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ORIGINAL ARTICLE

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Abstract Underwater torque (T') is defined as the product of the force with which the swimmer's feet tend to sink times the distance between the feet and the centre of volume of the lungs. It has previously been shown that experimental changes of T', obtained by securing around the swimmer's waist a plastic tube filled, on different occasions, with air, water or 2-kg lead, were accompanied by changes in the energy cost of swimming per unit of distance (C_s) at any given speed. The aim of this study was to investigate whether the observed increases of C_s with T' during front crawl swimming were due to an increase of active body drag (D_b), a decrease of drag efficiency (η_d) or both. The effect of experimental changes of T' on C_s, D_b and η_d were therefore studied on a group of eight male elite swimmers at two submaximal speeds (1.00 and 1.23 $m \cdot s^{-1}$). To compare different subjects and different speeds, the individual data for C_s, D_b, η_d and T' were normalized dividing them by the corresponding individual averages. These were calculated from all individual data (of C_s, D_b, η_d and T') obtained from that subject at that speed. It was found that, between the two extremes of this study (tube filled with air and with 2-kg lead), T' increased by 73% and that C_s, D_b and η_d increased linearly with T'. The increase of C_s between the two extremes was intermediate (~ 20%) between that of D_b (~ 35%) and of η_d (~ 16%). Thus, the actual strategy implemented by the swimmers to counteract T', was to tolerate a large increase of D_b. This led also to a substantial (albeit smaller) increase of η_d, the effect of which was to reduce the increase of C_s that would otherwise have occurred.

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Introduction

The energy cost of swimming the front crawl per unit distance (C_s), in subjects of comparable swimming skill at a given speed, has been shown to be linearly related to underwater torque (T') in any given subject (Pendergast et al. 1977). In turn, T', as has originally been defined by Pendergast and Craig (1974), is the product of the force with which the feet of a swimmer tend to sink times the distance from the feet to the centre of volume of the lungs.

It has also been shown (Capelli et al. 1995) that the experimental changes in T' (obtained by securing around the swimmers waist a plastic tube filled with air, water or different amounts of lead), led to consequent changes of C_s.

At any given speed, C_s has been found to depend on body drag (D_b) and on swimming efficiency (η_d; di Prampero et al. 1974). Therefore, the aim of this study was to investigate whether the changes of C_s induced by the experimental manipulations of T' are due to its effects on D_b and/or on η_d.

Methods

Subjects

The experiments were performed at two submaximal speeds (1.00 and 1.23 $m \cdot s^{-1}$) on a group of eight elite swimmers, members of the team of the State University of New York at Buffalo (SUNYAB) who where swimming in the National U.S. Collegiate Athletic Association's Men's Division I competitions. Their main anthropometric and physiological characteristics are reported in Table 1. Their maximal oxygen uptake ($\dot{V}O_{2max}$) was measured in an experimental session following the standard step protocol applied in the Department of Physiology at SUNYAB when testing the swimming team

Table 1 Anthropometric and physiological characteristics of the subjects. A_D Body surface area, T'_A, T'_W and T'_L underwater torque in the air, water and 2-kg lead configuration, respectively (see text for details)

Subject	Age (years)	Height (m)	Body mass (kg)	A_D (m^2)	$\dot{V}O_{2max}$ ($l \cdot min^{-1}$)	T'_A (N·m)	T'_W (N·m)	T'_L (N·m)
DH	19	1.88	77.6	2.04	4.39	12.62	17.28	22.22
RW	21	1.93	91.5	2.23	4.30	13.14	19.27	23.65
JV	23	1.88	88.3	2.16	5.93	12.10	17.73	23.37
DB	20	1.91	78.9	2.05	4.74	16.97	21.56	25.87
KR	21	1.76	73.6	1.91	5.68	11.81	16.28	21.00
PJ	23	1.78	78.4	1.97	3.90	7.48	12.08	15.75
EA	21	1.89	89.2	2.15	4.41	14.09	18.51	22.01
CB	21	1.89	88.4	2.17	4.77	14.19	19.34	23.65
Mean	21.1	1.86	83.2	2.08	4.76	12.80	17.76	22.19
SD	1.36	0.06	6.79	0.11	0.70	2.70	2.79	2.98

athletes during the season. The subjects were informed about the methods and aims of the study and gave their informed consent.

