose of defining of some more informative quantitative criteria on the force application curve a number of parameters were examined (Table 9). Parameter "Force above level (%)" presents discrete part of the drive phase with force higher than a particular level, which was defined as a percentage of maximal force.

Table 9. Correlation coefficients of Blade Efficiency and Relative Rowing Power with different criteria of Force curve.

Force above level (%)	10%	20%	30%	40%	50%	60%	70%	80%	90%
Blade Efficiency	0.48	0.49	0.50	0.47	0.44	0.40	0.36	0.30	0.36
Relative Rowing Power	0.15	0.27	0.30	0.24	0.16	0.11	0.12	0.22	0.17

The criterion "30%" had maximal correlation for both Blade Efficiency and Relative Rowing Power, hence it was selected for evaluation of rowing technique.

Examination of parameters reflecting earlier or later force emphasis did not demonstrate a relationship with efficiency parameters. The parameter "Maximal Force at Oar Angle" was practically the same between rowers' groups (Table 10) except for the difference between sculling and sweep rowing that reflects the different geometry of rowing (Table 6).

Table 10. Average "Maximal Force at Oar Angle" parameter in rowers' groups.

Group	Men	Women	Sculling	Sweep	Heavy-Weight	Light-Weight	Senior A	Senior B & Junior
Max.Force at (dg)	-22.9	-23.2	-21.1**	-26.1**	-23.6	-21.6	-23.6	-22.4
±SD	6.9	6.3	6.5	5.6	5.8	8.4	6.9	6.3

3.1.7. Power parameters

Absolute and Relative Rowing Power were very dependent on strokes rate (Figure 8).

Therefore, comparison of average data in rowers' groups did not show significant distinctions because of very high variation within groups (Table 11). Only one exception was found in comparing men and women in absolute Rowing Power. But when deviations from the rate trend line were derived, almost all differences were significant:

- man had 0.29 W/kg higher relative power than women,
- scullers had 0.38 W/kg higher relative power then sweep rowers,
- light-weight rowers had 0.45 W/kg higher relative power then heavy-weight rowers,
- senior A higher had 0.26 W/kg higher relative power then senior B & Junior ($p < 0.1$).

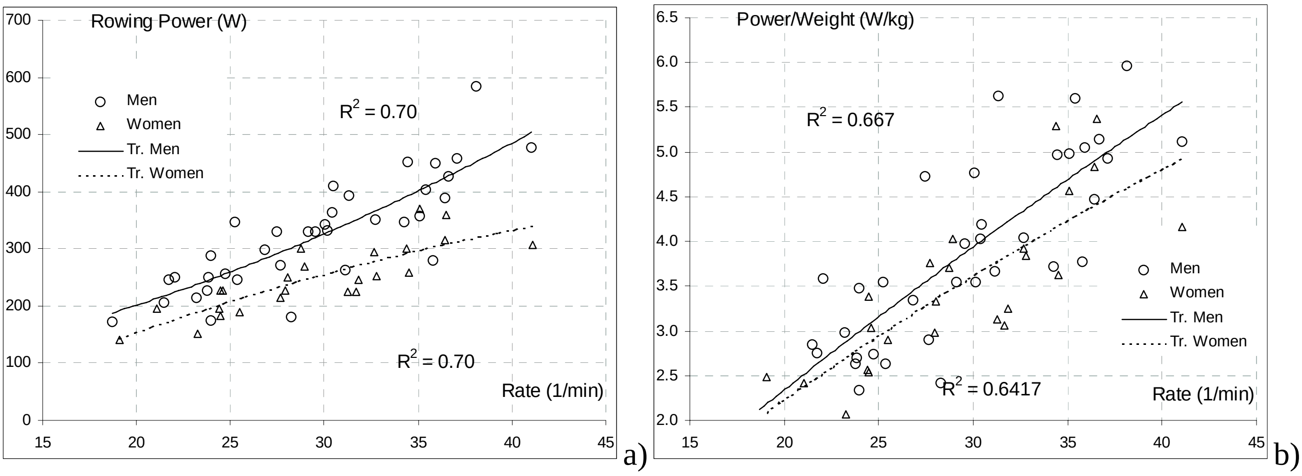

Figure 8. Dependence of Absolute (a) and Relative (b) Rowing Power on Stroke Rate

