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How fins affect the economy and efficiency of human swimming

P. Zamparo[1,2,]*, D. R. Pendergast[3], B. Termin[3] and A. E. Minetti[2]

[1]*Dipartimento di Scienze e Tecnologie Biomediche, Universita' degli Studi di Udine, Italy,* [2]*Centre for Biophysical and Clinical Research into Human Movement, Manchester Metropolitan University, Alsager, United Kingdom* and [3]*Centre of Research and Education in Special Environments, State University of New York at Buffalo, USA*

*Author for correspondence at present address: Centre for Biophysical and Clinical Research into Human Movement, Manchester Metropolitan University, Hassall Road, Alsager, ST7 2HL, UK (e-mail: P.Zamparo@mmu.ac.uk – PZamparo@makek.dstb.uniud.it)

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Summary

The aim of the present study was to quantify the improvements in the economy and efficiency of surface swimming brought about by the use of fins over a range of speeds (v) that could be sustained aerobically. At comparable speeds, the energy cost (C) when swimming with fins was about 40 % lower than when swimming without them; when compared at the same metabolic power, the decrease in C allowed an increase in v of about 0.2 m s^{-1}. Fins only slightly decrease the amplitude of the kick (by about 10 %) but cause a large reduction (about 40 %) in the kick frequency. The decrease in kick frequency leads to a parallel decrease of the internal work rate ($\dot{W}_{int}$, about 75 % at comparable speeds) and of the power wasted to impart kinetic energy to the water ($\dot{W}_k$, about 40 %). These two components of total power expenditure were calculated from video analysis ($\dot{W}_{int}$) and from measurements of Froude efficiency ($\dot{W}_k$). Froude efficiency (η_F) was calculated by computing the speed of the bending waves moving along the body in a caudal direction (as proposed for the undulating movements of slender fish); η_F was found to be 0.70 when swimming with fins and 0.61 when swimming without them. No difference in the power to overcome frictional forces ($\dot{W}_d$) was observed between the two conditions at comparable speeds. Mechanical efficiency [$\dot{W}_{tot}/(Cv)$, where $\dot{W}_{tot}=\dot{W}_k+\dot{W}_{int}+\dot{W}_d$] was found to be about 10 % larger when swimming with fins, i.e. 0.13±0.02 with and 0.11±0.02 without fins (average for all subjects at comparable speeds).

Key words: energetics, biomechanics, swimming, fin, human, energy balance.

Introduction

Passive locomotory tools for land locomotion have been shown to improve the economy and the speed of progression for any given metabolic power. Like bicycles (e.g. Minetti et al., 2001), roller-skates and skies for terrestrial locomotion, fins can be defined as passive tools for aquatic locomotion, as well as rafts, racing shells or hydrofoils. As pointed out by Abbott et al. (1995), four basic forces act on a boat (or a body) in water: lift, weight, drag and thrust. Human powered watercrafts are designed to decrease weight (e.g. buoyancy devices) and drag (e.g. streamlined shells, reduction of speed oscillations) and to increase lift (e.g. hydrofoils) and thrust (e.g. paddles, oars, propellers). Fins are meant to improve the fraction of the force (thrust) that is useful to propel the body forwards. In other words, they are meant to improve the propelling efficiency of aquatic locomotion.

Data on fin swimming are scarce and refer mainly to underwater (SCUBA diving) experiments that focus on the differences in economy of swimming at different depths (e.g. Morrison, 1973) or with different swim-fin designs (e.g. Pendergast et al., 1996). An analysis of the mechanical determinants of the improved economy brought about by the use of fins (in comparison to swimming without them) has never been attempted because quantification of the mechanical work performed during aquatic locomotion is not simple.

In the present study the energy cost, mechanical work and efficiency of swimming using the leg kick were measured/estimated with methodologies previously applied to human and fish locomotion. Using these data, we attempted to calculate a complete energy balance for swimming. The differences in economy and efficiency brought about by the use of fins allowed us to further investigate the relative importance of the mechanical determinants of aquatic locomotion in humans.

Approach to the problem

As is the case for human locomotion on land, the economy and efficiency of locomotion in water depend on the mechanical work (W_{tot}) that the muscles have to produce to sustain a given speed (see Fig. 1). This work is generally partitioned into two major components: (i) the work that has to be done to overcome external forces (the external work, W_{ext}) and (ii) the work that has to be done in order to accelerate