Biomechanics

The T' was measured by means of an underwater balance positioned on the bottom of an 80-cm deep swimming pool. The subject lay in the prone position, fixed by means of quick release belts, and breathing through a neutrally buoyant snorkel, on a webbed aluminium frame positioned 50-cm underwater. The frame and the subject were free to rotate upon a supporting fulcrum, the position of which could be appropriately arranged. A load cell (type F1, AEP transducers, I), located at the feet end of the frame, prevented its rotation. The fulcrum was positioned at the centre of volume of the lungs (CL), which is approximately located at the level of the horizontal mammillary line. The exact position of CL was determined as the point at which deep variations of lung volumes did not lead to any change of the force on the load cell. The T' was calculated as the product of the force exerted on the load cell (corrected for the mass of the frame in each experimental measurement) times the distance from the cell to the fulcrum (Capelli et al. 1995; Pendergast et al. 1977).

In the experiments T' was modified as follows: a flexible tube (4-cm outer diameter, 150-cm long) was secured around the waist of the subjects and filled on different occasions with 2 kg of lead, water or air (Capelli et al. 1995). Thus, T' was either increased, unchanged, or decreased compared to the natural condition (tube filled with water). Care was taken to position the tube always at the same location, as described in a previous paper (Capelli et al. 1995).

The individual values of T' in the three conditions, are reported in Table 1, along with the other anthropometric variables.

Energy cost of swimming

The C_s was assessed for all experimental configurations of T' (tube filled with water, air, or 2 kg of lead) at two constant speeds (1.00 and 1.23 $m \cdot s^{-1}$) corresponding to an energy requirement equal to or less than 85% of previously determined $\dot{V}O_{2max}$. The subjects swam in an annular pool 2.5-m wide, 2.5-m deep and of 60-m circumference at the swimmer's position and were paced by a platform moving at constant velocity about 60 cm above the water surface. The velocity of the platform in respect to the water was monitored by means of an impeller (PT-301, MEAD Inst. Corp., Riverdale, N.Y., USA) in the water 1.5 m in front of the swimmer and connected to a tachometer (F1-12 P Portable Indicator, MEAD Inst. Corp., Riverdale, N.Y., USA).

The oxygen uptake ($\dot{V}O_2$) was determined by a standard open circuit method. The expired gases were collected (for about 60 s) into an aerostatic balloon through a waterproof inspiratory and expiratory valve and hose system supported by the platform 3–4 min after the onset of the swim. The balloon was placed on the platform where an operator could time the expiratory collection period to the closest 0.1 s. The O_2 and CO_2 fractions in the expired air were determined by means of a previously calibrated paramagnetic O_2 analyser (Beckman C2, Palo Alto, Calif., USA) and an infrared CO_2 meter (Beckman LB-1, Palo Alto, Calif., USA); the gas volume was determined by means of a dry gas meter (American Meter Company, USA). The VO_2 values (at standard temperature and pressure, dry) were converted into energy assuming that 1 ml O_2 consumed by the human body yielded 20.9 J (which is strictly true for a respiratory quotient = 0.96) and divided by the speed to yield C_s in kilojoules per metre. Finally C_s was normalized to the body surface area (A_D, m^2) calculated according to Du Bois and Dubois (1915), to yield C_s in kilojoules per metre per metre squared.

Active body drag and drag efficiency

Active body drag at 1.00 and 1.23 $m \cdot s^{-1}$ was measured as described by di Prampero et al. (1974).

Briefly, known masses (from 0.5 to 2.5 kg) were attached to the swimmer by means of a rope and a safety belt that did not interfere with the swimming mechanics. The rope passed through a system of pulleys fixed to the platform in front of the swimmer, thus allowing the force to act horizontally along the direction of movement (see inset of Fig. 1). This force, defined added drag (D_a) led to a reduction in the swimmer's active D_b. As has been shown by di Prampero et al. (1974), when swimming at constant speed, this artificial reduction of D_b is associated with a consequent reduction of $\dot{V}O_2$. Hence, the energy required to overcome D_b becomes 0 when D_a and D_b are equal and opposite.

