Biomechanical Analysis of Rowing

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Abstract

The rowing performance is affected by the mechanical energy output exerted by the oarsman. By using the rowing tank, in which the water is flowed by the motor driven pump, such biomechanical parameters as the angular displacements of oar, the forces applied to an oar and to a stretcher were measured by means of specially designed apparatus. The results were as follows;

1). Skilled oarsmen indicated a larger area covered by F_c/Θ_H curve (i. e. relation between the force applied to the oarlock pin (F_c) and the angular displacement of an oar (Θ_H)), and the oar blade proceeding in the water almost parallel to the horizontal plane. In the unskilled oarsmen on the other hand, smaller area covered F_c/Θ_H curve and deeply inserted blade in the water were observed.

2). Skilled oarsmen indicated that the displacement of the seat (D_s) increased with the increasing angle of oar in horizontal plane (Θ_H), while the unskilled should no increase in D_s in the phase of the second half of stroke, suggesting that the kinetic energy due to the movement of the body of the oarsman on the sliding seat is transferred more to the oar in skilled oarsman than in unskilled man.

3). Gross mechanical efficiency increased linearly with the increasing force applied to the pin ($\overline{F}_c$) at low intensities. At higher intensities the gross efficiency indicated a range between 15% and 20%, which were almost same values as those in bicycle exercise.

The performance in a boat race is influenced by the magnitude of mechanical energy applied to water by oar blade, and in turn the mechanical energy output is affected by such parameters as the movements of an oar and a seat, and the forces applied to an oar and a stretcher. By measuring these parameters, it may be considered to evaluate the rowing techniques and energy capacity of athletes. However, it takes much time and necessitates labours and scientific techniques to measure them during actual rowing in the boat course. In this respect use of a rowing tank, in which water is circulated motor driven pump, makes each measurements comparatively easier. Although it is unavoidable to cause a feeling of the difference, in "touch" between rowing in the tank and actual rowing, it is convenient to substitue rowing tank for the actual course. In this study, apparatuses were devised to record electrically the force applied to an oarlock pin and a stretcher, the angular displacement of an oar, and the displacement of a seat during stroking. Using these apparatuses the mechanical energy and oxygen uptake during rowing were measured and also rowing techniques were evaluated from a biomechanical point of view.

1. Apparatus

Fig. 1 shows a specially designed oarlock pin, a stretcher and a seat. The inside details of an oarlock pin were shown in Fig. 2. The angular displacement of oar in the horizontal or vertical direction is observed by each potentiometer. The forces working on the front, back,

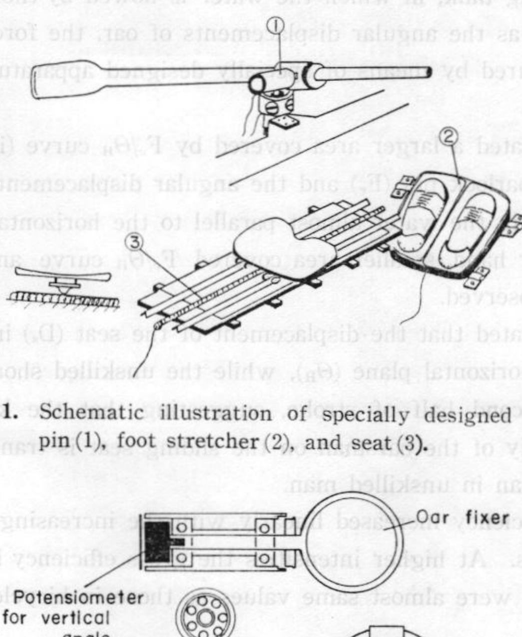

Figure 1. Schematic illustration of specially designed oarlock pin (1), foot stretcher (2), and seat (3).

