Bioenergetics and biomechanics of front crawl swimming

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Capelli, C., P. Zamparo, A. Cigalotto, M. P. Francescato, R. G. Soule, B. Termin, D. R. Pendergast, and P. E. di Prampero. Bioenergetics and biomechanics of front crawl swimming. *J. Appl. Physiol.* 78(2): 674–679, 1995.— "Underwater torque" (T′) is one of the main factors determining the energy cost of front crawl swimming per unit distance (C_s). In turn, 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 center of volume of the lungs. The dependency of C_s on T′ was further investigated by determining C_s in a group of 10 recreational swimmers (*G1*: 4 women and 6 men) and in a group of 8 male elite swimmers (*G2*) after T′ was experimentally modified. This was achieved by securing around the swimmers' waist a plastic tube filled, on different occasions, with air, water, or 1 or 2 kg of lead. Thus, T′ was either decreased, unchanged, or increased compared with the natural condition (tube filled with water). C_s was determined, for each T′ configuration, at 0.7 m/s for *G1* and at 1.0 and 1.2 m/s for *G2*. For T′ equal to the natural value, C_s (in $kJ \cdot m^{-1} \cdot m$ body surface area^{-2}) was 0.36 ± 0.09 and 0.53 ± 0.13 for *G1* in women and men, respectively, and 0.45 ± 0.05 and 0.53 ± 0.06 for *G2* at 1.0 and 1.2 m/s, respectively. In a given subject at a given speed, C_s and T′ were linearly correlated. To compare different subjects and different speeds, the single values of C_s and T′ were normalized by dividing them by the corresponding individual averages. These were calculated from all single values (of C_s or T′) obtained from that subject at that speed. The normalized C_s was found to be a linear function of the normalized T′ ($r = 0.84, P < 0.001; n = 86$) regardless of sex, speed, or swimming skill. We concluded that, in the speed range of 0.7–1.23 m/s, T′ is indeed the main determinant of C_s regardless of sex or swimming skill.

energy cost of swimming; exercise; underwater torque; buoyancy; oxygen consumption; body density

MAXIMAL SWIMMING performances depend on the maximal metabolic power of the swimmer and his or her swimming economy. Hence the importance of assessing the factors that determine the economy of swimming. The anthropometric characteristics that determine the economy of swimming the front crawl, as measured by the amount of energy spent per unit of distance (C_s), have been investigated by Chatard et al. (3, 4), who have shown that C_s is related to the underwater weight (UW). Pendergast et al. (13, 14) had previously shown that, in swimmers of comparable skill, C_s is linearly related to the "underwater torque" (T′) at speeds between 0.4 and 1.2 m/s. In turn, T′ was defined as the product of the force with which the feet tend to sink times the distance from the center of volume of the lungs (CL), located approximately at the horizontal mamillary line, to the feet (13, 14).

The aim of this study was to investigate further the dependency of C_s on T′. This was achieved by determining C_s while the subjects swam the front crawl at submaximal speeds (0.58–1.23 m/s) in two groups of recreational (*G1*) or elite (*G2*) swimmers in whom T′ had been experimentally modified. T′ is a function of the "true torque" (T) and UW (see *Eq. 2*). In this study, the experimental changes in T′ affected only the swimmer's UW, whereas T remained unchanged. Therefore, a multiple regression analysis between C_s and the two quantities that set T′ (UW and T) allowed us to also quantify the separate roles of UW and T in determining C_s.

PROCEDURES AND METHODS

The experiments were performed on two groups of subjects whose main anthropometric characteristics are reported in Table 1. *G1* included 10 recreational swimmers (6 men and 4 women) who swam at a competitive level and therefore could be considered of good technical level. *G2* consisted of eight elite college male swimmers [maximal O_2 consumption ($\dot{V}O_{2\,max}$) 3.9–5.9 l/min] who were members of the team of the State University of New York at Buffalo and who where swimming in the National (US) Collegiate Athletic Association's Men's Division I competitions. All the subjects were informed about the methods and aims of the study and gave their informed consent.