On this basis, and since the relationship between $\dot{V}O_2$ and D_a was shown to be linear over a relatively large range of $\dot{V}O_2$, we estimated the swimmer's D_b at any given speed and T', by extrapolating the $\dot{V}O_2$ versus D_a relationship to resting $\dot{V}O_2$. In turn, this last was assumed to be 0.5 $l \cdot min^{-1}$, which has been shown to correspond to the oxygen requirement at rest in water (Craig and Dvorak 1968).

Furthermore, since the power dissipated ($\dot{W}_d$) against drag is equal to the active D_b times the speed (v) ($\dot{W}_d = D_b \cdot v$), the reduction of D_b brought about by D_a, leads to an equal reduction of $\dot{W}_d$. In these conditions therefore:

$$\dot{W}_d = (D_b \cdot v) - (D_a \cdot v) = (D_b - D_a) \cdot v \quad (1)$$

Since for the same subject at the same speed v and D_b are constant (and hence Δv and $\Delta D_b = 0$), from Eq. 1 one obtains:

$$\Delta \dot{W}_d = -\Delta D_a \cdot v \quad (2)$$

Therefore, at any given v, the reciprocal of the slope of the $\dot{V}O_2$ versus D_a relationships of Fig. 1 is equal to the drag efficiency (η_d):

$$-\Delta D_a \cdot v / \Delta \dot{V}O_2 = \Delta \dot{W}_d / \Delta \dot{V}O_2 = \eta_d \quad (3)$$

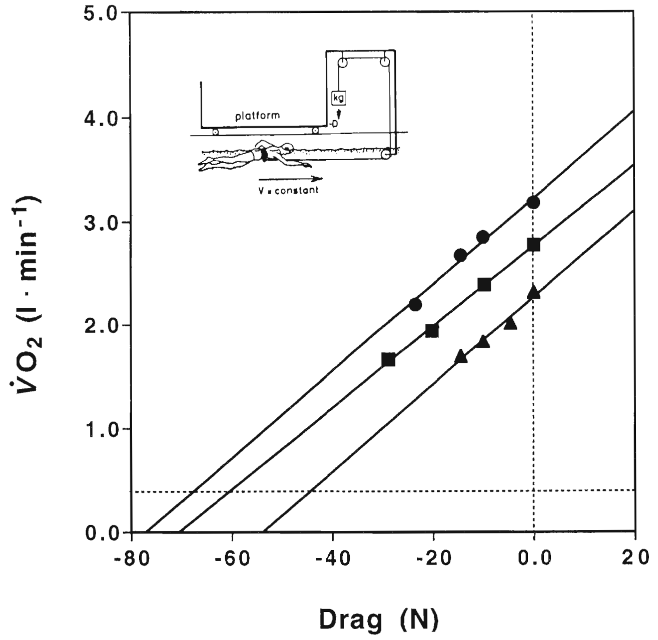

Fig. 1 Steady state oxygen uptake ($\dot{V}O_2$) as a function of the negative added drag for the three underwater torque configurations at 1.00 $m \cdot s^{-1}$ in one subject. The equations of the three regressions are: *circles* (air): $y = 0.041 \cdot x + 2.26$, $r^2 = 0.97$, $n = 4$; *squares* (water): $y = 0.038 \cdot x + 2.76$, $r^2 = 1.00$, $n = 4$; *triangles* (2-kg lead): $y = 0.041 \cdot x + 3.22$, $r^2 = 0.98$, $n = 4$. *Upper inset* is a diagram of the method used to apply known drag values to the swimmer's body (from di Prampero et al. 1974; see text for details). v Swimming velocity, $-D_a$ negative added drag

Experimental procedure

Each subject participated in six experimental sessions on different days, each session corresponding to one of the three T' configurations at one of the two v. The subject reported to the laboratory in the morning and the tube, corresponding to the randomly preselected T', was secured around his waist. After a brief warm-up, he was attached to the pulley system of the platform by a safety belt which was secured around his abdomen. At the beginning of the experimental session, a 2.5-kg load was applied to the pulley and the subject was asked to attain the requested v. After 3 min, once the steady state was attained, the operator started to collect expired gas into the balloon. After 1 min the expired gas collection was completed and the load on the pulley was diminished by about 0.5 kg. This procedure was repeated until, for the last stage, the subject swam without any added load. The $\dot{V}O_2$ values obtained for this last stage were used in the calculations of the energy cost of free swimming. This procedure allowed us to construct, for each v and T' condition, the relationships between $\dot{V}O_2$ and D_a.

