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Mechanical efficiency in rowing

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Summary. Five university oarsmen participated in a determination of mechanical efficiency when rowing in a tank. In the tank, water was circulated at 3 $m \cdot s^{-1}$ by a motor driven pump. The subjects rowed with the stepwise incremental loading, in which the intensity increased by 10% of the maximum force of rowing (max F_C) every 2 min. Power ($\dot{W}_O$) was calculated from the force applied to the oarlock pin (F_C) and its angular displacement (θ_H). Oxygen uptake and heart rate were measured every 30 s during rowing. Anaerobic threshold (AT) was determined from expired gas variables by Wasserman's method. AT of oarsmen was 74.6 ± 6.01% as a percentage of $\dot{V}_{O_{2max}}$. As the displacement of the handgrip in the stroke was independent of $\dot{W}_O$, the increment of $\dot{W}_O$ was caused by the increase of both F_C and stroke frequency. Gross efficiency without base-line correction (GE) increased with F_C with low intensities of rowing. In the region of 124–182 W of $\dot{W}_O$ GE was almost constant at 17.5%. Efficiency was 19.8 ± 1.4%, with resting metabolism as base-line correction (net efficiency), and 27.5 ± 2.9% when using the unloaded rowing as the base-line correction (work efficiency), and 22.8 ± 2.2% when calculating the work rate as the base-line correction (delta efficiency).

Key words: Oarsman — Tank rowing — Mechanical work of rowing — Efficiency of rowing

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Introduction

During rowing, an oarsman exerts force on the handgrip of an oar, and its reaction force propels the boat. The velocity of the boat is mainly due to the mechanical work performed by the oar, which is caused by the muscular contraction of the oarsman. The ratio between the energy expended by muscle contraction and the mechanical work done is defined as mechanical efficiency. Many different values for mechanical efficiency in rowing were observed in previous studies (14–26%) (Asami et al. 1981; Cunningham et al. 1975; Di-Prampero et al. 1971; Hagerman et al. 1978; Henderson et al. 1925).

Mechanical efficiency is influenced by various factors such as the equations of the calculation, the modes of muscular exercise, the methods for measuring both mechanical work and energy consumption, and the skills or techniques used in the muscular exercise. Gaesser and Brooks (1975) defined the different methods for calculation of mechanical efficiency as gross, net, work and delta efficiency, and the highest value of delta efficiency was reported. Cavagna and Kaneko (1977) reported that the increment in mechanical efficiency in high speed running may be caused by extra mechanical energy derived from the passive recoil of muscle elastic elements. As to the effect of skills or techniques of exercise on efficiency, Cunningham et al. (1975) reported that similar mechanical efficiencies were found in both experienced and inexperienced oarsmen, whereas Asami et al. (1981) suggested that higher mechanical efficiency might be obtained by more skillful rowing performance.

The purpose of the present study is to estimate gross, net, work and delta efficiencies during rowing, and to investigate the similarities and differences in the efficiency of rowing previously reported.

Subjects and methods

The subjects were 5 varsity oarsmen. Means and standard deviations of age, body height and weight of the subjects were 20.8 ± 1.5 years, 173.6 ± 4.0 cm, and 67.1 ± 4.0 kg, respectively.

The measurement was carried out using a rowing tank in which water was circulated at 3 $m \cdot s^{-1}$ by a motor driven pump. The oarsman sat in a normal rowing position, adjusting the seat and the slide assembly with the feet securely fastened. Before measurement each subject performed 5 strokes with maximal effort to determine the maximal value of the force he could apply to the oarlock pin (max F_C). After 10 min rest in his seat, the subject was requested to row, and the rowing intensity was increased from 0 to 100% max F_C in steps of 10% every 2 min. Estimation of rowing intensity was carried out by the coxswain, who monitored the force applied to the pin (F_C) on the oscillograph.

Oxygen uptake and heart rate were measured during rest and exercise every 30 sec by means of an automatic oxygen analyzer (Ergo Oxyscreen, Jaeger, FRG) and a cardiac telemeter (SAN-EI 2E31A).

