PROPULSIVE EFFICIENCY OF ROWING

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The purpose of this study was to examine propulsive efficiency in competitive rowing. Oar angle, handle force, boat velocity and acceleration were measured in 21 crews using telemetry. Energy waste and efficiencies of blade propulsion and boat velocity fluctuations were calculated. Stroke rate and average boat velocity had a positive effect on the blade propulsion but they decrease boat efficiency. Higher ratio of average handle force to the maximal one increases blade efficiency (r = 0.48). Shorter drive time increases boat efficiency (r = -0.69). Improvement of blade efficiency could affect rowing performance (3-5%) more than improvement of boat velocity efficiency (0.5-0.8%).

KEY WORDS: biomechanics, rowing, propulsive efficiency

INTRODUCTION: An important task of sport biomechanics is estimating the mechanical efficiency of competitive sports. The rowing efficiency could be divided into two main parts: internal (muscle) and external (propulsive) efficiencies. Energy applied to the oar handle is the dividing point between these two energy transformation processes.
The internal efficiency is determined mainly by effectiveness of muscle contraction and estimated for rowing in the range of 14-27% (Fukunaga et al., 1986; Lisiecki and Rychlewski, 1987). The external or propulsive efficiency is connected with hydrodynamics of the boat shell and oar blade and estimated to be in the range of 60-80% (Sanderson and Martindale, 1986, Affeld et al., 1993). The propulsive efficiency of rowing will be the focus of this paper.
Two main types of energy waste affect propulsive efficiency of rowing (Nolte, 1991, Smith and Spinks, 1995). The first one is connected with boat velocity fluctuation that increases drag force due to the non-linear character of the velocity-resistance relationship during movements in liquids and gases.
The second source is determined by characteristics of oar blade work in the water and could be defined as a function of hydrodynamic drag and lift forces (Zatsiorsky and Yakunin, 1991, Affeld et al., 1993).
Different approaches towards optimisation of rowing propulsive efficiency exist. Sanderson and Martindale (1986) suggested modifying the rower acceleration during recovery and enlarging the oar blade. They found boat velocity efficiency to be in a range of 93.5 – 95.5% for a single scull. Nolte (1991) recommended increasing of the stroke length and minimising displacement of the rower's centre of mass. Schwanitz (1991) believes that emphasis on the first part of the drive, especially before the 90-degree position, could give some advantage.

METHODS: Data were collected during on-water rowing in competitive boats (Sykes Racing) using a radio telemetry system. The angle between the oar and boat in the horizontal dimension was measured using a servo potentiometer. The force applied to the oar handle was measured by means defining the oar strain using an inductive proximity sensor. Boat shell acceleration along the horizontal axis was measured using a piezoresistive accelerometer. An electromagnetic sensor (Nielsen-Kellerman Co.) measured boat velocity.

Table 1 The Number of the Crews in Boat Types and Rowers Groups

	Single	Double	Quad	Pair	Four	Eight	Crews number	Rowers number
Men Heavy Weight	1	2	1		2	2	8	33
Men Light Weight	1			1	2		4	11
Women Heavy Weight	3		1			1	5	15
Women Light Weight		2	2				4	12
Total crews in boat type	5	4	4	1	4	3	21	71

The total number of 71 rowers in 21 crews was measured (Table 1).
Every crew performed a set of three test trials of one minute each, with unlimited recovery time. The stroke rates were 23.3, a = 1.9 min^{-1} in the first piece, 29.6, a = 1.7 min^{-1} in the second one and 35.8, a = 2.5 min^{-1} in the third one.
The data were collected and stored in a PC and then processed using special software. Typical patterns of biomechanical parameters of athlete's cyclic movements were produced. Then the patterns of derived parameters and the average patterns of the crew were calculated and used for analysis.
Calculation *of* energy waste. The following two assumptions were made:

1. Resulting force of water drag and lift applied to the centre of the oar blade and its vector orthogonal to the oar axis (estimated error 2-3%);
2. Relationship between boat velocity (v) and drag force (*Fdr*) described by the equation