Statistics

The regressions between $\dot{V}O_2$ and D_a were calculated using the least square linear analysis. The differences between the values of D_b, η_d and C_s due to the three T' conditions and the two v, were investigated using the multivariate analysis of variance (MANOVA); a post-hoc Bonferroni test (Systat 5.2.1 program for Macintosh computers) was then applied to determine significances of differences for the three variables (D_b, η_d and C_s) at the three configurations of T'.

Results

The results of a typical experiment in one subject at 1.00 $m \cdot s^{-1}$ are reported in Fig. 1 for the three T' studied. The function relating these two variables, as obtained on four to five observations, were linear in all the subjects at both v [mean r^2: 0.969 (SD 0.034) at 1.00 $m \cdot s^{-1}$ and 0.980 (SD 0.016) at 1.23 $m \cdot s^{-1}$, range: 0.865–0.999]. This made it possible to obtain the values of active D_b and η_d for each individual as described in the methods.

In Table 2 the C_s, D_b, and η_d for each individual are reported at both v and for the three T'. The coefficients of variation of C_s, D_b and η_d at a given T' and v, were fairly large, ranging from 11.1% to 32.0%. Therefore, in an attempt to reduce the interindividual variability, the data were normalized as follows. The average values of T' for the three experimental conditions of this study were calculated separately for each subject as:

Table 2 Individual values of body drag (D_b, Newtons), energy cost of swimming (C_s, kilojoules per metre per metre squared) and drag efficiency (η_d, percentage) at the two speeds studied and for the three conditions of underwater torque *A*, *W* and *L* air, water and 2-kg lead configuration of torque, respectively

Subjects	(1.00 $m \cdot s^{-1}$)			(1.23 $m \cdot s^{-1}$)		
	C_{sA}	C_{sW}	C_{sL}	C_{sA}	C_{sW}	C_{sL}
DH	0.34	0.42	0.47	0.44	0.44	0.54
RW	0.36	0.37	0.40	0.41	0.44	0.48
JV	0.41	0.40	0.43	0.45	0.55	0.56
DB	0.50	0.54	0.61	0.54	0.58	0.66
KR	0.45	0.49	0.55	0.55	0.56	0.67
PJ	0.37	0.46	0.49	0.48	0.53	0.52
EA	0.43	0.44	0.44	0.56	0.54	0.58
CB	0.40	0.46	0.43	0.32	0.59	0.52
Mean	0.41	0.45	0.48	0.47	0.53	0.57
SD	0.05	0.05	0.07	0.08	0.06	0.07
	D_{bA}	D_{bW}	D_{bL}	D_{bA}	D_{bW}	D_{bL}
DH	42.0	57.8	65.1	50.7	59.1	62.8
RW	61.1	48.5	62.6	51.8	56.6	55.1
JV	39.3	40.4	55.0	34.5	45.5	44.8
DB	45.7	49.6	51.3	50.6	77.9	68.8
KR	55.7	62.0	71.5	57.1	73.8	101.0
PJ	41.6	55.4	78.1	45.8	54.4	63.4
EA	38.2	44.9	49.9	45.7	45.0	53.3
CB	36.3	67.4	55.2	35.2	45.2	45.2
Mean	45.0	53.3	61.1	46.4	57.2	61.8
SD	8.9	9.0	10.1	8.0	12.8	18.0
	η_{dA}	η_{dW}	η_{dL}	η_{dA}	η_{dW}	η_{dL}
DH	6.86	7.36	6.89	5.96	6.99	6.06
RW	8.36	6.45	7.53	5.99	5.95	5.73
JV	4.88	5.07	6.22	3.74	3.92	3.91
DB	4.82	4.88	4.44	4.77	6.75	5.23
KR	7.05	7.28	7.28	5.52	7.21	9.60
PJ	6.10	6.76	9.15	5.19	5.47	6.46
EA	4.63	5.56	5.87	3.99	3.93	4.44
CB	4.52	7.48	6.24	3.27	3.67	4.19
Mean	5.90	6.36	6.70	4.80	5.49	5.70
SD	1.42	1.05	1.38	1.04	1.47	1.82

