Propelling efficiency of front-crawl swimming

HUUB M. TOUSSAINT, ANITA BEELEN, ANNE RODENBURG, ANTHONY J. SARGEANT, GERT DE GROOT, A. PETER HOLLANDER, AND GERRIT JAN VAN INGEN SCHENAU
Department of Exercise Physiology and Health, Faculty of Human Movement Sciences, Vrije Universiteit and Universiteit van Amsterdam, 1105 AZ Amsterdam, The Netherlands

TOUSSAINT, HUUB M., ANITA BEELEN, ANNE RODENBURG, ANTHONY J. SARGEANT, GERT DE GROOT, A. PETER HOLLANDER, AND GERRIT JAN VAN INGEN SCHENAU. *Propelling efficiency of front-crawl swimming.* J. Appl. Physiol. 65(6): 2506–2512, 1988.—In this study the propelling efficiency (e_p) of front-crawl swimming, by use of the arms only, was calculated in four subjects. This is the ratio of the power used to overcome drag (P_d) to the total mechanical power (P_o) produced including power wasted in changing the kinetic energy of masses of water (P_k). By the use of an extended version of the system to measure active drag (MAD system), P_d was measured directly. Simultaneous measurement of O_2 uptake ($\dot{V}O_2$) enabled the establishment of the relationship between the rate of the energy expenditure ($P\dot{V}_{O_2}$) and P_o (since when swimming on the MAD system $P_o = P_d$). These individual relationships describing the mechanical efficiency (8–12%) were then used to estimate P_o in free swimming from measurements of $\dot{V}O_2$. Because P_d was directly measured at each velocity studied by use of the MAD system, e_p could be calculated according to the equation $e_p = P_d/(P_d + P_k) = P_d/P_o$. For the four top class swimmers studied, e_p was found to range from 46 to 77%. Total efficiency, defined as the product of mechanical and propelling efficiency, ranged from 5 to 8%.

power; drag; kinetic energy; oxygen uptake; human

THERE ARE remarkably few systematic studies on the energetics of swimming. In most of these the mechanical power (P_o) that the swimmer has to deliver has been considered simply as the product of body drag and swimming velocity (10, 12, 14, 15). However, this approach neglects the fact that some of the P_o generated by the swimmer is necessarily expended in giving water a kinetic energy change, since the propelling thrust is made against masses of water that acquire a backward momentum. Clearly the apportionment of P_o into the power used to overcome drag (P_d) and the power expended in giving water a kinetic energy change (P_k) will be an important determinant of the swimmer's performance.

P_d at a swimming velocity (v) and drag force (F_d) is given by

$$P_d = F_d \cdot v \qquad (1)$$

The second component, P_k, is given by

$$P_k = \tfrac{1}{2} m (\Delta u)^2 f \qquad (2)$$

where m is the mass of the pushed away water, Δu is its velocity change, and f is the stroke frequency (19).

If the whole body is taken as free body diagram, external power is defined as the sum of products of the external forces and the velocity of their point of application. Thus the power balance during swimming can be described by

$$P_o - P_d - P_k = dE/dt \qquad (3)$$

where P_o is the total mechanical power delivered by the swimmer (minus internal losses of mechanical power, e.g., rotational energy of segments) and dE/dt is the change in kinetic energy of the swimmer. Since the intracyclic velocity oscillations in front-crawl swimming are negligible (10), changes in the kinetic energy of the swimmer can be considered to be 0 (i.e., $dE/dt = 0$) and therefore

$$P_o = P_d + P_k \qquad (4)$$

The ratio of P_d to P_o has been defined as the propelling efficiency (e_p) (1, 16, 19, 23), which is given by

$$e_p = P_d/(P_d + P_k) = P_d/P_o \qquad (5)$$

From these considerations it will be apparent that swimming performance will depend not only on a high P_o but will also depend on a high e_p. It is important to remember that e_p is a measure of the way the P_o generated by the swimmer is apportioned between P_d and P_k. It does not include any element of the efficiency of energy conversion to P_o within the body. This is a separate issue usually expressed as (apparent) mechanical efficiency (e_m), which is calculated as the ratio of the energy equivalence of O_2 uptake ($\dot{V}O_2$) to the P_o delivered.

Recently, a mathematical model for human front-crawl swimming was developed by de Groot and van Ingen Schenau (6). By assuming lift and drag propulsive forces acting on the hand and forearm, they predicted an e_p of 56% at optimum position. This compares with an experimentally determined value of 80% for fish (23), which at the highest swimming velocities studied agrees with the predictions of the mathematical model of Lighthill (13). The difference in values for e_p between fish and human swimming was explained by the larger propelling surfaces of the body (in particular the fins), relative to the total body surface. However, no experimental data on human e_p were available.