Anaerobic threshold (AT) during tank rowing was determined from plots of $\dot{V}_E$, $\dot{V}_{CO_2}$, $\dot{V}_E/\dot{V}_{O_2}$ and $FeCO_2$ against exercise time. According to Wassermann et al. (1973), $\dot{V}_{O_2}$ just below the non-linear increment of $\dot{V}_E$ was designated as AT. Steady-state $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ were used to estimate caloric output (Diem 1962).

Only that component of force, exerted on the oarlock pin in the direction of the boat axis (F_C), is useful for progression of the boat. F_C was measured by means of a strain gauge transducer (Shinkogh LC-200KE58, Japan) which was mounted on

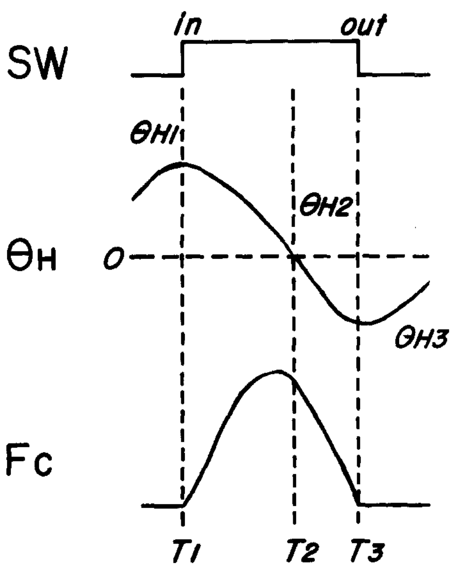

Fig. 1. Schematic representation of the calculation of the mechanical work of rowing. T1 indicates the moment when the oar blade goes into the water, T2 the moment when the angle between oar and water direction is 90 degrees, and T3 the moment when the oar blade comes out of the water

Table 1. $\dot{V}_{O_{2max}}$ and AT in tank rowing

Subj.	$\dot{V}_{O_{2max}}$ l/min	$\dot{V}_{O_{2max}}$ ml/kg·min	AT $\dot{V}_{O_2}$ l/min	AT % $\dot{V}_{O_{2max}}$ %
TS	3.60	59.0	2.66	76.9
TA	4.08	59.4	3.38	83.0
HI	4.65	64.7	3.20	67.9
SI	3.45	51.0	2.46	71.3
IK	3.80	57.5	2.82	74.2
Mean	3.92	58.3	2.90	74.6
SD	0.47	4.9	0.38	6.0

a modified pin rigidly connected to the floor. The angular movement of the oar in the horizontal plane (θ_H) was measured by an electropotentiometer mounted on the pin. An electrical switch was attached to the edge of the oar blade, to indicate whether the blade was in or out of the water. The output of all transducers was directly connected to an oscillograph and a data recorder. The stored data were analyzed by a micro processor (SANEI 7T07).

Mechanical work (W_O) was calculated as

$$W_O = \frac{ab}{a+b}(\sin\theta_{H1} \cdot \int_{T_1}^{T_2} F_C\,dt + \sin\theta_{H3} \cdot \int_{T_2}^{T_3} F_C\,dt)$$

where F_C is the force applied to the pin, a and b the lever arm of the force applied on the handgrip and that applied on the blade, respectively, θ_H the angle between the oar and the line perpendicular to the water flow, and T the time (Fig. 1). Mechanical power ($\dot{W}_O$) was calculated as,

$$\dot{W}_O = W_O \cdot f$$

where f is stroke frequency.

The mechanical efficiencies under the rowing intensities of AT were determined by the following equations according to Gaesser and Brooks (1975).

$$\text{Gross efficiency (GE)} = \frac{W_O}{E} \times 100$$

$$\text{Net efficiency (NE)} = \frac{W_O}{E-e} \times 100$$

$$\text{Work efficiency (WE)} = \frac{W_O}{E-Eu \cdot f} \times 100$$

$$\text{Delta efficiency (DE)} = \frac{dW_O}{dE} \times 100$$

where E is the gross energy output including resting metabolism, e the resting energy, Eu the energy output per stroke during unladen rowing ($W_O = 0$), f the stroke frequency with laden rowing, dW_O the increment in work performed above the previous work rate, and dE the increment in energy consumption above that at the previous work rate.