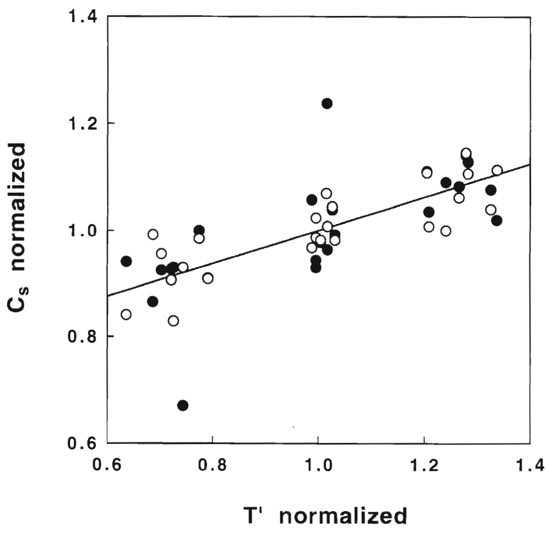

Fig. 2 Normalized values of energy cost of swimming (C_s) as a function of the normalized values of underwater torque (T') at the two speeds studied (*unfilled circles*: 1.00 $m \cdot s^{-1}$; *filled circles*: 1.23 $m \cdot s^{-1}$). The relationship between the two parameters is described by: $C_s = 0.688 + 0.312 \cdot T'$, $n = 48$, $r = 0.730$, $P < 0.001$. See text for details

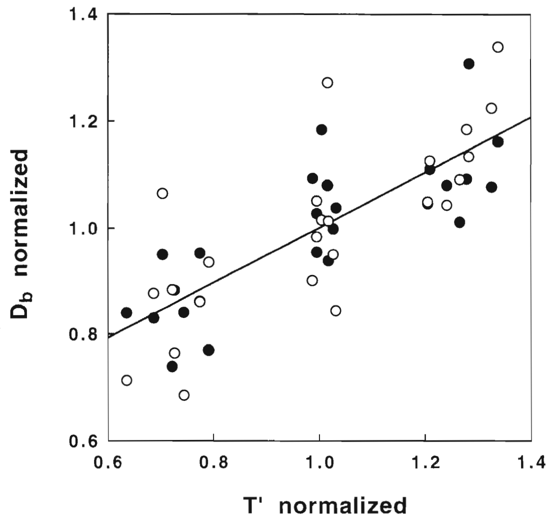

Fig. 3 Normalized values of active body drag (D_b) as a function of the normalized values of underwater torque (T') at the two speeds studied (*unfilled circles*: 1.00 $m \cdot s^{-1}$; *filled circles*: 1.23 $m \cdot s^{-1}$). The relationship between the two parameters is described by: $D_b = 0.481 + 0.519 \cdot T'$, $n = 48$, $r = 0.780$, $P < 0.001$. See text for details.

$\bar{T}'_j = (T'_{Aj} + T'_{Wj} + T'_{Lj})/3$, where T'_{Aj}, T'_{Wj} and T'_{Lj} indicate the three experimental conditions of T' (A = air, W = water, L = 2-kg lead) applying to the jth subject. Each individual T' for a given subject was then divided by the subject's average to obtain a dimensionless normalized index (e. g. $T'_{Aj\,norm} = T'_{Aj}/\bar{T}'_j$). The normalized dimensionless indexes for C_s, D_b and η_d were calculated in a similar manner, with the obvious difference that, for each of these three variables two sets of normalized indexes were obtained, corresponding to the two v investigated

The procedure adopted to normalize the data reduced the range of the intersubject coefficient of variation from 11.1%–32.0% (for the raw data of Table 2) to 3.6%–14.7%.