Table 11. Average data for rowers' groups: Absolute Rowing Power, Relative to body Weight and Relative power normalised per stroke rate

Group	Men	Women	Sculling	Sweep	Heavy-Weight	Light-Weight	Senior A	Senior B & Junior
Rowing Power (W) ±SD	325** 96	247** 58	292 91	291 91	302 93	267 78	312 97	269 76
Power/Weight (W/kg) ±SD	3.85 1.07	3.58 0.89	3.84 0.96	3.56 1.05	3.64 0.95	3.95 1.11	3.86 1.08	3.59 0.89
Power/Weight to Rate (W/kg) ±SD	0.12* 0.62	-0.16* 0.52	0.15* 0.54	-0.24* 0.60	-0.13* 0.47	0.32* 0.73	0.13 0.65	-0.14 0.50

The influence of Rowing Power on Boat Velocity is absolutely clear and was touched on above (3.1.1). But how does Rowing Power affect efficiency parameters?

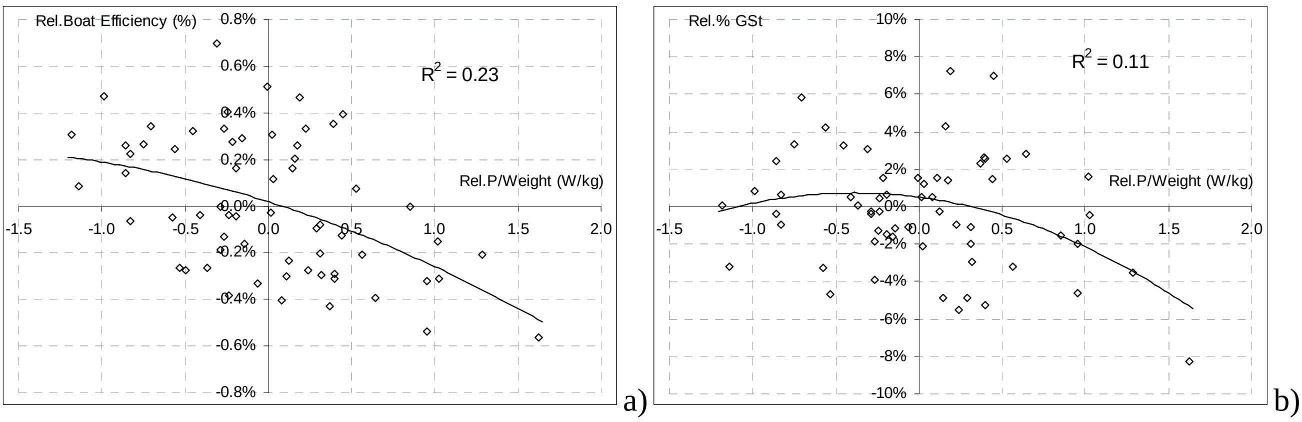

Figure 9. Relationship between Relative Rowing Power and Boat Efficiency (a) and between Relative Rowing Power and Boat Velocity in percentage to Gold Standard (b), both normalised relative to the rate trend.

Because of both parameters were rate-dependent, their deviations from the rate trend line were taken (Figure 9a).

It was found that increasing of Relative Rowing Power has negative effect on Boat Efficiency that means increasing of velocity fluctuation with higher power application at the same rate. It is interesting that increasing of rowing power does not increase boat velocity at the same stroke rate (Figure 9b). This means that correlation between rate and power should be balanced. In other words, it is does not make sense to apply more force rather than increase rate to achieve higher boat velocity.