In both groups T′ was modified as follows. A flexible tube (4 cm OD, 150 cm long) was secured around the waist of the subjects and filled on different occasions with 1 or 2 kg of lead (2 kg only in *G2*), water, or air. In each subject, the tube was positioned at the center of mass (CM), which was assumed to be located at a level of 56.16% of the subject's height from the heels in men and 55.67% in women (9).

Biomechanics

T′ was defined by Pendergast et al. (14) as the product of the force with which the feet tend to sink (F) times xf (distance between CL and the feet). Therefore, as shown in Fig. 1*B*, T′ is a measure of the net effect of the buoyancy (B) and of the weight (W), each multiplied by the appropriate lever arm

$$T' = W \cdot xw - B \cdot xb \qquad (1)$$

where xw is the distance from CL to CM and xb is the distance from CL to the center of buoyancy. T′ can also be expressed as

$$T' = UW \cdot xw + T \qquad (2)$$

In turn, T is given by

$$T = B \cdot wb \qquad (3)$$

where wb is the distance between CM and the center of volume (Fig. 1*A*).

The equality of *Eqs. 1* and *2* can be proven by replacing

TABLE 1. *Anthropometric characteristics of G1 and G2 subjects*

	Men (n = 6)	Women (n = 4)
	G1	
Age, yr	22.7±6.24	22.7±6.05
Height, m	1.80±0.06	1.67±0.02
Weight, kg	77.0±4.43	61.0±5.44
BSA, m²	1.99±0.06	1.67±0.02
BD, g/cm³	1.075±0.005	1.055±0.012
Fat, %	9.79±2.06	19.58±5.42
	G2	
Age, yr	21.1±1.36	
Height, m	1.86±0.06	
Weight, kg	83.2±6.79	
BSA, m²	2.08±0.11	
BD, g/cm³	1.068±0.012	
Fat, %	13.28±5.18	
t_{50},* s	21.92±0.25	
t_{200},* s	106.83±4.17	

Values are means ± SD; n, no. of subjects. For group of elite swimmers (*G2*), n = 8 men except *n = 4 men. BSA, body surface area; BD, air-free body density; t_{50} and t_{200}, best performance time over 50 and 200 yd, respectively.

UW with the difference between weight and buoyancy (UW = W − B). *Equation 2* can then be rewritten as

$$T' = W \cdot xw - B \cdot xw + T \qquad (4)$$

or, because $T = B \cdot wb$ (*Eq. 3*)

$$T' = W \cdot xw - B \cdot xw + B \cdot wb$$
$$T' = W \cdot xw - B(xw - wb) \qquad (5)$$

Figure 1B shows that $xw - wb = xb$, thus demonstrating that *Eqs. 1, 2,* and *5* are equal. However, because the two most important quantities affecting the biomechanics of swimming, UW and T, appear explicitly in *Eq. 2*, this last appears to be the most useful for practical purposes.

In both groups, T′ was measured by means of an underwater balance positioned on the bottom of an 80-cm-deep swimming pool. The subject laid in the prone position, fixed by means of quick-release belts, and breathed through a snorkel on a webbed aluminium frame positioned 50 cm underwater. The frame and the subject were free to rotate on 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 rotation. The fulcrum was positioned at 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. T′ was calculated as the product of the force exerted on the load cell (F, corrected for the weight of the frame in each experimental measure) times the distance from the cell to the fulcrum (*xf*; Fig. 1B). In *G1*, T′ was assessed in four conditions: tube filled with water, tube filled with 1 kg of lead, tube filled with 2 kg of lead, and tube filled with 1.9 liters of air. In *G2*, T′ was measured in three conditions: tube filled with water, tube filled with 2 kg of lead, and tube filled with 1.9 liters of air. Finally, T′ was normalized by the body surface area (BSA, in m²) to yield T′ in newtons per meter per meter squared of BSA.