$$Fdr = k\, v^2 \quad (1)$$

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

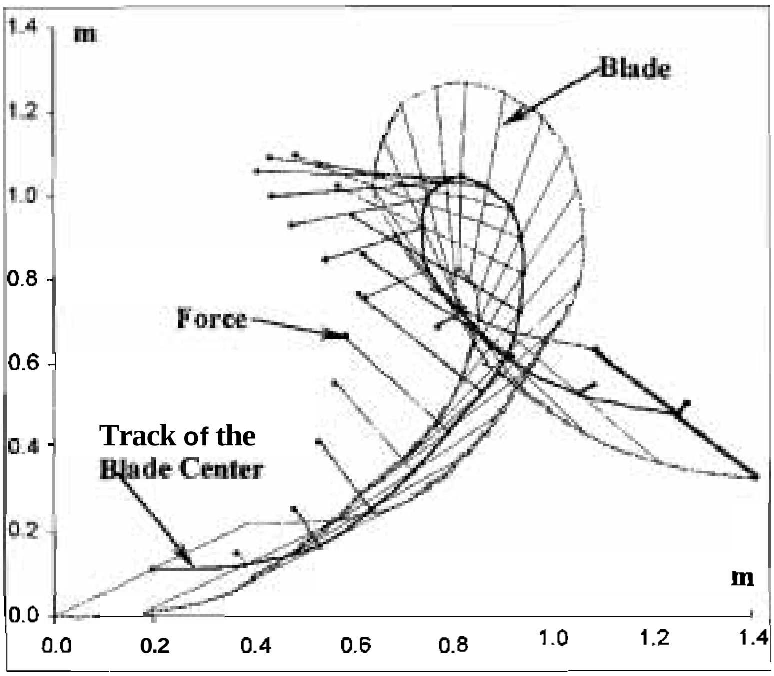

Figure **1.** Oar blade track during drive phase *of* the stroke

The force applied to the oar blade (Fb) was calculated using measured handle force and oar gearing. The track of the oar blade during the stroke cycle was determined using oar angle and boat velocity data (Figure 1) and blade velocity (vb) was derived. The waste power in the blade rupture through the water (Pwb) was calculated as a vector product of blade force and velocity:

$$Pwb = Fb\, v_b \quad (2)$$

The total instantaneous power applied to the handle (*Ph*) was calculated as a product of handle force torque and oar angular velocity. Propulsive efficiency of the blade (e_b) was derived as a ratio of the handle power (Ph) to the propulsive instantaneous power (Pp):

$$e_b = Pp / Ph = (Ph - Pwb) / Ph \quad (3)$$

The drag coefficient k was calculated for each test trial using instantaneous blade force (*Fb*) and boat velocity (v) in the equation:

$$k = \sum F_b \,/ \sum v_i^2 \quad (4)$$

Waste energy due to boat shell velocity fluctuation (*Pws*) was calculated using the equation

$$Ews = \sum k\, v_i^3 - k\, v^3 = k\left(\sum v_i^3 - v^3\right) \quad (5)$$

where v is an average shell velocity during the stroke cycle.
Efficiency of boat shell propulsion (e_s) was calculated using propulsive power (Pp) and its waste in shell velocity fluctuation (Pws). Overall mechanical efficiency of rowing propulsion (e) 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 (*Vreal*) to a maximal one (Vmax) that could be available in terms of whole produced power spent on boat propulsion. We call this parameter "propulsive effectiveness" and derived it for shell propulsion (f_s):

$$f_s = Vreal / Vmax = (es\ Pp / k)^{1/3} / (Pp / k)^{1/3} = es^{1/3} \quad (6)$$

and the same way for blade propulsion:

$$f_b = eb^{1/3} \quad (7)$$

Overall velocity effectiveness of rowing (f) was the product of blade and shell parameters.

RESULTS: Factors Influencing the Blade Efficiency: The main biomechanical parameter influencing blade efficiency was boat velocity (Figure 2a). Therefore, blade efficiency was different in distinct boat types (Both Boat and Blade Efficiencies were higher in bigger boats. This affected significant differences in Overall Efficiency **between** small and big boats. Statistical analysis did not show significant differences of efficiency parameters between male, female and lightweight, heavyweight rowers' groups.
Table 2) and some differences were found between sculling and sweep rowing. No significant differences were found in blade efficiency between male, female and lightweight heavyweight rowers.
Significant relationship between the ratio of average to maximal forces and blade efficiency was found (r = 0.48, $p<0.01$) that shows the importance of this parameter for rowers' technique evaluation. This parameter depended slightly on stroke rate and did not depend on rower's sex and weight or on boat type. The average value of this parameter for the whole sample was 53.8±3.3%.
Factors Influencing Boat Efficiency: The first factor influencing boat efficiency was stroke rate. Increasing the rate led to increasing the velocity variation and loss of efficiency in every crew (Figure 2b). On average, about 1.4% of velocity was lost at a rate of 20 min^{-1} because of this factor and about 2.4% at 40 min''.
The second important factor was ratio of the drive time to the stroke time. Correlation between these parameters was significant (r = -0.73, $p<0.001$), but it could be partly explained by the influence of rate, because both of them were rate-dependent. Therefore, the deviations of both drivelstroke ratio and boat efficiency from their rate-based trends were taken. This gives significant correlation between them (r = -0.69, $p<0.001$) that means a gain of boat efficiency by decreasing the drive/stroke ratio.
The oar angle parameters (catch and release angles) did not influence boat efficiency as well as handle force application parameters.