In the present investigation we were able to measure P_o and P_d by using a technique developed in our laboratory (7, 18, 21, 22). Thus we are able to report for the first time experimental determinations of e_p in swimming humans.

TABLE 1. *Individual data for age, height, weight, and personal best time on 100-m free style*

Subj	Age, yr	Ht, m	Wt, kg	100-m Time, s
PH	21	1.83	71	54.5
GK	21	1.83	67	53
KV	26	1.96	90	52.5
FW	21	1.83	80	55

METHODS

Subjects. Four male swimmers competing at international and national levels were studied (mean height 1.86 m, weight 77 kg, age 22.3 yr; see Table 1). Mean personal best time of the subjects in 100-m front crawl was 53.8 s. Throughout the experiments the water temperature was 26.9°C.

Apparatus. P_d was measured by means of an extended version of the system to measure active drag (MAD system) (7). Simultaneous measurement of P_d and $\dot{V}O_2$ necessitates the opportunity to swim continuously over the system. Therefore two lanes of push-off pads were mounted alongside each other to make continuous swimming possible. A general view of the system is given in Figs. 1 and 2.

The MAD system allowed the swimmer to push off from fixed pads at each stroke. Hence, no power was expended in giving water a kinetic energy change as in normal free swimming, and so $P_o = P_d$. The push-off pads were mounted 1.35 m apart on two 23-m horizontal rods 0.8 m below the water surface. At one end of the swimming pool, one rod was connected to a force transducer. The force signal was low-pass filtered (15-Hz cutoff frequency), on-line digitized (100-Hz sampling frequency), processed, and stored on disk by means of a microcomputer. In all the experiments described in this study, the swimmers used their arms only; their legs were supported and fixed together by a small buoy. Therefore, the average propulsive force applied by the arms equaled the average F_d (7, 22).

The result from the thrusts made from the 16 pads is shown in the force record (Fig. 2). The first and last push-off are neglected to eliminate the influence of the push-off from the wall (first pad) and the deceleration of the swimmer at the end of the lane (last pad). The remaining force signal is time integrated, yielding the average F_d. The mean velocity was computed from the time (dashed line, Fig. 2) needed to cover the distance between the second and last pad (18.9 m, Fig. 2). P_d was calculated from the product of the mean F_d and the mean velocity according to *Eq. 1*.

The resonance frequency of the earlier system (7) was improved from 8 to 20 Hz (Fig. 3) by the application of aluminum vertical and horizontal rods of higher stiffness. These improvements increased the reproducibility of the F_d measurements at the mean of the velocity range from 4.1 to 0.92 N (1%) (see Fig. 4).

Drag force. The reproducibility of the F_d measurements was examined by repeated measurements of drag on one subject on 7 different days. On each day the subject was asked to swim 10 lanes at different but constant velocities (range 0.9–1.9 $m \cdot s^{-1}$). On each occasion, mean F_d and mean swimming velocity (v) were measured. These v/F_d data were least-squares fitted to the function