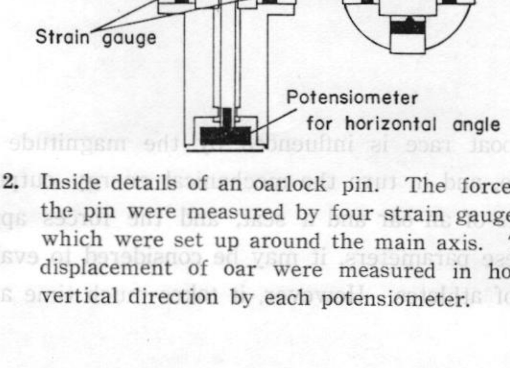

Figure 2. Inside details of an oarlock pin. The forces applied to the pin were measured by four strain gauge transducers which were set up around the main axis. The angular displacement of oar were measured in horizontal and vertical direction by each potensiometer.

and right and left of the pin were measured by four strain gauge transducers which were set up around the main axis. The force applied to the stretcher was measured by means of pressure transducers set on the ball of foot, and these pressure forces were recorded separately on the right and left side foot. The movement of the seat was recorded by means of linear potentiometer which was attached to the back side of the seat.

2. Movements and pressure of oar, seat and stretcher during rowing in the tank

In figures 3 and 4 the angular displacement of the oar, the forces obtained from the oarlock pin and stretcher, and the displacement of the seat were indicated. The flow rate of the water in the rowing tank was 3.2 ms^{-1}. The rowing frequency was about 30 strokes per min. with maximum effort. In Fig. 4 the symbol SW represents the signals whether an oar blade was in or out of the water. Θ_H represents the changes in the angle of an oar in the horizontal plane and Θ_V in the vertical plane. Zero degree in Θ_H shows that the position of oar is per-

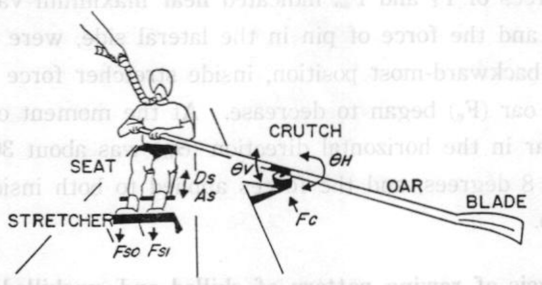

Figure 3. Schematic presentation of specially designed apparatus

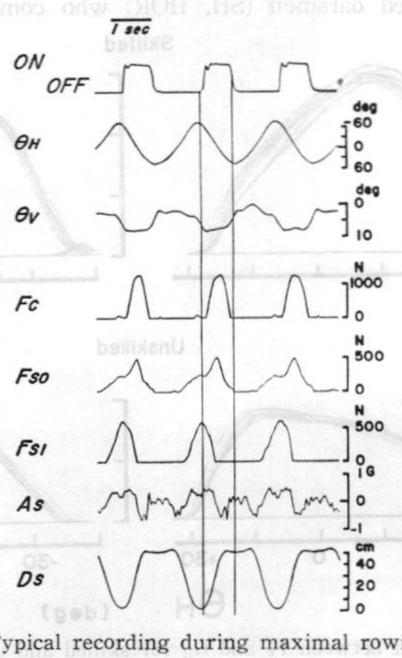

Figure 4. Typical recording during maximal rowing in tank.

pendicular to the water flow. Zero in Θ_V curve also shows an oar being horizontal. $\bar{F}_f$ represents the force applied to the pin in the direction parallel to the water flow, which is the propelling force applied to the boat. F_l represents the force applied to the pin working in the perpendicular direction to the water flow, which is the force pressed the boat to the lateral side. F_{so} represents the force applied to the outside stretcher which is set at the far side from the pin, while F_{si} represents the force obtained from the inside stretcher located at the near side to the pin. D_s shows the displacement of the seat, in which zero means the foremost position of the seat.