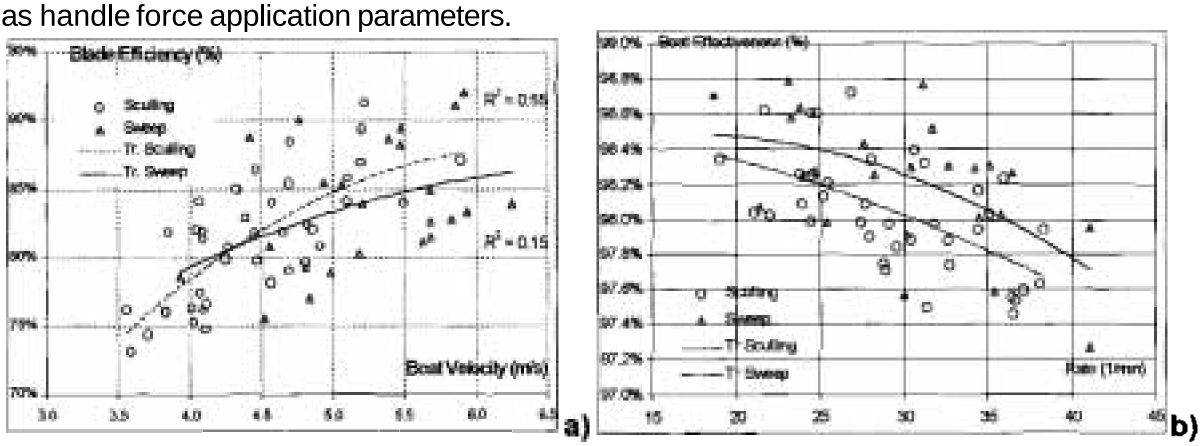

Figure 2 - Dependencies of blade efficiency on boat velocity (a) and boat effectiveness on stroke rate (b)

Overall Efficiency. Overall efficiency of rowing was significantly different in boat types (Both Boat and Blade Efficiencies were higher in bigger boats. This affected significant differences in Overall Efficiency between small and big boats. Statistical analysis did not show significant differences of efficiency parameters between male, female and lightweight, heavyweight rowers' groups.
Table 2). On average, propulsion of boat-rowers system consumes only 77.6±5.6% of

mechanical energy applied to oar handle. 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 affected significant differences in Overall Efficiency between small and big boats. Statistical analysis did not show significant differences of efficiency parameters between male, female and lightweight, heavyweight rowers' groups.

Table 2. Mechanical **Efficiency** of Rowing in Different Boat Types.

rtb Boat type	Single	a	Pair and double	a	Four and quad	σ	Eight	σ
Boat **Efficiency** (%)	93.81	0.8%	94.096	0.7%	94.8%	1.1%	95.196	0.7%
Blade Efficiency **(%)**	78.5%	3.1%	81.9%	4.7%	83.5%	6.7%	85.3%	5.5%
Overall Efficiency (%)	73.7%	3.1%	76.9%	4.1%	79.2%	6.7%	81.1%	5.2%
Drag Coefficient	3.19	0.27	4.98	0.41	6.68	1.00	10.29	1.16
Drag C. per Rower	3.19	0.27	2.49	0.20	1.67	0.25	1.29	0.14

Overall rowing effectiveness was boat-type-dependent as well. On average, results could be 8.2% better if the energy waste was absolutely removed. The major reason for velocity loss is the blade efficiency (6.4%) and the minor one is the boat velocity fluctuation (1.9%).

CONCLUSIONS: The values of propulsive rowing efficiency found in this study were slightly higher than the data in previous research. Future experiments which include determination of drag and lift components of the blade force would provide more accurate results. However, presented rowing efficiency in different boat types and at various stroke rates could be valuable for practitioners.
Improvement of blade efficiency could yield a much higher effect on rowing **performance** (3-5%) than improvement of boat velocity efficiency (0.5-0.8%). Dependencies of these two components of efficiency on stroke rate and boat velocity produce conflicting requirements: Blade efficiency increases with rowing intensity, but boat efficiency is reduced.
Average force and especially ratio average to maximal forces are essential for increasing blade efficiency. The findings of the study indicate that more attention should be paid to shortening the drive time, especially at high stroke rates. Faster rate of increasing force and longer maintenance **must** be emphasised instead of applying highest peak force in the middle of the drive. The figures of drag coefficient derived in the study could refer to the approximate calculation of rowing power for achieving target boat velocity in each boat type.

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