$$F_d = A \cdot v^n \tag{6}$$

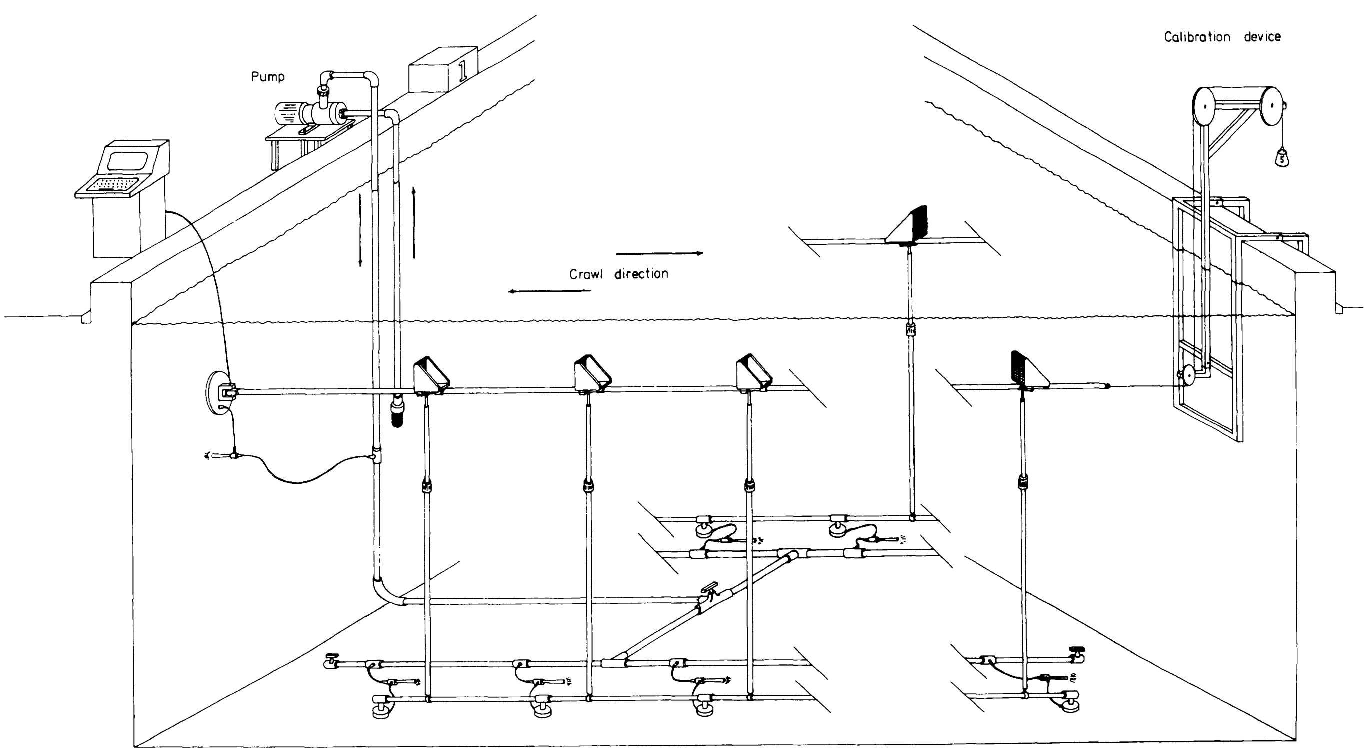

FIG. 1. Schematic side view of system to measure active drag (MAD system) used in this study. Two segments of both measuring and dummy MAD are shown. Calibration device is shown on *right* and force transducer on *left*. For a more detailed description, see Refs. 8 and 22.

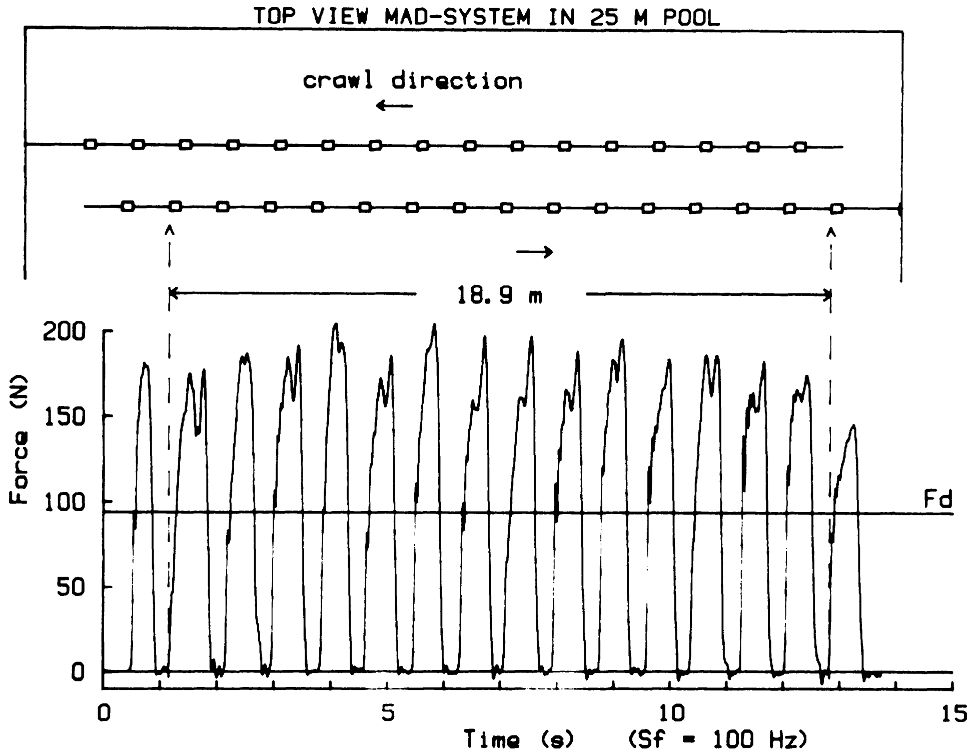

FIG. 2. Top view of measurement system. Measurements (*below*) and dummy measurements of active drag are arranged so that continuous swimming is possible. Force record is the result of 16 thrusts from push-off pads. First and last thrusts are ignored. Remaining force signal is time integrated, yielding average force. Time necessary to cover the distance between the second and last pad (18.9 m) is measured from force curve (- - -). Average velocity = 18.9/(measured time).