From these recordings, the rowing movement of subject NIW was described as follows; at the moment of a blade being put in to the water, the angle of the oar in horizontal plane was 30 degrees, while in the vertical plane that was about 8 degrees. At this moment the outside stretcher indicated maximum value of about 40 kg, and the seat began to move backward which was called "stroke phase". The force applied to the stretcher began to increase in "forward phase" or "recovery phase". When the angle of the oar in the horizontal plane (Θ_H) was about 90 degrees, the forces of F_f and F_{so} indicated near maximum values. At this moment, on the other hand, F_{si} and the force of pin in the lateral side, were about zero. When the seat was stopped at the backward-most position, inside stretcher force (F_{si}) reached the value of zero and the force of oar (F_c) began to decrease. At the moment of the blade coming out of water, the angle of oar in the horizontal direction (Θ_H) was about 30 degrees and that in the vertical plane (Θ_V) about 8 degrees, and the forces applied to both inside and outside stretchers had already reached zero.

3. Analysis of rowing pattern of skilled and unskilled oarsmen

Figure 5 indicates the relation between F_c and Θ_H in a stroke. Upper two curves were obtained from the most skilled oarsmen (SH, HOR) who competed in the 1984 Los Angeles

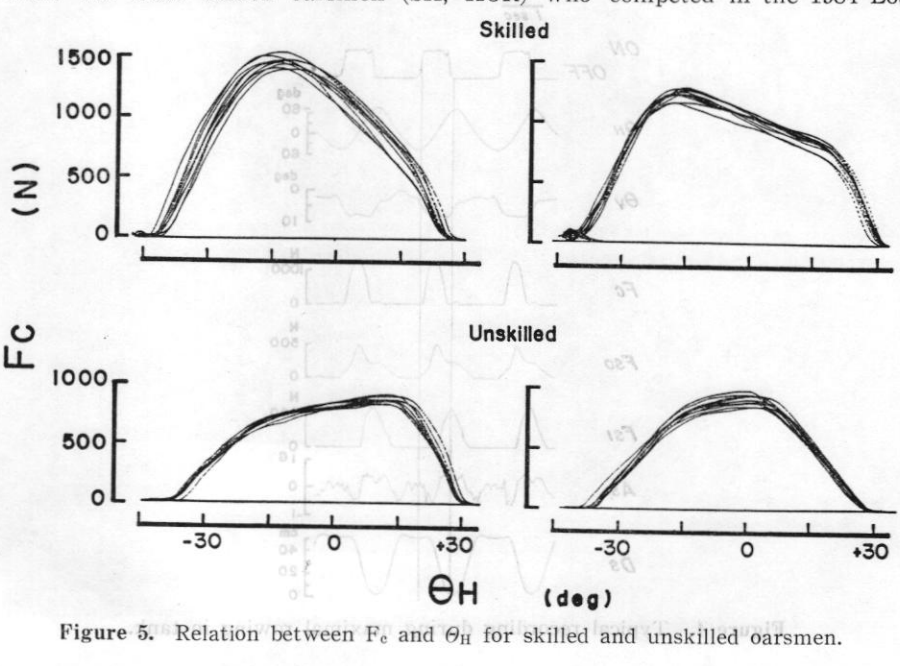

Figure 5. Relation between F_c and Θ_H for skilled and unskilled oarsmen.