The MANOVA among the three normalized dependent variables (C_s, D_b and η_d) and the two independent ones (v and T') showed a significant dependency on T' (C_s: $r = 0.739$, $P < 0.00001$; D_b: $r = 0.775$, $P < 0.00001$; η_d: $r = 0.518$, $P < 0.005$) but not with v ($P > 0.998$ throughout). The relationships between the normalized values of C_s, D_b, η_d and the normalized values of T' were therefore calculated combining the data obtained at the two v investigated on all the subjects (see Figs. 2, 3, 4). They are described by the following equations:

$$C_s = 0.688 + 0.312 \cdot T' \; (n = 48,\ r = 0.730,\ P < 0.001) \quad (4)$$

$$D_b = 0.481 + 0.519 \cdot T' \; (n = 48,\ r = 0.780,\ P < 0.001) \quad (5)$$

$$\eta_d = 0.737 + 0.263 \cdot T' \; (n = 48,\ r = 0.518,\ P < 0.001) \quad (6)$$

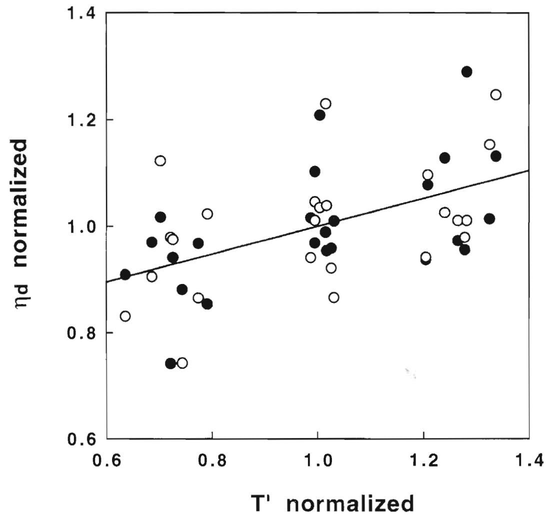

Fig. 4 Normalized values of drag efficiency (η_d) as a function of the normalized values of underwater torque (T') at the two speeds studied (*unfilled circles*: 1.00 $m \cdot s^{-1}$; *filled circles*: 1.23 $m \cdot s^{-1}$). The relationship between the two parameters is described by: $\eta_d = 0.737 + 0.263 \cdot T'$, $n = 48$, $r = 0.518$, $P < 0.001$. See text for details

The Bonferroni post-hoc test applied to the normalized data (at both v), showed that C_s and D_b were significantly different ($P < 0.05$) at all configurations of T'. In contrast, no significant differences were observed for η_d between the largest and intermediate T' values (tube filled with 2 kg of lead or with water) whereas η_d at the smallest T' value (tube filled with air) was significantly smaller than in the two other T' configurations ($P < 0.05$, see Table 3).

Table 3 Bonferroni post-hoc test. Differences between the three configurations of underwater torque [tube filled with air (*A*), water (*W*) or 2-kg lead (*L*)] with regard to the three normalized variables, C_s energy cost of swimming, D_b body drag, η_d drag efficiency. Combined data at both speeds.

		A	W	L
	A	1.0000		
C_s	W	0.0003	1.0000	
	L	0.0000	0.0294	1.0000
	A	1.0000		
D_b	W	0.0001	1.0000	
	L	0.0000	0.0129	1.0000
	A	1.0000		
η_d	W	0.0335	1.0000	
	L	0.0014	0.7764	1.0000

The differences are considered significant for $P < 0.05$.

Discussion

Critique of methods

As described in the Methods, active D_b and η_d were obtained as has been proposed by di Prampero et al. (1974). Since Toussaint et al. (1990) have raised serious criticisms to this approach, it seems necessary to discuss it in some detail.

The total mechanical power the swimmer has to deliver at constant speed ($\dot{W}_{tot}$) is the sum of:

1. The useful power to overcome drag ($\dot{W}_d$) and,
2. The power dissipated to accelerate water backwards, i.e. to impart kinetic energy to a given mass of water ($\dot{W}_k$) (Toussaint et al. 1988b):

$$\dot{W}_{tot} = \dot{W}_k + \dot{W}_d \quad (7)$$

As shown by Eq. 1, when a known force is attached to the swimmer the power used to overcome drag is decreased by an equal amount. In addition however, the kinetic energy term of Eq. 7 is likely to change as a function of the added drag. As a first approximation, $\dot{W}_k$ may be assumed to be proportional to the power used to overcome drag. Therefore, from Eq. 1:

$$\dot{W}_k = [(D_b - D_a) \cdot v] \cdot \mathrm{b} \quad (8)$$

where b is a constant.