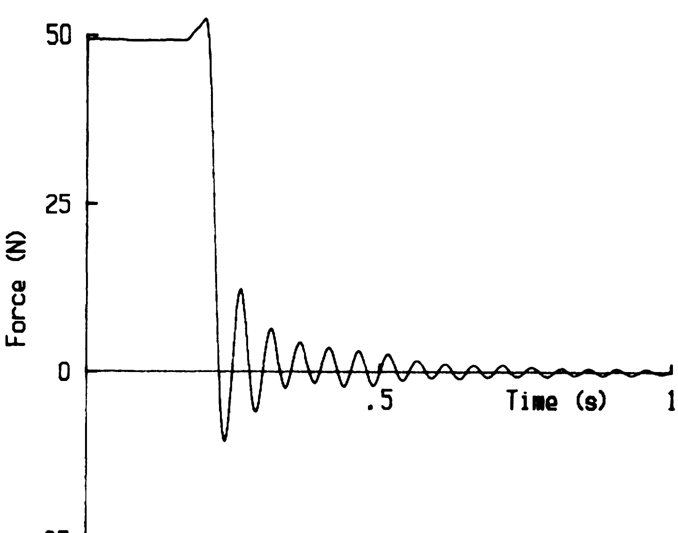

FIG. 3. Response of the system to a quick release of a 5-kg wt. Resonance frequency of the system appears to be ±20 Hz. (In this determination sampling frequency was increased to 1,000 Hz).

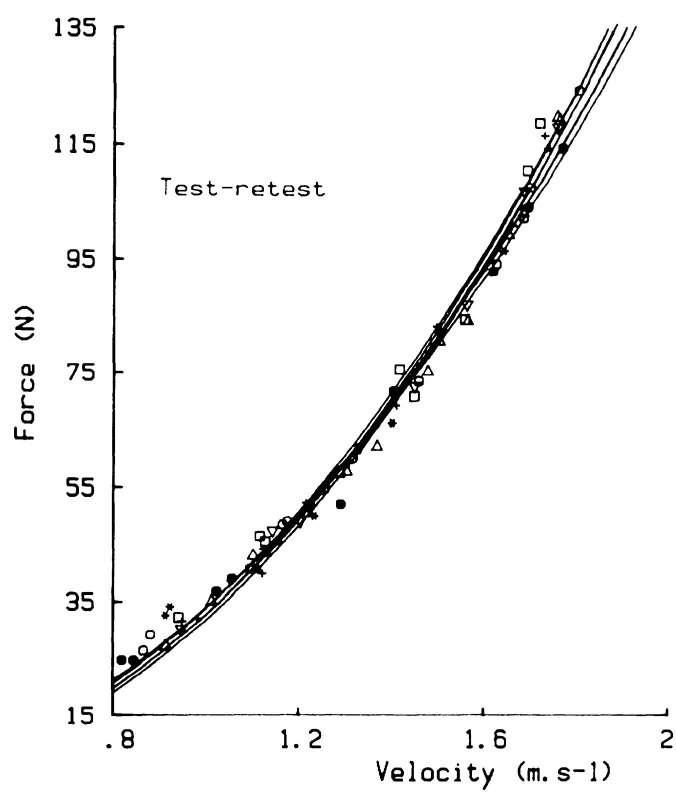

FIG. 4. Results of 7 measurements (different symbols) of drag dependent on velocity in 1 subject. At mean velocity of 1.51 $m \cdot s^{-1}$ mean force was 82.26 N. Reproducibility of this force measured on 1 subject was ±0.91 N (coefficient of variation ±1%).

where A and n are constants of proportionality (Fig. 4). The validity of the described method to measure drag was discussed by Vaart et al. (22).

Power and mechanical efficiency. Each subject performed several 400-m swims at different velocities ranging from 1.0 to 1.29 $m \cdot s^{-1}$. This range was determined by the need to ensure that all exercise was within the range of aerobic performance and also that subjects were able to maintain a normal swimming technique even at the lowest velocity. The subject swam 400 m twice, once using the MAD system and once free at the same velocity.

During the measurements, subjects were aided in keeping a constant swimming velocity by a pacing device consisting of underwater lights on the push-off pads that were programmed to flash consecutively along each lane at the required speed. The reproducibility of the actual swimming velocity was within 2.1%.

In both forms of swimming, $\dot{V}O_2$ was measured with a Douglas bag technique. The bags were mounted on a trolley, which was pushed along the side of the swimming pool. Respiratory tubing was suspended directly over the swimmer by means of a boom. The swimmer wore a specially designed respiratory valve, which fixed the inspiration and expiration tubes in line. In a previous investigation we demonstrated that the "streamlining" of this design was such that there was no measurable increase in drag (21). Four Douglas bag collections were made over the last 200 m (after at least 2 min 15 s) by which time a constant level of $\dot{V}O_2$ had been reached. $\dot{V}O_2$ was calculated from O_2 and CO_2 concentration, measured with a Mijnhardt Oxylyser (UG64) and a Mijnhardt Capnolyser (UG55), respectively, and the volume of the expired air, which was measured with a dry gas meter. The resulting four values were averaged. The $\dot{V}O_2$ was taken to reflect the rate of energy expenditure at the submaximal exercise levels studied.