3.2. Blade efficiency.

First of all, let's explain the impropriety of the model of blade efficiency based on force dissipation being dependent on oar angle. For easier understanding, this dissipation could be compared with force dissipation during frictionless rolling of a cart (Figure 10). In both cases the resulting force *F* dissipates on two forces. One of them is a dynamic force *Fd* that moves the object and creates propulsive power. Another one is a static force *Fs* that does not create any power because there is not displacement along this force. Therefore, this force dissipation only changes the force-time-velocity ratio and does not cause any energy losses.

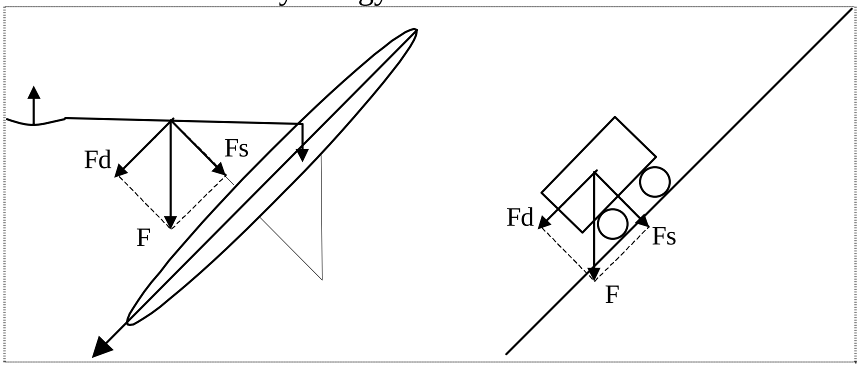

Figure 10. Comparison dissipation of forces applied to an oarlock and to a rolling cart

Biomechanical parameters in this group of were calculated on a basis of assumption that shift of the oar blade through water is a waste of rower's energy. The Blade Efficiency was derived as a ratio of Power that was spend on boat propulsion to the total Rowing Power.

The main biomechanical parameters influencing Blade Efficiency were Boat Velocity (Figure 11a), Ratio of Average to Maximal Force (Figure 7) and part of the drive with Force level above 30% from maximal (Figure 11b). Therefore, Blade efficiency was different in distinct boat types (Table 12).

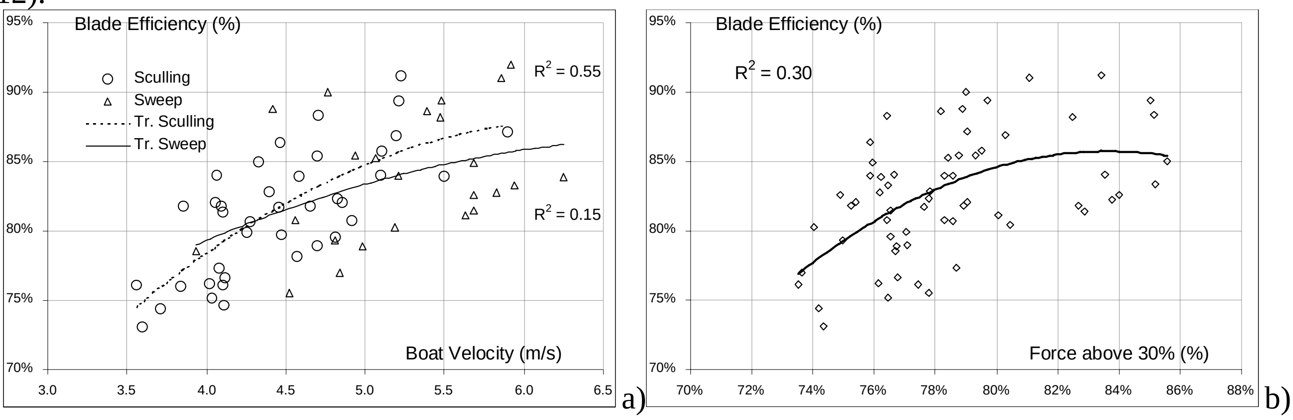

Figure 11. Dependence of Blade Efficiency on Boat Velocity (a) and part of the stroke drive with Force level above 30% from maximal (b).