For *G2*, a separate series of measurements made it possible to calculate the two quantities the sum of which yields T′ (*Eq. 2*) as follows. After T′ was determined, the fulcrum was

positioned at CM so that xw became zero. Hence, $F \cdot xf$ was equal to $B \cdot wb$ (= T; see Fig. 1A and *Eq. 3*). In this same group, UW was also directly determined by means of a second load cell (type F1, AEP transducers, I) that supported the fulcrum so that the sum of the net forces at the feet end of the frame (F) and at the fulcrum yielded UW (Fig. 1B). T and UW were measured at full expiration and inspiration, and the average value (normalized for BSA) was used in all subsequent analysis. Finally, the distance between the fulcrum and CM (the position of which was calculated as described above) was labeled xw.

Bioenergetics

C_s was determined measuring O_2 consumption ($\dot{V}O_2$) at constant and submaximal speeds. In each subject, the measurements of $\dot{V}O_2$ were repeated for all experimental configurations of T′ (tube filled with water, air, or 1 or 2 kg of lead) as described below for *G1* and *G2*.

G1. $\dot{V}O_2$ was determined by standard open-circuit method in each subject for all experimental configurations of T′ (tube filled with water, air, or 1 or 2 kg of lead). For all subjects the selected speed (0.58–0.82 m/s) corresponded to an energy requirement less than or equal to estimated $\dot{V}O_{2\,max}$. After 4 min of constant speed swimming by the subject (in a 50-m
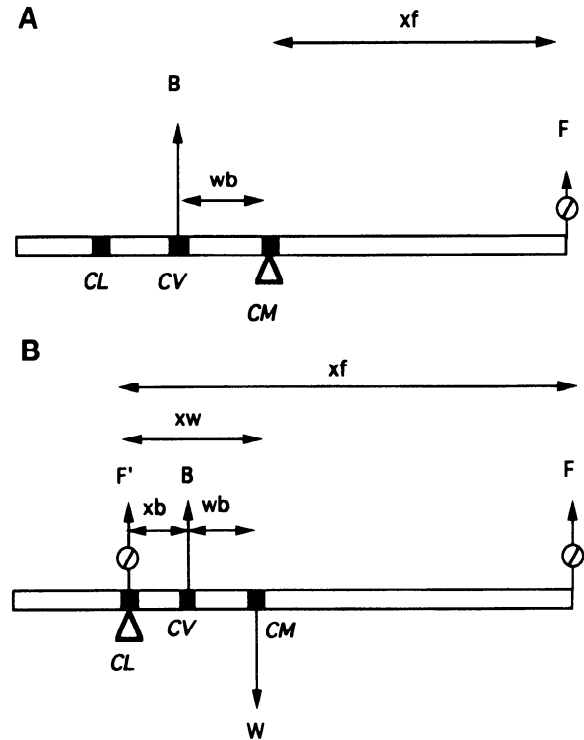