The rate of energy expenditure (expressed as the power equivalence, $P\dot{V}_{O_2}$, in W) was estimated from the $\dot{V}O_2$ (l·min^{-1} STPD) by use of the formula

$$P\dot{V}_{O_2} = 1/60 \cdot 10^3 \cdot [4.2 \cdot (4.047 + RER)] \cdot \dot{V}O_2 \quad (7)$$

where RER is the respiratory exchange ratio.

Some additional measurements of $P\dot{V}_{O_2}$ were made at higher velocities while the subjects swam along the push-off pads to establish the $P_d/P\dot{V}_{O_2}$ relationship. The rate of energy expenditure measured during swimming on the MAD system ($P\dot{V}_{O_2\,MAD}$), reflected P_o, which was equal to P_d, since the push off was made against the fixed pads ($P_k = 0$).

At each velocity, a mean value of P_d was calculated from the eight lengths swam over the measuring MAD system. The relation between $P\dot{V}_{O_2\,MAD}$ and P_o could be calculated

$$P_o = a \cdot P\dot{V}_{O_2} - b \quad (8)$$

where a and b are constants of the regression equation. This regression equation describes the mechanical efficiency (e_m), i.e., the conversion of metabolic energy to mechanical energy.

Propelling efficiency. The individual regressions describing the e_m were then used to calculate P_o during free swimming from the measured $P\dot{V}_{O_2}$ ($P\dot{V}_{O_2\,free}$, *Eq. 7*). In free swimming $P_o = P_d + P_k$. Since P_d was known for each subject and swimming speed from the measurements on the MAD system, the value of e_p could then be computed according to *Eq. 5*.

Measurements were made on separate days to prevent subjects becoming fatigued.

RESULTS

Measurements were made during free swimming and on the MAD system in a range of matched speeds (1.08–1.29 m·s^{-1}), which required $\dot{V}O_2$'s that ranged from 1.84 to 4.11 and from 1.40 to 3.59 l·min^{-1}, respectively. Average values for the $\dot{V}O_2$ for both MAD and free swimming dependent on velocity are presented in Table 2. The RER ranged from 0.71 to 0.95. $P\dot{V}_{O_2}$ calculated from the $\dot{V}O_2$ data (according to *Eq. 7*) ranged from 626 to 1,440 W and from 487 to 1,256 W, respectively.

TABLE 2. *Average O_2 uptake in both swimming conditions dependent on velocity*

Velocity, m·s^{-1}	*PH*		*GK*		*KV*		*FW*	
	MAD	Free	MAD	Free	MAD	Free	MAD	Free
1.08					1.68	2.61		
1.13	1.90	2.48	1.59	1.93	1.88	3.04	1.97	2.98
1.18	2.36	3.07	1.65	2.06	1.80	2.94	2.00	3.37
1.23	2.33	3.26	1.80	2.32	1.85	3.24	2.13	3.50
1.29	2.80	3.33	1.90	2.72	2.15	3.55	2.30	3.78

Values expressed as l·min^{-1} STPD. MAD, system to measure active drag.

Figure 5 presents the raw (each point represents 1 Douglas bag) individual data on the four subjects studied for $P\dot{V}_{O_2}$. This is given in relation to v^3, since power is the product of force times velocity and the F_d is dependent on v^2 (18). In both swimming situations the $P\dot{V}_{O_2}$ data are highly correlated for each subject to v^3. At any given velocity, the $P\dot{V}_{O_2}$ when swimming free was consistently higher than that when swimming on the MAD system. This is as expected, since in free swimming additional energy is dissipated in giving water a kinetic energy change. The individual SD of the $P\dot{V}_{O_2}$ measurements was <4.5%.

In an extended series of experiments, additional data were collected to establish the relationship between $P\dot{V}_{O_2\,MAD}$ measured by means of the MAD system and P_d (equal to P_o). In Fig. 6 the individual regression equations are presented. Correlation coefficients ranged from 0.87 to 0.98. By the use of these individual regression equations, the P_o when swimming free was calculated from the measured $P\dot{V}_{O_2\,free}$.

Knowing the P_o, swimming free and P_d as determined on the MAD system at the same velocity, we calculated e_p according to *Eq. 5* for each velocity studied. Values for P_d, P_o, and e_p are presented in Table 3. Values for P_d varied from 36 to 67 W over the velocity range studied. In these top class swimmers, e_p values ranged from 46 to 77%. A surprisingly large difference in e_p between individuals was found.

DISCUSSION

Theoretical considerations indicated that the mechanical power delivered by a swimmer could be divided into two components: P_d and P_k. However, previous investigators have been unable to measure this latter component (10, 12, 14, 15). To calculate e_p, it is necessary to have an accurate determination of P_o and P_d during swimming. This is now possible with the development of the MAD system described in this study. The validity of this method for the measurement of active drag has been examined and discussed recently by Vaart et al. (22). Although not finally resolved, we believe that the method is valid and represents the best method currently available.