Results

Typical recordings of θ_H, F_C and SW with maximal rowing are shown in Fig. 2. θ_H indicated

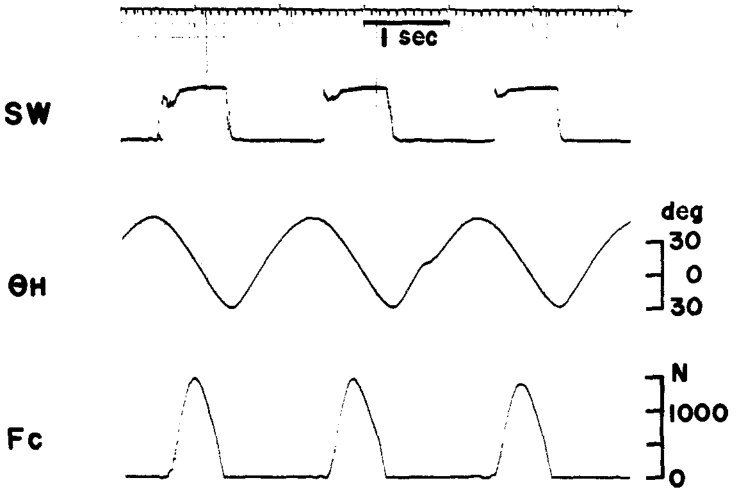

Fig. 2. A recording showing the time (SW) when the oar blade is in or out of water, the angular displacement of the oar (θ_H), and the force applied to the pin (F_C) during a rowing stroke. $\theta_H = 0$ represents the oar being perpendicular to the water flow

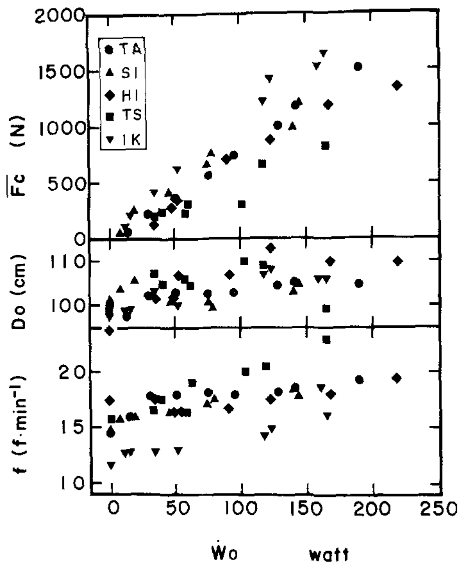

Fig. 3. Mean force applied to the oarlock pin, $\bar{F}_C$, displacement of handgrip, D_O, and stroke frequency, f, as functions of mechanical power, $\dot{W}_O$

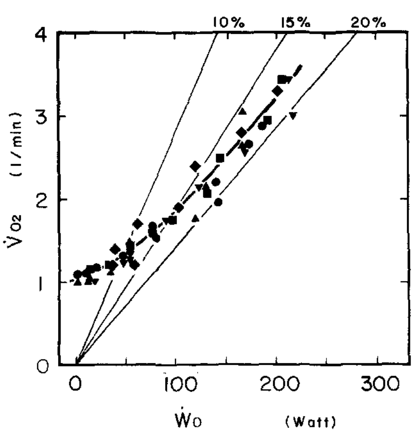

Fig. 4. Relationship between O_2 uptake, $\dot{V}_{O_2}$, and mechanical power, $\dot{W}_O$. The three oblique lines represent gross mechanical efficiencies