From the practical point of view Figure 11b shows that increasing of the "Force above 30%" by 10% will follow to increasing of the Blade Efficiency by about 6% - propulsive power by about 8% - boat velocity by 1.5-2.0%.

There were no significant differences found in Blade Efficiency in rowers' groups and its average level was 80-83%. However, it significantly depends on boat type (Figure 12 and Table 12) and was higher in big boats.

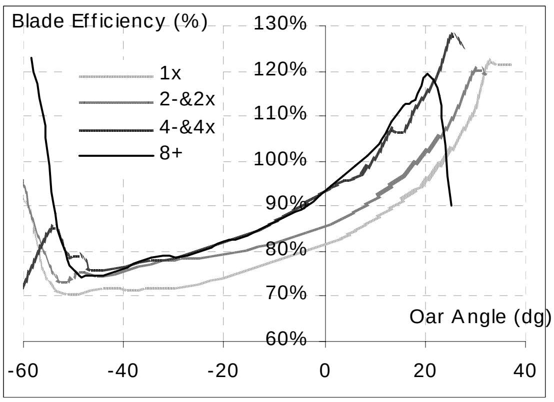

Figure 12. Dependence of Blade Efficiency on Oar Angle for different boat types

Figure 12 shows that value of blade efficiency was higher then 100% at the end of drive phase. The reason of this phenomena is the return of recuperated energy of the rower's body movement. This should be investigated in more detail using data estimating force balance in the rower-boat-environment system.

3.3. Overall Efficiency

Overall efficiency of rowing was significantly different in boat types (Table 12). On average, only 77.6±5.6% of mechanical energy applied to oar handle is utilised in the propulsion of the boat-rower system. The main reason of the 22.4% energy waste is the water shift by the oar blade (17.8%) and the less significant one is the boat velocity fluctuation (5.6%).

Both Boat and Blade Efficiencies were higher in bigger boats. This effected significant differences in Overall Efficiency between small and big boats (73.7%, 3.1% in a single against 81.1%, 5.2% in eight).

Table 12. Mechanical Efficiency of rowing in different boat types.

Boat type	1x	±SD	2-&2x	±SD	4-&4x	±SD	8+	±SD	Average	±SD
Boat Efficiency (%)	93.8%	0.8%	94.0%	0.7%	94.8%	1.1%	95.1%	0.7%	94.4%	1.0%
Blade Efficiency (%)	78.5%	3.1%	81.9%	4.7%	83.5%	6.7%	85.3%	5.5%	82.2%	5.6%
Overall Efficiency (%)	73.7%	3.1%	76.9%	4.1%	79.2%	6.7%	81.1%	5.2%	77.6%	5.6%
Drag Coefficient	3.19	0.27	4.98	0.41	6.68	1.00	10.29	1.16	NA	NA
Drag C. per Rower	3.19	0.27	2.49	0.20	1.67	0.25	1.29	0.14	NA	NA

Overall Velocity Efficiency was boat-type-dependent as well (Table 13). On average, rowing results could be the 8.2% better if the energy waste was absolutely removed. The main reason of velocity loss is the Blade Efficiency (6.4%) and the less significant one is the boat velocity fluctuation (1.9%).

Statistical analysis did not show significant differences of Overall Efficiency in rowers' groups.

Table 13. Velocity Efficiency of rowing in different boat types.

Boat type	1x	±SD	2-&2x	±SD	4-&4x	±SD	8+	±SD	Average	±SD
Boat Efficiency (%)	97.9%	0.3%	97.9%	0.3%	98.2%	0.4%	98.3%	0.2%	98.1%	0.3%
Blade Efficiency (%)	92.2%	1.2%	93.5%	1.8%	94.1%	2.6%	94.8%	2.0%	93.6%	2.2%
Overall Efficiency (%)	90.3%	1.3%	91.6%	1.6%	92.5%	2.7%	93.2%	1.9%	91.8%	2.2%

The Figure 2b and Table 12 can be useful for approximate calculation of rowing power demand for achieving of the target boat velocity and vice versa. For example, if target velocity for men's single is 5.1 m/s (100% of Gold Standard), then rowing power should be about 575W:

$$\text{Prowing} = \text{Ppropulsive} * \text{Efficiency} = k * V^3 * E = 3.19 * 5.10^3 * 0.737 = 540$$

The same calculation for men's eight give us 387W ($1.29 * 6.25^3 * 0.811 = 387$).