Thus, substituting Eqs. 1 and 8 into Eq. 7, and expressing the overall mechanical power in $\dot{V}O_2$

$$\dot{V}O_2 \cdot \eta_o = \dot{W}_{tot} = [(D_b - D_a) \cdot v] + [(D_b - D_a) \cdot v\mathrm{b}] \quad (9)$$

where η_o ($= \dot{W}_{tot}/\dot{V}O_2$) is the overall efficiency of swimming.

It can be seen from Eq. 9 that when D_a equals D_b, $\dot{V}O_2$ becomes zero. Therefore, at any given v, the swimmer's active D_b can be obtained by extrapolating to resting $\dot{V}O_2$ the linear relationship between $\dot{V}O_2$ and D_a experimentally obtained at that v. Indeed re-arranging Eq. 9 and setting $\dot{V}O_2 = 0$, one obtains:

$$D_b \cdot (v + v\mathrm{b}) = D_a \cdot (v + v\mathrm{b}) \quad (10)$$

It must be pointed out that for large values of negative D_a, the relationship between $\dot{V}O_2$ and D_a tends to deviate from a straight line, becoming less steep. This is probably due to the fact that the larger values of $-D_a$ affect the mechanics of swimming. Thus, the above approach can be applied only within a limited range of D_a, as was done in this study (see Methods).

The η_o was defined above as the ratio between $\dot{W}_{tot}$ and total metabolic energy input ($\dot{V}O_2$, Eq. 9). Toussaint et al. (1988b) have defined two additional efficiencies:

1. The propelling efficiency (η_p) as given by the ratio between the power to overcome drag and $\dot{W}_{tot}$; and
2. The η_d as given by the ratio of the power to overcome drag and $\dot{V}O_2$; η_d, in turn, is equal to the product of η_o times η_p:

From Eq. 9

$$\eta_o = \dot{W}_{tot}/\dot{V}O_2$$

and

$$\eta_p = \dot{W}_d/\dot{W}_d + \dot{W}_k = \dot{W}_d/\dot{W}_{tot} \quad (11)$$

$$\eta_o \cdot \eta_p = \eta_d = \dot{W}_d/\dot{V}O_2 \quad (12)$$

Eq. 1 can be substituted into Eq. 12 to obtain:

$$\eta_d = (D_b - D_a) \cdot v/\dot{V}O_2 \quad (13)$$

Finally since for the same subject at the same speed v and D_b are constant (and hence Δv and $\Delta D_b = 0$), from Eq. 13 one can obtain:

$$\Delta\eta_d = -\Delta D_a \cdot v/\Delta\dot{V}O_2 \quad (14)$$

Thus Eq. 14 is identical with Eq. 3 which, as described in the Methods, was used throughout this study to calculate η_d. It shows formally that the reciprocal of the slope of the linear relationship between $\dot{V}O_2$ and D_a (see Fig. 1) times v is indeed a measure of D_a.

As discussed above, for large values of $-D_a$, the relationship between $\dot{V}O_2$ and D_a tends to deviate from a straight line. Thus $\Delta\eta_d$ is equal to η_d only within a limited range of D_a, as used in this study (see Methods).

In conclusion, at any given v the D_a obtained by extrapolating the $\dot{V}O_2$ versus D_a relationship to resting $\dot{V}O_2$ is equal and opposite to the active D_b the swimmer has to overcome at that v. Furthermore, the reciprocal of the slope of the $\dot{V}O_2$ versus D_a relationship times v, is equal to the η_d at that v.

We think therefore that, notwithstanding the opinion of Toussaint et al. (1990), the approach which has been proposed by di Prampero et al. in 1974 is basically correct and equally are the data for D_b and η_d reported in this study. It is only fair to point out here that the above is strictly true if, and only if, the kinetic energy term is proportional to the mechanical power needed to overcome drag (Eq. 8). This seems a reasonable assumption; it needs, however, experimental support.

Energy cost of swimming

The values of C_s determined in this study were similar to those which have been reported for elite male swimmers by Chatard et al. (1990) which amounted to 0.43 and 0.48 $kJ \cdot m^{-1}$ per m^2 A_D at 1.1 and 1.2 $m \cdot s^{-1}$, respectively, and by Holmér (1974) which amounted to 0.41 and 0.52 $kJ \cdot m^{-1}$ per m^2 A_D at 1.0 and 1.2 $m \cdot s^{-1}$, respectively.