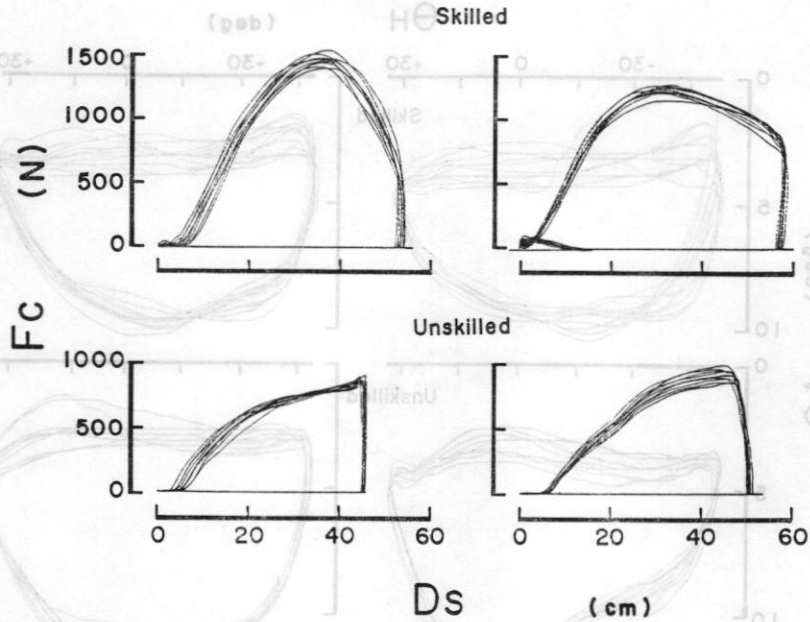

Figure 6. Relation between F_c and D_s.

Olympics. Lower curves were for the second class oarsmen (FUK, AWA). These force-angle curves showed significant differences between skilled and unskilled athletes. In the skilled peak point of F_c were observed before Θ_H reached zero, which mean maximum force was exerted in the first half of the stroke, while in the unskilled exerted the peak force in the second half of the stroke.

The area surrounded by force-angle curves implies mechanical work exerted by an oar. The skilled clearly indicated larger force-angle curve area than the unskilled. It was considered that higher mechanical work exerted by an oar was the fundamental factor to get good performance in a boat race. Changes in F_c were shown with displacement of seat (D_s) in Fig. 6. Zero in abscissa (D_s) represents the position in which the seat was drawn forward-most up. The peaks of F_c curve of the skilled men were observed while the seat was moving backward. In the unskilled athletes the peaks of F_c were observed at maximum backward-most position of the seat. On the assumption that the movement of the seat expresses almost the same as that of the center of gravity of the body, the kinetic energy derived from the movement of an oarsman could be transfered to the mechanical energy of the oar. The magnitude of mechanical energy transfered from the movement of the body to the oar may be considered to be expressed by the area surrounded by F_c-D_s curve. Larger area of F_c-D_s curve in the skilled athletes that they could transfered more mechanical energy from the movement of the body to the oar than that could in the unskilled.

In rowing, the oar rotates on the axis of an oarlock pin in both horizontal and vertical plane. The relation of the angular displacement of the oar between both in horizontal (Θ_H) and vertical (Θ_V) planes are indicated in Fig. 7. As shown in this figure, higher Θ_V in the unskilled than that in the skilled athletes implies that the oar blade in the skilled were more deeply in-

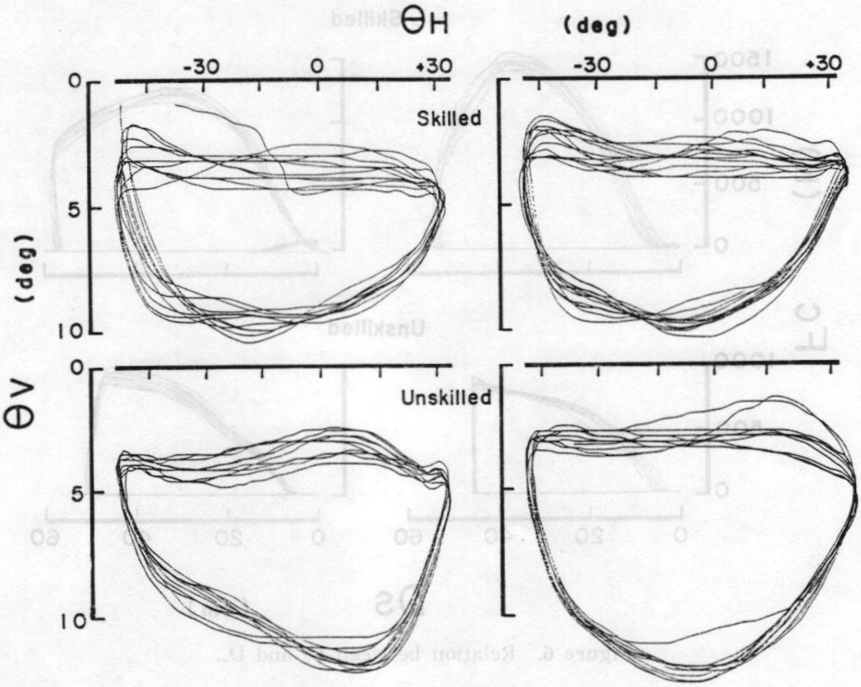

Figure 7. Relation between Θ_H and Θ_V.