This 40% difference between eight and single looks quite surprising, but the Table 14 confirm this consideration because both force and power were higher in small boats. These data generates an idea that reserves of performance enhancement are larger in big boats and they could be used by means of optimisation of biomechanical parameters of rowing in these boats.

Table 14. Average Rate, Handle Force and Velocity, Rowing Power in different boat types

Boat type	1x	2-&2x	4-&4x	8+
Average Rate (1/min)	28.7	29.1	30.0	30.7
Average Handle Force (N)	357	354	322	308
Average Handle Velocity (m/s)	1.44	1.45	1.54	1.58
Rowing Power (W)	301	311	278	280

4. Case study: comparison of four men's fours

For illustration of the study findings the comparison of biomechanical data of four men's coxless fours was done. Two of them were heavyweight (MH4-1 and MH4-2) and other two were lightweight (ML4-1 and ML4-2). The best performed crew was the MH4-1 (two gold medals at Olympic Games, gold at the last World Championship in the coxed four). The ML4-1 won a bronze medal and MH4-2 was fourth at the last World Championship. The least successful was the ML4-2 that took fifth place at the World Cup. Biomechanical data of each crew is presented in Table 15. Only results of the second test trial are presented as they have the least deviation of stroke rate.

Table 15. Biomechanical parameters of four men's fours

	Crew:	MH4-1	ML4-1	MH4-2	ML4-2
1	Aver.Height (m)	1.96	1.81	2.00	1.81
2	Aver.Weight (kg)	91.0	71.8	93.5	74.5
3	Rate (1/min)	30.4	31.1	30.2	29.3
4	Boat Velocity (m/s)	5.48	5.39	5.19	5.04
5	Velocity/Gold St.(%)	94.2%	93.8%	89.3%	87.7%
6	Velocity Variation (%)	12.7%	11.0%	14.7%	12.9%
7	Drag Coefficient	7.55	5.70	6.85	5.44
8	Boat Efficiency (%)	98.3%	98.8%	97.9%	98.3%
9	Drive/Stroke (%)	47.8%	44.8%	48.4%	47.6%
10	Catch (dg)	-61.2	-53.0	-58.2	-61.9
11	Release (dg)	32.6	30.2	33.0	25.6
12	Amplitude (dg)	93.8	83.2	91.2	85.5
13	Lenght/Height (%)	77.9%	79.1%	74.7%	66.5%
14	Max. Force (N)	725	586	777	474
15	Average Force (N)	413	306	369	245
16	Aver.Force/Weight (N/kg)	4.56	4.27	3.95	3.30
17	Aver/Max Force (%)	56.8%	52.4%	47.7%	52.3%
18	Catch Slip/30% (%)	0.6%	1.5%	3.1%	4.4%
19	Angle - Slips (%)	79.7%	78.2%	74.0%	73.6%
20	Finish Slip/30% (%)	19.7%	20.3%	22.8%	21.9%
21	Rowing Power (W)	365	263	331	181
22	P/Weight (W/kg)	4.03	3.66	3.54	2.42
23	Propulsive Power (W)	327	232	255	133
24	Waste Power (W)	37.9	30.5	76.2	48.0
25	Blade Efficiency (%)	89.4%	88.6%	76.7%	74.9%
26	Overall Efficiency (%)	94.7%	94.9%	89.6%	89.2%

The average patterns of the main biomechanical parameters in these crews are presented on Figure 13. The velocity patterns are presented as deviations from average velocity for easer comparison (Figure 13a). Force applied to the handle was taken as a ratio to the body weight of the rowers (Figure 13c) with the same purpose.