The values for e_p of our top class swimmers ranged from 46 to 77%. For *subjects KV* (58%) and *FW* (49%), the values are in accordance with the predictions from the mathematical model of de Groot and van Ingen Schenau (6). For *subjects GK* and *PH*, the values for e_p

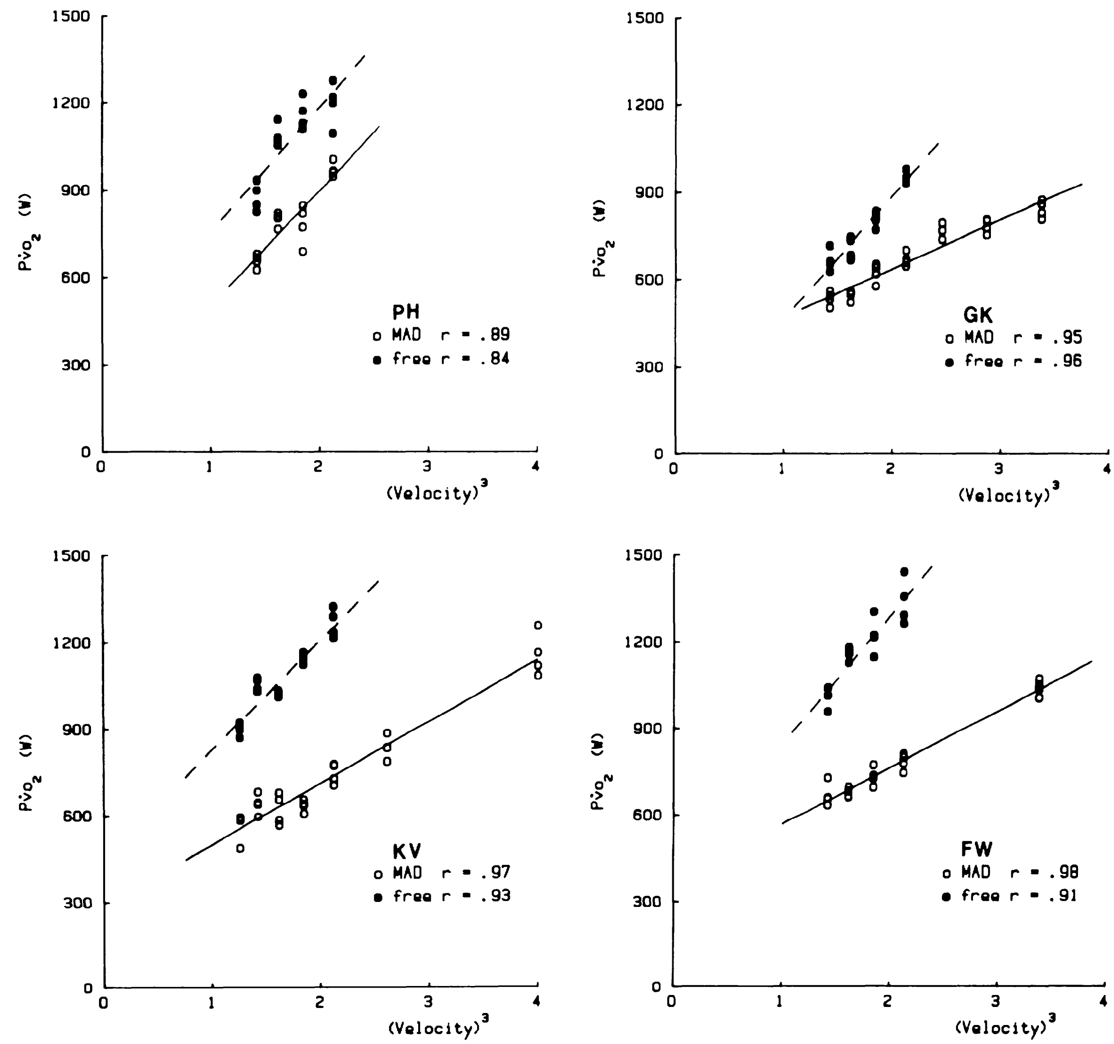

FIG. 5. Rate of energy expenditure (measured as O_2 uptake and converted to watts, $P\dot{V}_{O_2}$) in relation to cube of velocity measured in 4 subjects (*PH, GK, KV, FW*). Each point represents 1 Douglas bag. ○, Values measured while swimming on MAD system. ●, Values measured while swimming free. Difference between regression lines reflects power wasted in changing kinetic energy of water, i.e., driving water backward.