FIG. 1. Scheme of measuring system. △, Fulcrum; ⊘, load cell; CV, center of volume; CL, center of volume of lungs; CM, center of mass. *A*: assessement of true torque (T). Subject rests with center of mass over fulcrum. Buoyancy (B) times wb [distance from its application point (CV) to fulcrum] yields true T (*Eq. 3*). T is equal to product of net force read on load cell (F) and xf (distance from load cell to fulcrum). *B*: assessment of underwater torque (T′). Subject rests with CL over fulcrum. Product of B and xb [distance from its application point (CV) to fulcrum] is subtracted from body weight (W) times xw [distance from its application point (CM) to fulcrum] to yield T′ (*Eq. 1*). In turn, T′ is equal to net force applied to load cell (F) times xf (distance from load cell to fulcrum). Underwater weight (UW) was calculated as sum of net forces (F) and (F′) after 2nd load cell (F′) was positioned in series with a cable supporting the fulcrum.
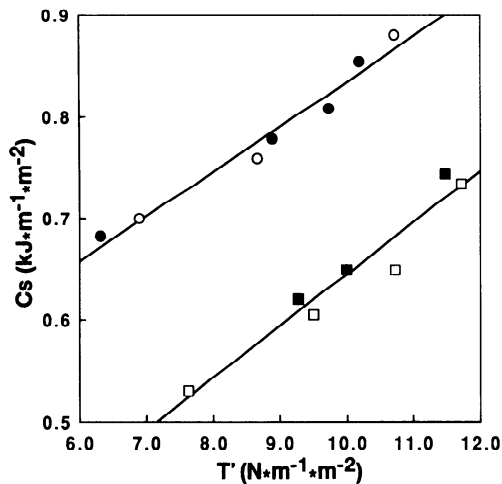
FIG. 2. Cost of swimming [C_s, in $kJ \cdot m^{-1} \cdot m^{-2}$ body surface area (BSA)] as function of experimentally changed T' ($N \cdot m^{-1} \cdot m^{-2}$ BSA) in 2 recreational swimmers [*CM* (circles) and *VM* (squares)]. Data were obtained in 2 different experimental sessions (filled or open symbols). Lines, data obtained by pooling all data for same subject [described for *CM* by $C_s = 0.044T' + 0.393$ ($r^2 = 0.971$; $n = 7$) and for *VM* by $C_s = 0.051T' + 0.135$ ($r^2 = 0.938$; $n = 7$)].

indoor pool), the expired gases were collected (for ~60 s) through a waterproof two-way respiratory valve (17) and an expiratory hose (4 cm ID, 3.5 m long) into a Douglas bag, which was carried by an operator walking along the deck of the pool. Expired air was analyzed for gas composition by using a paramagnetic O_2 analyzer (Oxinos 1-C, Leybold-Heraeus, Hanau, Germany) and an infrared CO_2 meter (BINOS 1, Leybold-Heraeus) that were calibrated before each series of experiments with gases of known composition. The volume of the expired gases was assessed by means of a dry gas meter (SIM Brunt, Milan, Italy).

The speed was maintained constant throughout the test by having the swimmer follow a submerged colored marker in the pool. The marker was pulled 1.5 m in front of the swimmer by an operator walking at constant speed along the border of the pool. The walking speed of the operator was kept constant by an acoustic pacer (Balise Temporelle, Baumann, Zurich, Switzerland) so that at each signal the operator passed in front of equally spaced (5 m) visual marks. The actual average speed (in m/s) was always calculated from total distance (250–350 m) and time. At the 4th min after the end of the swimming test, capillary blood was sampled from the ear lobe and the lactate concentration ([La$^-$]$_b$) was determined by a polarimethric method (Microzym-L, SGI, Toulouse, France).

C_s was calculated as follows. $\dot{V}O_2$, expressed in liters of O_2 (STPD) per minute, was converted to kilowatts, assuming that 1 liter of O_2 consumed by the human body yields 20.9 kJ (which is strictly true for a respiratory quotient of 0.98). The obtained value was then divided by the speed (in m/s) to yield C_s in kilojoules per meter. [La$^-$]$_b$ at the end of the test was >2.0 mM in four subjects: *CM* at all investigated T', *VM* at the two highest T', and *VV* and *SG* at the highest T' only. In these subjects the contribution of the anaerobic sources to C_s was taken into account as follows. The blood lactate concentration at rest was subtracted from the value of [La$^-$]$_b$ attained at the 4th min after the test (1). The energetic equivalent of the change in [La$^-$]$_b$ was then calculated assuming that the increase of 1 mM lactate/l blood releases an amount of energy equal to 60 J/kg (~3 ml O_2/kg; Refs. 5, 6). Finally, the overall C_s was determined by dividing the energetic value of the change in [La$^-$]$_b$ by the overall distance covered and

adding it to the aerobic energy cost obtained as described above. The anaerobic contribution derived from lactic sources was 8–15.9% of C_s for *CM*, 5.7 and 8.3% for *VM*, 6.7% for *SG*, and 11.4% for *VV*. C_s was finally normalized by dividing it by BSA to yield C_s in kilojoules per meter per meter squared of BSA.