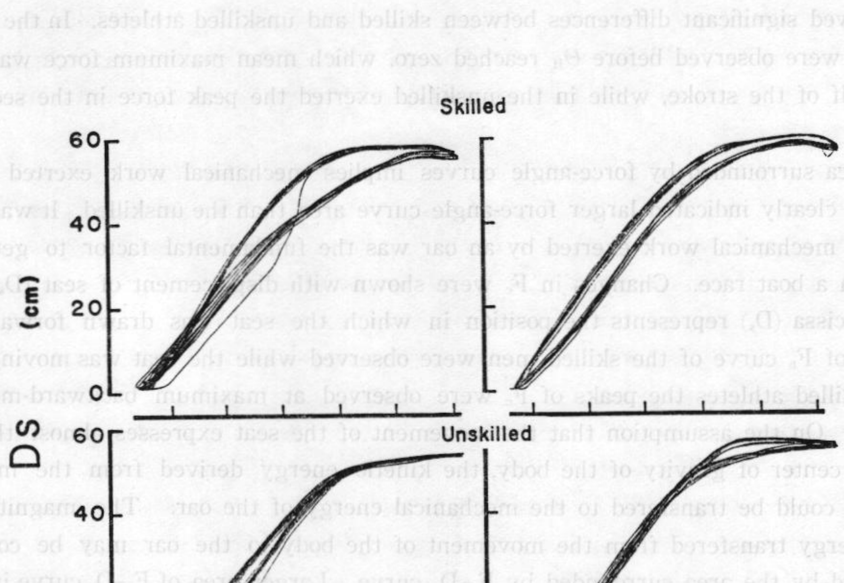

Figure 8. Relation between D_s and Θ_H.

serted into the water than in the unskilled and the oar blade in the skilled also proceeded in the water almost parallel to the horizontal plane.

Fig. 8 shows the relationship between Θ_H and D_s. In skilled athletes D_s increased with increasing Θ_H, while in the unskilled no increase in D_s was observed in the phase of the second half of a stroke. It may be considered that the increment of Θ_H with increasing D_s shows that the mechanical energy is smoothly transfered from the body to the oar.

4. Mechanical efficiency in tank rowing

The ratio of energy expended by the muscle contraction to the mechanical work is defined as a mechanical efficiency. Many different values for a mechanical efficiency in rowing were observed in previous studies (14–26%)[1,5,7,9,10]

The mechanical efficiency is influenced by the various factors such as the equation to be used in the calculation, the mode of the muscular exercise, the method for measuring mechanical work and energy consumption, and the technical skilled to be performed in the muscular exercises. Gaesser and Brooks[8] attempted to compare the different methods for calculation of the mechanical efficiency such as gross, net, work and delta efficiency, and they reported the highest value of delta efficiency. Thys, et al.[11] and Cavagna and Kaneko[3] reported that the efficiency of exercise which contained eccentric contraction of muscle was higher than that of the concentric contraction, which implied higher mechanical efficiency in higher speed running or jumping with high frequency. As for the effect of skills or techniques of exercise on the efficiency, Cunningham et al.[5] reported that the similar mechanical efficiencies were found for both experienced and inexperienced oarsmen, whereas Asami et al.[1] suggested that higher mechanical efficiency might be obtained from more skillful rowing performance.