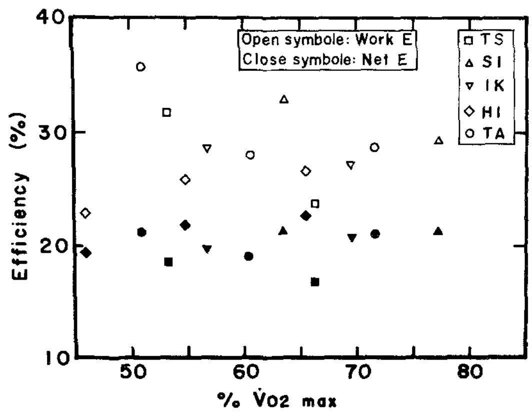

Fig. 5. Changes in work and net efficiencies with the exercise intensity of rowing (% $\dot{V}_{O_{2max}}$)

about 45° at the moment when the oar blade went into the water, and was about 30° at the moment the blade came out of the water. The peak value of F_C in a stroke was about 1500 N. The times when the oar went in and out of the water were 0.76 s and 1.16 s on average, respectively.

The anaerobic threshold of the oarsmen was 74.6±6.01% $\dot{V}_{O_{2max}}$, as shown in Table 1.

Changes in stroke frequency (f), displacement of the oar handgrip (D_O), and the mean force applied to the oarlock pin ($\bar{F}_C$) are shown in Fig. 3, as functions of mechanical power ($\dot{W}_O$). Linear increases of $\bar{F}_C$ were observed with increasing $\dot{W}_O$, whereas D_O was independent of $\dot{W}_O$. A small increment in f occurred with low rowing intensities (less than about 100 W of $\dot{W}_O$).

The relationship between oxygen uptake ($\dot{V}_{O_2}$) and mechanical power ($\dot{W}_O$) under the exercise intensities of AT in rowing is shown in Fig. 4. With unladen rowing ($\dot{W}_O = 0$) $\dot{V}_{O_2}$ was 1.12±0.11

$l \cdot min^{-1}$ (mean ± s.d.). With low rowing intensities below about 100 W of $\dot{W}_O$, $\dot{V}_{O_2}$ increased curvilinearly with increase in $\dot{W}_O$. At higher intensities, however, a rectilinear relation was observed between $\dot{V}_{O_2}$ and $\dot{W}_O$, and gross efficiency ranged from 15 to 20%.

Changes in work and net efficiencies are shown in Fig. 5, as a function of rowing intensity (% $\dot{V}_{O_{2max}}$). Efficiencies were independent of intensity within a range of 45 to 75% $\dot{V}_{O_{2max}}$. There were some scatters of 17—22% (NE) and 22—35% (WE) in the efficiencies.

Mean mechanical efficiencies obtained in the region of 124—182 W of $\dot{W}_O$ indicated the highest value for WE (27.5%) and the lowest for GE (17.5%) (Table 2).

Discussion

In the present study the increment in $\dot{W}_O$ was caused mainly by increase in $\bar{F}_C$, while it was independent of D_O. This result is in agreement with that of DiPrampero et al. (1971), who showed that displacement of the handgrip was practically constant at each rowing frequency, while the average pull and the work done per stroke increased with increasing stroke frequency. The increment in efficiency (GE) by increasing $\bar{F}_C$ and f within low intensities of rowing (the present study), agreed with previous studies, in which the efficiency of bicycle exercise was increased by increasing the work rate (Gaesser and Brooks 1975) and the efficiency in rowing increased with stroke frequency (DiPrampero et al. 1971).

Mickelson and Hagerman (1982) reported AT of 83.5% $\dot{V}_{O_{2max}}$ for oarsman on a rowing ergometer: the 10% lower AT (74.2% $\dot{V}_{O_{2max}}$) observed in the present study may be due to the lower aerobic capacity of our subjects (Japanese University team, $\dot{V}_{O_{2max}}$ 3.92 ± 0.47 $l \cdot min^{-1}$), than Mickelson's United State Olympic Rowing Team ($\dot{V}_{O_{2max}}$ 5.53 ± 0.46 $l \cdot min^{-1}$).