G2. Also in this group, $\dot{V}O_2$ was measured by standard open-circuit method. In each subject, $\dot{V}O_2$ was determined at two constant speeds (1.00 and 1.23 m/s) for all experimental configurations of T' (tube filled with water, air, or 2 kg of lead). For all subjects the two selected speeds corresponded to an energy requirement <85% of the previously determined $\dot{V}O_{2\,max}$. The subjects swam in an annular pool 2.5 m wide, 2.5 m deep, and 60 m circumference over the swimmer's course and were paced by a platform moving at constant water velocity above the water surface (7). The water velocity was measured by means of an impeller (PT-301 hand-held probe, MEAD, Riverdale, NY), connected to a tachometer (F1-12 P portable indicator, MEAD), immersed in the water 1.5 m in front of the swimmer and moving with the platform. Three to 4 min after the onset of swimming, the expired gases were collected through a waterproof inspiratory-expiratory valve into an aerostatic balloon (time of collection 60 s). The O_2 and CO_2 fractions in the expired air were determined by means of a previously calibrated paramagnetic O_2 analyzer (Beckman C2, Palo Alto, CA) and an infrared CO_2 meter (Beckman LB-1); the gas volume was determined by means of a dry gas meter (American Meter). C_s in kilojoules per meter per meter squared of BSA was then calculated as described above for *G1*.

Anthropometry

For *G1*, body density (in g/cm^3) was obtained from skinfold thickness and/or body circumferences according to the method of Jackson et al. (11) and percent fat was calculated according to the technique of Siri (15). For *G2*, body density and percent fat were obtained according to the method of Sloan and Weir (16).

BSA (in m^2) was calculated in accordance with the equation published by Du Bois and Dubois (8).

RESULTS

The values of C_s determined in *G1* at speeds between 0.6 and 0.8 m/s amounted to 0.36 ± 0.09 and 0.53 ± 0.13

TABLE 2. *Intercept, slope, and r^2 of individual linear regressions between C_s and T'' in G1 subjects*

Subj	Sex	Intercept	Slope	r^2	n	Speed, m/s
BD	M	0.286	0.017	0.864	4	0.82
KS	M	0.248	0.031	0.995	4	0.81
SG	M	0.314	0.046	0.862	3	0.59
CA	M	0.294	0.016	0.970	4	0.68
CM	M	0.417	0.041	0.972	4	0.70
VM	M	0.158	0.048	0.963	4	0.70
CS	F	0.217	0.039	0.984	4	0.60
PA	F	0.246	0.016	0.913	4	0.58
ML	F	0.256	0.023	0.970	4	0.70
VV	F	0.346	0.026	0.940	4	0.60

C_s, energy cost of swimming (in $kJ \cdot m^{-1} \cdot m^{-2}$ BSA); T', underwater torque (in $N \cdot m \cdot m^{-2}$ BSA) as defined by Pendergast et al. (13, 14); n, no. of observations. *CM* and *VM* repeated the experiments on 2 separate sessions (see Fig. 2). Data reported in this table refer to 1 session only and correspond to filled circles for *CM* and open squares for *VM* in Fig. 2.
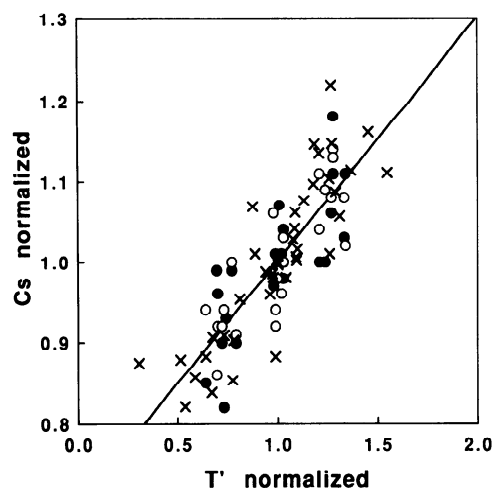
FIG. 3. Normalized values of C_s as function of normalized values of T' in all subjects [recreational swimmers at 0.58–0.82 m/s (×), elite swimmers at 1.00 m/s (●), and elite swimmers at 1.23 m/s (○)]. Data are interpolated by linear equation $C_s = 0.699 + 0.302T'$ ($r^2 = 0.706$; $n = 86$).