The relationship between T' and C_s has been reported and discussed in detail in a recent paper by Capelli et al. (1995) to which the reader is referred for further details.

Drag efficiency

The values of η_d reported in this study (in the natural configuration: tube filled with water) are close to those that have been reported by others (Pendergast et al. 1977) in elite male swimmers at comparable v (5.0%–7.4% from 0.8 to 1.2 $m \cdot s^{-1}$) and obtained following the same experimental procedure. They are also comparable with the values that can be obtained (by means of Eq. 12) from data of Toussaint (1990) on the basis of their values of overall (η_o, 8.1%) and propelling (η_p, 62.5%) efficiency: 5.1% at an average v of 1.2 $m \cdot s^{-1}$ in elite male swimmers.

As shown in Table 2 and Fig. 3 the values of η_d obtained in this study are lower at the higher v. This can tentatively be explained (according to Eq. 12) with differences in η_p at the two v. This last has indeed been shown to decrease with v (Toussaint et al. 1988c) from about 65% at 1.00 $m \cdot s^{-1}$ to about 55% at 1.3 $m \cdot s^{-1}$.

Active body drag

The values reported in this study for D_b (see Table 2) in the natural configuration (tube filled with water) are similar to those reported by Pendergast et al. (1977) in elite male swimmers at comparable v (53.9–80.4 N from 0.8–1.2 $m \cdot s^{-1}$) and obtained following the same experimental procedure.

These are larger than those which have been reported by Toussaint (1990) on competitive swimmers: 52.7 (SD 9.4) W at an average v of 1.2 $m \cdot s^{-1}$. This difference may be due to the fact that the method employed by Toussaint and co-workers has required the subjects to swim with the arms only, a fact that may have affected the biomechanics of swimming in a manner difficult to predict. Moreover, since in their studies the subject's legs were supported by a "small buoy", the low values of active D_b they have reported are likely due to an alteration in the subject's natural T'. Since this last is a measure of the sinking force at the feet and, as shown in Fig. 3, is linearly related to the subject's active D_b, a buoyant force applied at the feet obviously leads to a decrease of T' and hence of the active D_b.

As has been pointed out by Pendergast et al. (1977), female swimmers are characterized by lower values of T' and D_b in comparison with male swimmers matched for technical skill and speed. Since D_b increases with T' (see Fig. 2), the different values of active and passive D_b reported for men and women by several authors using different methods (Clarys 1979; Pendergast et al. 1977; Toussaint et al. 1988a) at comparable v, may be at least in part attributed to their different T'.

General discussion and conclusions

The primary effect of an experimental increase of T', as in the present study, is to increase the tendency of the body to assume a vertical position in water. This can lead to either one of the following two possibilities, or to a combination thereof:

1. The tendency of the feet to sink can be actively counteracted by the swimmer increasing the frequency or strength of the leg kick;
2. Alternatively, if not actively counteracted, this tendency may lead to a substantial increase of the swimmer's D_b.

In both cases, and obviously enough, in any combination thereof, C_s is bound to increase.

Indeed, C_s was found to increase with T' (see Fig. 2): e.g. its average value (at both v) increased by 20% for an average increase of T' of 73%, as observed between the two extreme conditions of this study (tube filled with 2 kg of lead versus tube filled with air, see Tables 1, 2).

The experimental modification of T' in a given subject is associated also with a statistically significant increase of the active D_b: e.g. 35% on the average between the two extreme conditions of T' (see Table 2, Fig. 3). It must be pointed out that, even if the tube itself (as well as the pulley system) can influence D_b (and hence $\dot{V}O_2$ and η_d), the results of the investigation were compared only among the three conditions of modified T' throughout.

The increase of D_b was substantially larger (about twice on average) than that of the observed increase of C_s; it was offset by an increase of η_d: e.g. η_d increased by 16% on the average between the two extreme conditions of T' (see Table 2, Fig. 4).

Thus, the actual strategy employed by the swimmers to counteract T' was to tolerate a large increase of D_b. This led also to a smaller increase of η_d the effect of which was to reduce the increase of C_s that would, otherwise have occurred.

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