To measure the mechanical efficiency of rowing in the present study, the oarsmen sat in a normal rowing position, being allowed to adjust the seat, the slide assembly and the foot to conform to his wishes. Before the measurement the subject performed 5 strokes of rowing with maximum effort so as to estimate the maximum value of force in a stroke exerted to the oarlock pin (F_{cmax}). After 10 minutes of resting on the rowing seat, the subjects were requested to row with the stepwise incremental loading method, i. e. rowing intensity was increased up to 100% F_{cmax} at 10% per every 2 minutes. The determination of the intensity was carried out by the instruction of a coxwain who monitored recordings of the force applied to the pin (F_c) on the oscillograph. Oxygen uptake and heart rate were measured during resting and exercise conditions at every 30 seconds by means of an automatic oxygen analyzer (ERGO OXYSCREEN, JEAGER, WEST GERMANY) and telemeter (SANEI 2E31A), respectively.

The mechanical work (W_o) exerted by an oarsman was calculated from the following equation;

$$W_o = \overline{F}_c \times \frac{a+b}{a \cdot b} \times (\sin \Theta_{H1} + \sin \Theta_{H2})$$

where $\overline{F}_c$ is the mean force applied to the pin, a and b are the lever arms of the force applied to the oar by the handgrip and that the force applied to the blade, respectively, and Θ_H is the angle between the oar and the line perpendicular to the water flow. The mechanical power ($\dot{W}_o$) is calculated from

$$\dot{W}_o = W_o \times f$$

where f is stroke frequency in a minute. The mechanical work is obtained every stroke during rowing.

The mechanical efficiencies are determined by the following equations which were defined by Gaesser and Brooks[8].

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

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

$$\text{Work efficiency} \quad (WE) = \frac{W_o}{E_1 - E_2} \times 100$$

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

where E is gross energy output including resting metabolism, e ; resting energy, E_1 ; energy output in loaded rowing, E_2 ; energy output in unloaded rowing ($W_o=0$), dW_o ; increment in work performed above previous work rate, and dE ; increment of energy consumption above that of a previous work rate.

The relationship between oxygen uptake ($\dot{V}_{O_2}$) and mechanical work in various rowing intensities, under the condition of anaerobic threshold, was shown in Fig. 9. At the unloaded rowing ($\dot{W}_o=0$) $\dot{V}_{O_2}$ was 1.12±0.11 $l\cdot min^{-1}$ (mean±s.d.). At low intensity of rowing, below about

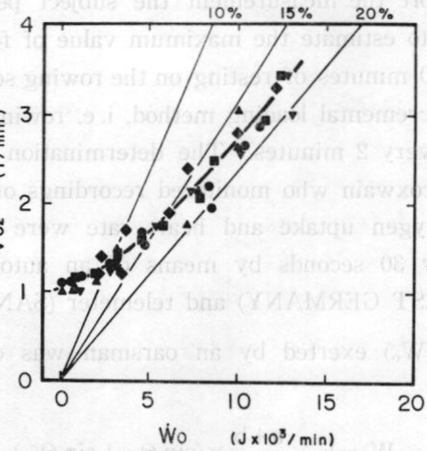

Figure 9. Relationship between $\dot{V}_{O_2}$ and $\dot{W}_o$. Isoefficiency lines, the inclination of which is the ratio between values in abscissas and ordiates are based on energy equivalent of 20.93 J/L O_2.

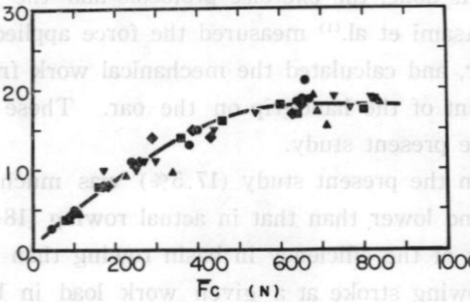

Figure 10. Changes in gross efficiency with mean force applied to pin ($\bar{F}_c$).