kJ·m^{-1}·m^{-2} BSA in women and men for the "natural torque" condition (i.e., tube filled with water). These results are similar to those reported by Pendergast et al. (14) in unskilled subjects swimming at 0.7 m/s (0.44 and 0.53 kJ·m^{-1}·m^{-2} BSA in women and men, respectively).

The relationship between C_s and T' is shown for two representative subjects of G1 swimming at 0.7 m/s in Fig. 2. Both sets of data can be appropriately interpolated by linear regressions and show that the measurements are fairly consistent, since the points obtained in separate experimental sessions fall essentially on the same line. Indeed, the linear regression of C_s of day 1 vs. C_s of day 2 (for the same values of T') was very close to the identity line ($y = 0.071 + 0.903x$, $r^2 = 0.970$; $n = 6$).

A linear dependency of C_s on T' was observed for all subjects in G1. The corresponding statistics are reported in Table 2, which summarizes the individual values of intercept, slope, r^2, and the number of observations.

The values of C_s determined for G2 at 1.00 and 1.23 m/s were 0.45 ± 0.05 and 0.53 ± 0.06 kJ·m^{-1}·m^{-2} BSA, respectively, in the natural torque condition. These values are similar to those reported for elite male swimmers by Chatard et al. (3), which amounted to 0.43 and 0.48 kJ·m^{-1}·m^{-2} BSA at 1.1 and 1.2 m/s, respectively, and by Holmér (10), which amounted to 0.41 and 0.52 kJ·m^{-1}·m^{-2} BSA at 1.0 and 1.2 m/s, respectively.

The subjects in G2 were of similar swimming skill. Therefore, the data obtained on all eight subjects at a given speed were pooled. The average relationship between C_s and T' was then calculated from the pooled data; they are described by

$$C_s = 0.298 + 0.017T' \qquad (6)$$

at a swimming velocity of 1.00 m/s ($r = 0.608$, $P < 0.01$; $n = 24$) and by

$$C_s = 0.352 + 0.020T' \qquad (7)$$

TABLE 3. Mean values of T', UW, and T in G2 subjects after T' was experimentally changed

Condition	T', N·m	UW, N	T, N·m
Air	12.80±2.70	−3.65±6.32	14.20±2.18
Water	17.76±3.01	12.49±6.76	13.54±2.22
2 kg of lead	22.19±2.98	25.69±7.07	12.60±2.24

Values are means ± SD; $n = 8$ men. UW, underwater weight (average of full inspiration and expiration); T, true torque (average of full inspiration and expiration).

at a swimming velocity of 1.23 m/s ($r = 0.573$, $P < 0.01$; $n = 24$). These regressions show that in G2 also the relationship between C_s and T' can be appropriately described by straight lines.

The above results and discussion show that T' is indeed one of the main determinants of C_s. To evaluate further its role regardless of speed, swimming skill, or sex, the data obtained on all subjects of both groups were combined as described below. Each value of C_s, obtained from a given subject at a given speed, was divided by the individual average of C_s determined from the same subject at that speed. Similarly, each value of T' was divided by the corresponding average. The normalized (dimensionless) data for C_s and T' are plotted in Fig. 3, which shows that all data fall essentially on the same regression ($C_s = 0.699 + 0.302T'$; $r = 0.841$; $n = 86$).

Thus, ~70% of the overall variability of C_s among subjects of both sexes, swimming at speeds from 0.7 to 1.23 m/s, and widely different in terms of swimming skill is due to the variability of T'.