Presented data shows that MH4-1 and ML4-1 had significantly higher Boat Velocity at practically the same stroke rate. This correlates with their competitive results. This was despite the highest Drag Coefficient of these crews. The main reasons for the better results are the following:

- Boat Efficiency was higher in MH4-1 and ML4-1 by about half a percent by means of lower Velocity Variation. Both these crews had a smaller velocity decrease at beginning of the drive as well as a faster gain in the middle of the drive.
- It is interesting that only the best crew, MH4-1 did not show a loop of the acceleration curve at the catch. This means that their oar and footstretcher forces were better coordinated.
- During recovery better crews had higher boat acceleration straight after release, but did not emphasise footstretcher pulling and boat acceleration before catch. This correlates with theoretical considerations.
- Drive to Stroke Time Ratio was lower in better crews, meaning a shorter Drive Time at the same stroke rate.
- Oar Angle Amplitude as well as Length/Height Ratio were higher in better crews.

- The main coefficients effecting better Blade Efficiency in MH4-1 and ML4-1 were higher Average/Maximal Force Ratio and lower Catch and Release Slips. Noticeably, MH4-2 had the highest of the peak force in the middle of the drive, but it was inefficient in the beginning and end of the drive phase.
- The better crews had higher absolute and relative Power as well as higher Blade Efficiency, showing the possibility of combined improvement in both parameters.

The Overall Efficiency of rowing was 5.1% lower in MH4-2 than in MH4-1. If this difference was avoided then 2000 m result of the MH4-2 could be 15-18 s better.