(68% and 73%, respectively) are consistently higher. It is possible that body dimensions may contribute to these differences, but we have insufficient data to make any worthwhile speculation on this issue. Resolution of this must await study of a much larger group of elite swimmers of different body builds. Although the values for e_p are not as high as those found for fish (80%), they are higher than was expected considering the relative small propulsive area (e.g., hand and forearm). However, e_p values >50% do not seem to be unreasonable if we consider the next example. Suppose a swimmer has a maximal P_o of 250 W, an e_p of 50%, and a drag-velocity relationship of $F_d = 30\ v^2$. His maximal free-swimming velocity can be computed to be $v^3 = (0.5 \cdot 250)/30 = 4.17$; hence $v = 1.6\ m \cdot s^{-1}$. On the MAD system where $e_p = 1$, $v^3 = 250/30 = 8.3$; hence $v = 2.0\ m \cdot s^{-1}$. The actual increase in maximal swimming velocity on the MAD system would then be <25%, and this is in accordance with our own unpublished observations.

To calculate the P_o swimming free, it was assumed that the regression equation of $P\dot{V}_{O_2 MAD}$ on P_o during MAD swimming could be used to compute P_o from $P\dot{V}_{O_2}$ during free swimming. This assumption would be valid only if the movement pattern was essentially the same in both forms of swimming. The fact that this is indeed the case is supported by the close similarity between the electromyographic activity of selected muscles during free and MAD swimming (3). This was also confirmed by the swimmers' own assessments, which, although subjective, are based on great experience and many hours of training. Of course it must be realized that some energy costs will not be reflected in the P_o measured. These will include the cost of overcoming the hydrostatic pressure on the lungs, making turns at the end of the pool, and recovering the arms to the point of entry. However, these additional costs are likely, in our view, to be a rather small and constant proportion of the total and will of course be the same in both forms of swimming. One methodological issue that might be commented on is the effect of floating the feet with a small buoy. However, it should be remembered that this is done in the same way both in MAD and free swimming, and thus any effect will be cancelled out in the calculation of e_p.