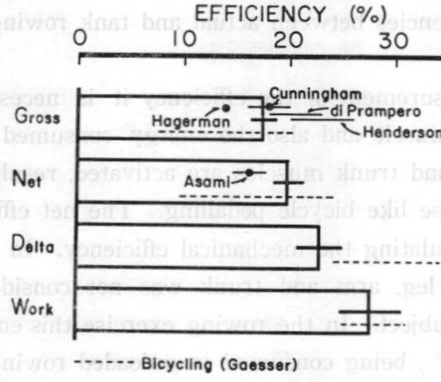

Figure 11. Comparison of mechanical efficiency between present study and previous reports.

7000 J·min^{-1} of $\dot{W}_o$, $\dot{V}_{O_2}$ increased curvilinearly with the increase of $\dot{W}_o$. At higher intensities, however, the rectilinear relation was observed between $\dot{V}_{O_2}$ and $\dot{W}_o$, and the gross efficiency indicated a range between 15% and 20%.

The relation between $\bar{F}_c$ and GE was shown in Fig. 10. GE increased linearly with increasing $\bar{F}_c$ in the low intensities, while above about 500 N of $\bar{F}_c$ the efficiency indicated almost constant value of 17.5%.

In the present study, no changes in the range of Θ_H were observed, i. e. independent of $\dot{W}_o$, so that the increment of $\dot{W}_o$ was caused by the increase in $\bar{F}_c$ and stroke frequency. This result was in good agreement with that of DiPrampero et al.[7], in which the displacement of handgrip was practically constant at all rowing frequencies, while the average pull and the work done per stroke increased with the frequency. The increment of the efficiency with increasing F_c in the present study agreed with some previous studies, which showed that in bicycle pedalling exercise the efficiency increased with increase in work rate and that the efficiency in rowing increased with the increasing stroke frequency[7].

Some different values of the mechanical efficiency during rowing exercise were reported as follows; 20–26% (Henderson and Haggard[10]), 18–23% (DiPrampero et al.[7]), 18.1±1.9%(Asami et al.[1]). The comparison of the efficiency between the present study and the previous reports were shown in Fig. 11. Differences if these reported values could be explained in terms of the measurements in the works done, the exercise protocols and the calculation of the efficiency. DiPrampero et al.[7] and Asami et al.[1] measured the force applied to the oar by using strain gauge mounted on the oar, and calculated the mechanical work from the product of the force on the oar and displacement of the handgrip on the oar. These experimental methods were almost same as that of the present study.

The gross efficiency in the present study (17.5%) was much the same as that in basin tank rowing (10-20%)[7] and lower than that in actual rowing (18-23%)[7]. DiPrampero et al.[7] reported that lower values of the efficiency in basin rowing than in actual rowing was caused by higher frequency of rowing stroke at a given work load in basin, because higher stroke frequency costs greater energy per minute due to more transverse component (energy loss) of the force applied to the pin. The stroke frequency in the present study (15-20 $f \cdot min^{-1}$) was lower than that in actual rowing (20-25 $f \cdot min^{-1}$) of DiPrampero et al.[7]. This result suggests that the difference in the efficiencies between actual and tank rowing was not solely due to the difference in stroke frequency.

To obtain an accurate measurement of the efficiency it is necessary to measure the mechanical work exerted by the muscle and also the energy consumed only for that work. In rowing, not only arm but leg and trunk muscles are activated, resulting more recruited muscle mass than other type of exercise like bicycle pedalling. The net efficiency has been the most frequently used method in calculating the mechanical efficiency. In this calculation, however, the energy cost of the moving leg, arm and trunk was not considered in the estimation of work done by the exercising subject. In the rowing exercise this energy cost could not ignored because of about $1\,l \cdot min^{-1}$ of $\dot{V}_{O_2}$ being consumed in unloaded rowing. In consideration of this unloaded energy cost, the work or delta efficiency is theoretically acceptable. Whipp and Wasserman[13] reported that 10% higher values of the work efficiency were considerably higher than gross and net efficiency in the bicycle exercise. As shown in Fig. 11, although delta efficiency in the present study indicated a little lower than that in bicycle exercise, it was considered that mechanical efficiencies in rowing indicated almost same values as those in bicycle exercise.

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