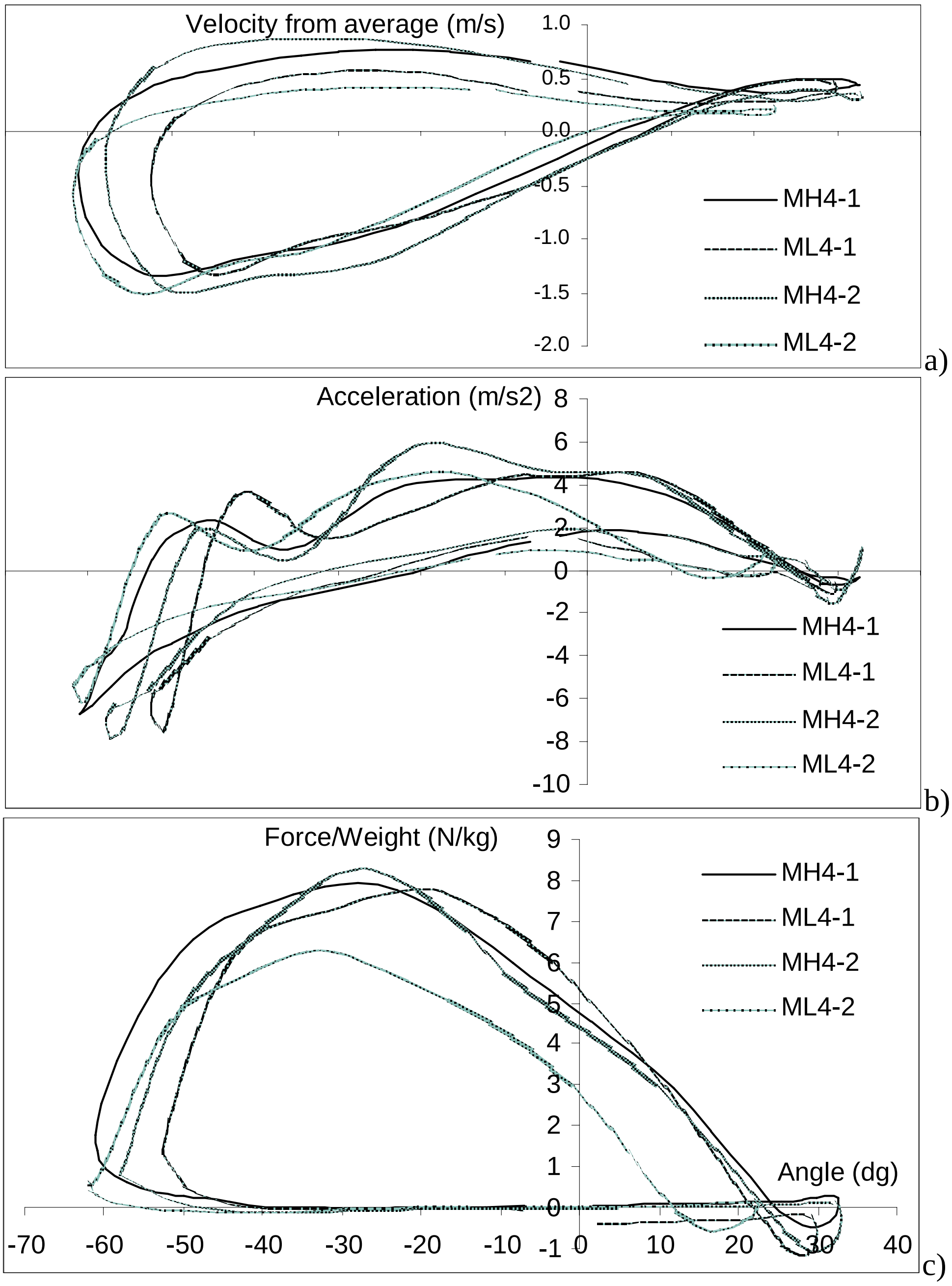

Figure 13. Average patterns of Boat Velocity (a), Acceleration (b) and Relative Force (c) in four men’s fours

5. Conclusions

1. The average mechanical efficiency of rowing was 77.6±5.6% and was higher in bigger boats. The main reason of energy waste is water shift by the oar blade (17.8%) and the less significant one is the boat velocity fluctuation (5.6%).
2. Rowing Power is the main factor effecting the increase of Boat Velocity, but gain of Rowing Power should be done in proportion with Stroke Rate, because the higher Force application at the same rate decreases Efficiency of rowing. Rowing Power was significantly higher in small boats.
3. Increasing of stroke rate in the range 20-40 str/min occurs mainly by means of decreasing of recovery time and reducing drive/stroke ratio. However, the benefit of attempting to increase stroke rate by reducing recovery time is limited and at rates above 40 str/min it should be done by means of reducing the drive time. Moreover, shortening of the drive time at the same stroke rate significantly increases efficiency of boat velocity.
4. The catch angle was slightly higher in sculling (64.1±3.2) than in sweep (58.6±4.8), but release angle was significantly higher in sculling (40.8±3.6) than in sweep rowing (30.8±3.8). Moderate correlation was found between relative stroke length and rowing performance.
5. Average Force and especially Average to Maximal Forces are essential for increasing of Blade Efficiency. The parameters of Catch and Release Slips were derived using criteria of "30% Maximal Force" and it was found that their reduction resulted in a gain of Blade Efficiency.
6. Improvement of boat velocity efficiency would result in less improvement in rowing performance (0.5-0.8%) than improvement of blade efficiency (3-5%). Dependencies of these two components of efficiency on stroke rate and boat velocity have controversial traits: blade efficiency increases with rowing intensity, but boat efficiency is reduced at the same time.

The findings of the study gave possibility to introduce the following directions of rowing technique improvement:

- More specific exercises should be undertake to increase of racing Stroke Rate;
- More attention should be paid to the shortening of the Drive Time especially at high stroke rates;
- Crews with a shorter stroke length should increase it up to 80-82% of the rower's height, preferably by means of increasing of release angle;
- Faster rising and more sustained force must be emphasised instead of applying highest peak force in the middle of the drive;
- More experiments with oar gearing and blade size/shape should be undertaken, as this is the area where changes have the greatest potential to enhance performance, especially in big boats.

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