Table 2. Mechanical efficiencies (ME) in tank rowing

Subj.	$\dot{W}_O$ Watt	Gross E %	Net E %	Work E %	Delta E %
TS	103—167	15.5	17.8	26.9	21.5
TA	131—192	17.9	20.4	30.9	21.6
HI	124—213	18.5	20.8	24.2	20.7
SI	144—174	18.6	21.0	30.1	24.8
IK	119—162	16.8	19.1	25.6	25.6
Mean	124—182	17.5	19.8	27.5	22.8
SD		1.3	1.4	2.9	2.2

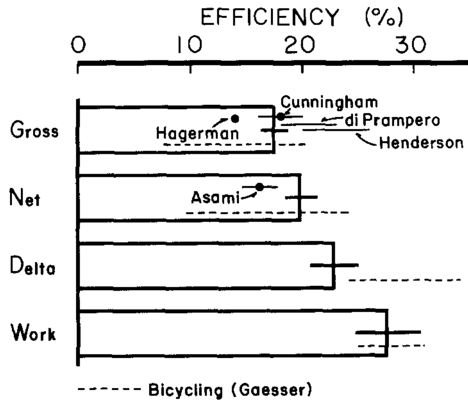

Fig. 6. Comparison of mechanical efficiencies between the present study and previous reports

Previous values for mechanical efficiency during rowing differ: 20-26% (Henderson and Haggard 1925), 18—23% (DiPrampero et al. 1979), 18.1 ± 1.9% (Cunningham et al. 1975), 14% (Hagerman et al. 1978) and 16.2 ± 1.6% (Asami et al. 1981). Comparison of efficiencies in our results and previous reports is shown in Fig. 6. Differences in these reported values could be explained by differences in the methods of measuring the work done and calculating the efficiency. The gross efficiency in the present study (17.5%) was nearly the same as that in static tank rowing (10—20%) and lower than that during actual rowing (18—23%) (DiPrampero et al. 1971). According to DiPrampero et al. (1971) the lower efficiency during static tank rowing than during actual rowing might be caused by the higher stroke frequency at a given work load in the tank: by increasing stroke frequency, there is a greater energy cost per minute since more transverse force is applied to the pin, which does not contribute to propulsion of the boot (energy loss). As the stroke frequency in tank rowing in the present study (15—20 $f \cdot min^{-1}$) was lower than that in actual rowing (20—35 $f \cdot min^{-1}$ in DiPrampero et al.) it is not sufficient to consider that the difference in efficiency between actual and tank rowing was due to the difference of stroke frequency alone.

Rowing is an intermittent-type activity, in which a period of intense effort, mainly in the legs, back and arms, is followed by slightly longer recovery phase as the oarsman comes forward to take the next stroke. In this recovery phase, the mechanical energy to bring the oarsman's body close to the foot braces is obtained from both the force of inertia stored by the shell and the muscle strength required to flex the knees and hips. In tank rowing, however, the pin and foot braces are rigidly fastened to the floor, so that the force of inertia stored in the shell is absent, and additional muscle strength is required to accelerate the body forwards: this may increase energy expenditure at a given rowing frequency in the tank, and thus produce a lower efficiency in tank rowing than when rowing in a moving boat.

Asami et al. (1981) reported lower net efficiency in tank rowing, using the same apparatus as the present study for measuring mechanical work output. This is due to the differences in exercise intensity between maximal rowing by Asami et al. (1981) and steady rate rowing by the present study, because of the lower efficiency in maximal work than that in light steady work (Asmussen 1976; Christensen and Hogberg 1950).

Hagerman et al. (1978) and Cunningham et al. (1975) reported lower efficiency in rowing ergometer exercises. The rowing ergometer used by both Hagerman et al. (1978) and Cunningham et al. (1975) was equipped with a flywheel, and the mechanical work was calculated by the number of revolutions of the wheel and the friction force of the brake belt. It was considered, therefore, that in ergometer rowing an additional force was necessary to accelerate the flywheel at the start of work after every interval, resulting in a lower mechanical efficiency with the rowing ergometer. On the other hand, a higher efficiency on the rowing ergometer reported by Henderson and Haggard (1925) could be explained in terms of the measurement of work done, that is, the force was measured as "pumping water against a resistance".

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