These data confirm and extend the previous observations by Pendergast et al. (13, 14), who showed that in groups of subjects of comparable swimming skill the variability of C_s was mainly due to the natural T'. These data also show that in a given subject an experimental change in T' is accompanied by a linear change in C_s. It is also interesting that the better (G2) swimmers were able to overcome an equal variation in T' with a lesser increase in C_s, as shown by the smaller slopes of the equations applying to G2 (Table 2, Eqs. 6 and 7).

As shown in Biomechanics, T' is the sum of T and the product of UW and xw (the distance between CM and CL; Fig. 1B). The average values of UW, T (mean of the measurements obtained in full inspiration and expiration), and T' for the eight G2 subjects in all experimental conditions are reported in Table 3. Because the G2 subjects were of similar swimming skill, the data summarized in Table 3 make it possible to assess the relative role of the two components of T' (UW and T) in determining C_s. The analysis was performed by computing a multiple linear regression between C_s at 1.00 and 1.23 m/s (dependent variable) and T and UW (independent variables)

$$C_s = 0.331 + 0.012T + 0.0062UW \qquad (8)$$

at a swimming velocity of 1.00 m/s ($r = 0.621$; $n = 24$) and

$$C_s = 0.403 + 0.012T + 0.0075UW \qquad (9)$$

TABLE 4. *Partial correlation coefficients of multiple regression analysis between* C_s, *T, and UW in G1 and G2 subjects*

Swimming Velocity, m/s	Variable	C_s	UW	T
G1				
0.6-0.8	C_s	1.000		
	UW	0.335	1.000	
	T	0.679	0.076	1.000
G2				
1.00	C_s	1.000		
	UW	0.596	1.000	
	T	0.006	−0.274	1.000
1.23	C_s	1.000		
	UW	0.599	1.000	
	T	−0.031	−0.274	1.000

at a swimming velocity of 1.23 m/s ($r = 0.615$; $n = 24$). The product-moment correlation coefficient of Pearson shows that C_s at both speeds is correlated with UW ($t = 3.634$, $P < 0.005$ and $t = 3.571$, $P < 0.005$, respectively) but not with T (Table 4). In the above analysis we preferred to use UW alone rather than the product $UW \cdot xw$, (where xw is the distance between CM of the subject and the fulcrum of the underwater balance; see PROCEDURES AND METHODS and Fig. 1B). Indeed, $UW \cdot xw$ is relevant only in our measuring conditions wherein the subject is fixed onto a rigid supporting frame. In the absence of external supporting structures, as is the case in swimming, the subject would sink or raise after a vertical translation governed only by his or her UW. Hence the decision to use UW in the regression analysis. In any case, the use of $UW \cdot xw$ in the above equation leads to identical results.

In *G1*, only T' was measured in all conditions. Hence, to make the above multiple regression analysis possible, the two relevant variables (UW and T) were computed as follows. The volume of the subject's body was calculated from the ratio of the body weight to the body density. The total lung capacity or the residual volume of the subjects was calculated according to Cotes [as reported by Brambilla and Pizzamiglio (2)] and was then added to the body volume to obtain the overall volume of the water displaced by the immersed subject in full inspiration or complete expiration, respectively. This overall volume was then subtracted from the body mass, and the resulting difference was multiplied by the acceleration of gravity (9.81 m/s²) to obtain UW in newtons.

Once the individual UW values were obtained, they were multiplied by xw [the measured distance between the fulcrum and the calculated CM of the subject, which was assumed to be located at a level of 56.1% of the subject's height from the heels in men and 55.67% in women (9)]. $UW \cdot xw$ was finally subtracted from the measured T' (assessed in the natural condition, i.e., with the tube filled with water) to yield the corresponding calculated values of T (*Eq. 2*). Because T was found to be practically unaffected by the modifications of T' in *G2* subjects (Table 3), the calculated T in *G1* subjects was considered constant as well, and its value was used in the regression analysis.