With these qualifications in mind the apparent e_m,

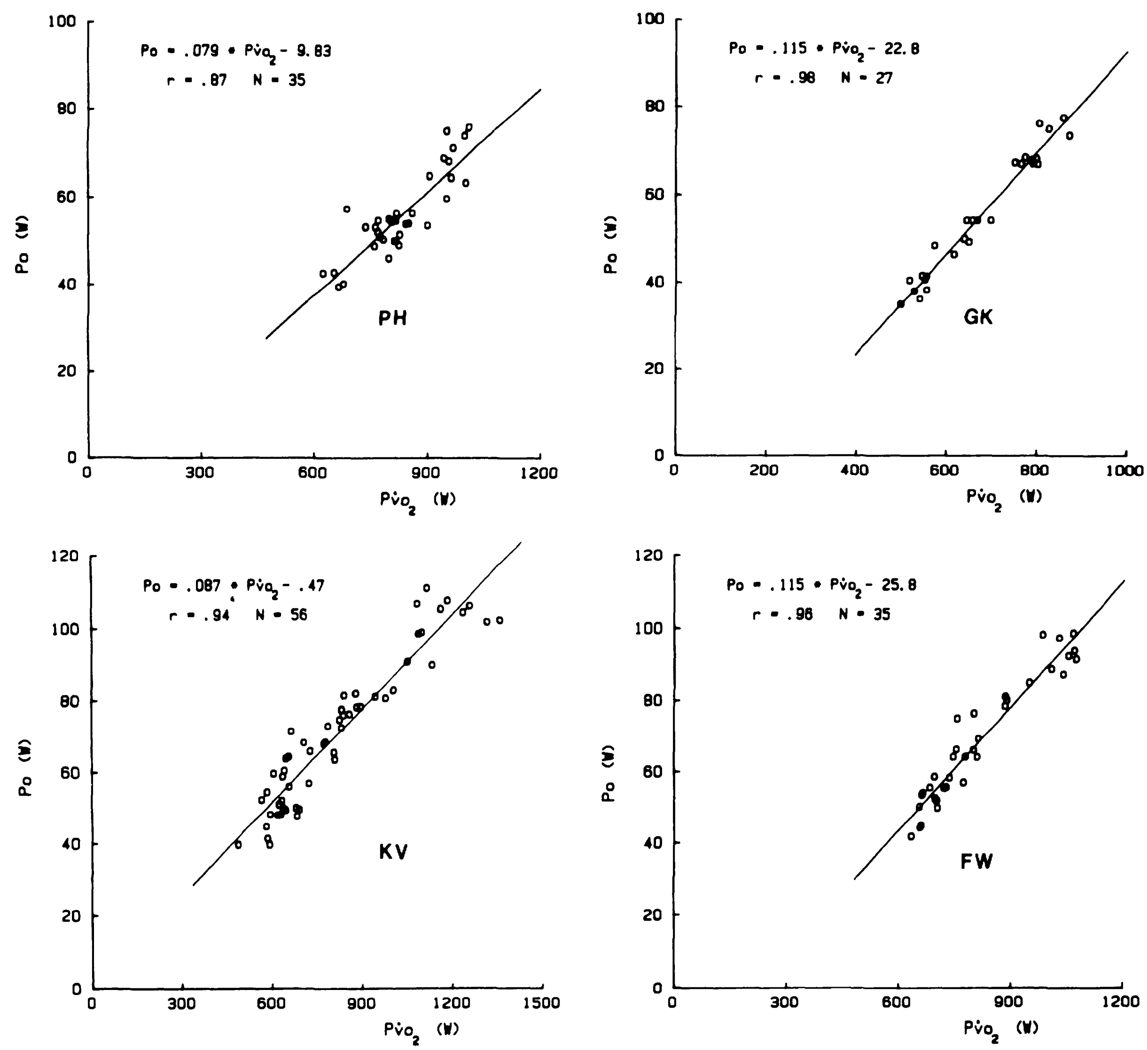

FIG. 6. O_2 uptake and mechanical power output (P_o) were measured simultaneously while swimming on MAD system. Regression equation of P_o (measured using MAD system where $P_o = P_d$) on power equivalence of O_2 uptake ($P\dot{V}_{O_2}$) measured with Douglas bag technique is given. Each point represents 1 Douglas bag.

TABLE 3. *P_d, P_o, and e_p dependent on velocity*

Velocity, $m \cdot s^{-1}$	*PH*			*GK*			*KV*			*FW*		
	P_d, W	P_o, W	e_p, %	P_d, W	P_o, W	e_p, %	P_d, W	P_o, W	e_p, %	P_d, W	P_o, W	e_p, %
1.08							41.6	78.0	53			
1.13	41.5	58.7	71	36.6	52.9	69	49.1	91.3	54	42.4	91.4	46
1.18	52.4	74.3	71	41.3	58.7	70	52.9	88.3	60	54.8	108.5	51
1.23	53.9	80.3	67	48.8	70.2	70	60.6	98.3	62	57.6	115.2	50
1.29	65.5	85.2	77	57.6	88.1	65	67.8	109.2	62	64.4	127.8	50

P_d, power to overcome drag; P_o, mechanical power output; e_p, propelling efficiency.

defined as the ratio between total P_o and the rate of energy expenditure could be calculated. Values of e_m ranged from 8 to 12%, and these are comparable with similar calculations for e_m in other forms of arm work such as wheelchair riding (up to 11.5%) (24) and arm cranking (8–10%) (5). In this context it should be remembered that the data in this paper are based on swimming with the arms only and that this is by far the most important source of P_o (up to 86%) (20) in normal front-crawl swimming.

"Total" efficiency defined as the product of e_m and e_p (reflecting the O_2 cost of performing "useful" work), ranged from 5 to 8%. These values are similar to the values reported by Holmér (9), who reported efficiencies of 4–7.7%, and Pendergast et al. (14), who reported values of 2.7–9.4%, despite the fact that these previous investigators were unable to make reliable estimates of drag in the active situation (22). Probably, the drag values that they used, which were approximately twice the values reported in this study, compensated for the fact that the e_p, which is ~50%, was not taken into account in the earlier studies. Their data may be an example of two wrongs making one right.

No correlation appears to exist between drag and swimming performance (8) or between $\dot{V}O_{2\,max}$ and maximal swimming performance (10, 19). However, there is unanimous agreement that proficient swimmers are much more economical in terms of energy expenditure than less skilled swimmers (2, 9, 11, 14, 15). Costill et al. (4) reported no difference in $\dot{V}O_{2\,max}$ between competitive and recreational swimmers, whereas the mean maximum swimming velocity of the competitive swimmers was significantly higher (1.29 vs. 0.89 $m \cdot s^{-1}$). They suggested that the energy cost is strongly influenced by among other things the effective application of force during the arm stroke, as noted by the distance per stroke at a specific swimming velocity. The relationship between stroke technique and energy cost of swimming is also pointed out by De Groot and van Ingen Schenau (6), who calculated the effects of lift and drag propulsion generated by the hand and arm on the wasted power P_k. They reported that the application of drag forces induces five to six times more wasted power (P_k) compared with the same propulsive force generated by lift forces. They concluded that maximal swimming speed is not only dependent on the magnitude of the propulsive forces. The best technique seems to be the one that leads to high lift-to-drag ratios. They showed that this technique results in longer strokes because the backward component of the hand speed is lower compared with a straight backward pull. This suggests that values of e_p can be used to evaluate the effectiveness of individual stroke technique.

Finally it is concluded that e_p is a very important factor determining performance and that in competitive swimming the ability to swim faster arises from the capacity *1*) to reduce drag, *2*) to increase the propelling force, and *3*) to perform at a high e_p.

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