When T' was experimentally changed by loading or

unloading the subjects (see PROCEDURES AND METHODS), the individual values of T, obtained as described above, were subtracted from the measured values of T'. The resulting $UW \cdot xw$ values (*Eq. 2*) were finally divided by xw to yield UW corresponding to the loaded (or unloaded) conditions.

To validate this procedure, we performed the same set of calculations in the *G2* subjects, in whom all three variables (T', T, and UW) were separately and independently measured. The values of UW obtained from the difference between the measured T' and the calculated T (see above) were not significantly different from those measured directly (Student's *t*-test for paired data; $P < 0.2$; $n = 24$). This finding is illustrated in Fig. 4, which shows that the calculated and measured values are close to the identity line.

This finding encouraged us to use the calculated values of UW and T in the multiple linear regression applied to the *G1* subjects. This regression turned out to be

$$C_s = 0.1268 + 0.037T + 0.0078UW \qquad (10)$$

at a swimming velocity of 0.6–0.8 m/s ($r = 0.763$; $n = 39$). The product-moment correlation coefficient of Pearson shows that C_s is significantly correlated with both UW and T ($t = 2.523$, $P < 0.05$ and $t = 5.815$, $P < 0.001$, respectively; Table 4).

DISCUSSION

This study confirms and extends the previous data by Pendergast et al. (13, 14), who showed that, for swimmers of comparable skill, C_s is linearly related to the natural T'. In addition, the present data show that, also in a given subject, modifying experimentally the individual T' induces proportional changes in C_s. Furthermore, the increase in C_s due to a given experimental increase in T' was shown to be less in the elite (compared with the good) swimmers.
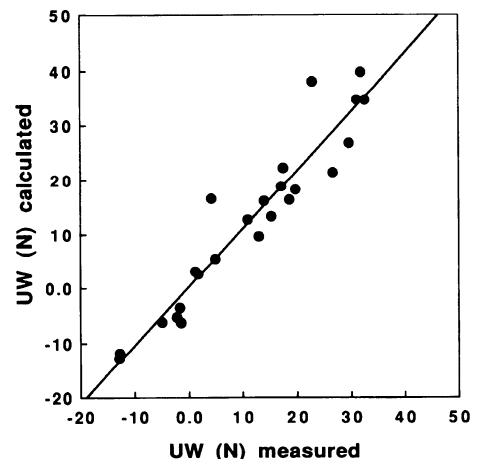
As shown by *Eq. 2*, T' is a function of UW and T of

FIG. 4. Values of UW calculated for elite swimmers vs. measured values. Relationship between these 2 parameters is described by linear regression [calculated UW = 0.347 + 1.074 measured UW ($r^2 = 0.904$; $n = 24$)] that is very close to identity line. See text for details.

the swimmer. The roles of these two components of T′ in determining C_s were evaluated separately, and it was shown that in the group of "good" swimmers at 0.7 m/s (G1), C_s was significantly correlated with both UW and T, whereas in "elite" swimmers at 1.0 and 1.2 m/s (G2), C_s was significantly correlated only with UW. This difference between G1 and G2 can be tentatively explained as follows.

It has been shown that at low speed (0.4–0.7 m/s) the majority of the energy expenditure is devoted to maintaining the horizontal position in water (12). At higher speed (>1.0 m/s) the fraction of the energy expenditure necessary to overcome the water resistance exceeds the amount used to keep the gliding body horizontal in water. Our results support this observation, since C_s is correlated to T, which quantitatively describes the rotational tendency of the immersed body, only at low speeds, i.e., in G1 subjects. Even though the effects of different swimming skill cannot be ruled out, this finding suggests that the different correlation between C_s and T in G1 and G2 may be due to the differences in the speed between the two groups and hence to the different fractions of metabolic energy spent to overcome drag or rotation.

Regardless of the precise settlement of the above question, T′ as defined by Pendergast et al. (13, 14) is a function of both UW and T, i.e., of both factors that can, and do, affect C_s, albeit differently at different speeds. As such, T′ can be expected to be a better predictor of C_s than either UW or T alone, as experimentally found.

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