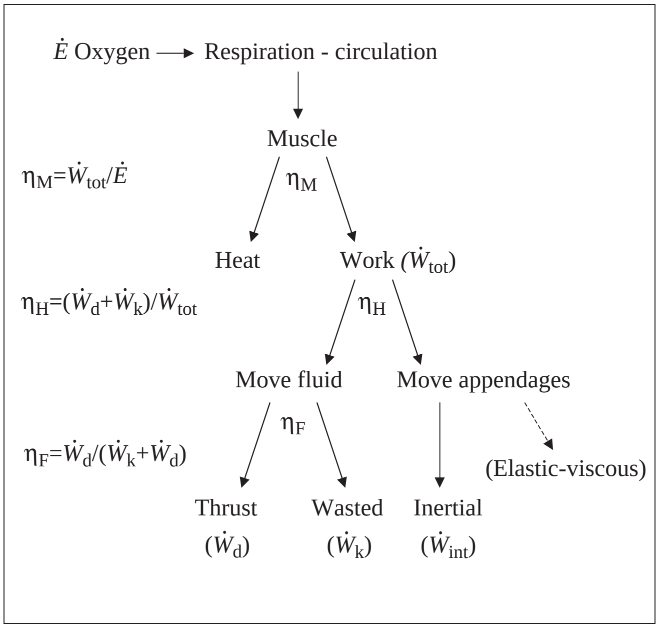

Fig. 1. A flow diagram of the steps of energy conversion in aquatic locomotion (adapted from Daniel, 1991). See text for abbreviations and Discussion for details.

and decelerate the limbs with respect to the centre of mass (the internal work, W_{int}). The contribution of the elastic and viscous factors to total work expenditure is thought to play a minor role in swimming and is not considered here.

The external work in aquatic locomotion is generally partitioned into two components: W_d, the work that is needed to overcome drag that contributes to useful thrust; and W_k, the work that does not contribute to thrust. Both types of work give water kinetic energy but only W_d effectively contributes to propulsion.

The resistance to motion (and hence W_d) in swimming can be measured by towing the subjects (passive drag) or while the subjects are actually swimming (active drag). Active drag is higher than passive drag, due to changes in frontal surface area and fluid dynamics caused by arm/leg movements and, as such, is a better estimate of the force opposing motion. In contrast with passive drag, active drag is difficult to assess and is generally obtained indirectly from measures of energy expenditure (e.g. di Prampero et al., 1974; Toussaint et al., 1988).

The term W_k is a quantity even more difficult to measure than W_d. The contribution of this factor was estimated in swimming humans by Toussaint and coworkers (1988). They compared the difference in the energy consumed while swimming on the MAD (Measuring Active Drag) system to the energy consumed while swimming freely. With this device the subject swims by pushing off fixed pads positioned at the water surface and hence does not waste any energy to give water momentum; in these conditions his/her $\dot{V}_{O_2}$ reflects the energy expended to overcome drag only. However, only arm propulsion could be investigated with that set-up, since the legs are fixed together and supported by a small buoy.

An alternative way of obtaining an estimate of the term W_k comes from studies of animal locomotion. As discussed by Lighthill (1975), Alexander (1977) and Daniel et al. (1992), many animals (e.g. eels) proceed in water with undulatory movements. Waves of bending, produced by rhythmic muscular contractions, can be observed moving along the body in a caudal direction, giving the water backward momentum from both sides of the fish's body. At high Reynolds number (*Re*), thrust arises from the lateral acceleration of the body segments. The viscous forces, which dominate motion at low *Re* values, are negligible. Humans swim at *Re* values of about 10^6, which are comparable to those of slender fish (e.g. 10^5 for eels, as estimated by Alexander, 1977).

During steady state aquatic locomotion, at high *Re* and for a given (forward) speed *v*, the efficiency of the undulatory movement of a slender fish is given by:

$$\eta_F = (c + v) / 2c\,, \tag{1}$$

where *c* is the wave speed and η_F is the Froude efficiency (e.g. Lighthill, 1975; Daniel, 1991). In order to produce effective propulsion, η_F must lie between 0.5 and 1.0: the speed of the backward bending wave should be higher than the average forward speed of the fish.

η_F is also defined as:

$$\eta_F = W_d / (W_d + W_k)\,, \tag{2}$$

(e.g. Lighthill, 1975; Daniel, 1991). Expressed in this way, η_F reflects the ability of the swimming body to impart useful kinetic energy to the water. Thus, the term W_k can be calculated from η_F (as measured by means of Equation 1) and from active body drag (W_d) by rearranging Equation 2:

$$W_k = (W_d/\eta_F) - W_d\,. \tag{3}$$

Whereas arm propulsion (e.g. in the arm stroke) is more analogous to rowing (the hands are used as oars which move water backwards), other swimming styles (e.g. the butterfly or swimming with a monofin) resemble the undulating movements of slender fish. Waves of bending similar to the ones described for slender fish were reported for subjects swimming the butterfly stroke (Ungerechts, 1983; Sanders et al., 1995). The leg (flutter kick) is similar to the butterfly (dolphin) kick, but whereas in the dolphin kick the legs are moved synchronously, in the flutter kick they are moved alternatively, out of phase by half a cycle (see Fig. 2A). Thus, waves of bending can be expected also when swimming using the leg kick (with and without fins); hence, an estimate of the Froude efficiency can be attempted as well as an estimate of the contribution to propulsion by the use of fins.

Finally, the internal work (W_{int}) can be measured from kinematic analysis according to a method originally proposed by Cavagna and Kaneko (1977). When swimming using the leg kick, the internal work is likely to be similar to that of walking, as in both cases the legs move with a sinusoid-like pattern, almost symmetrically with respect to the centre of

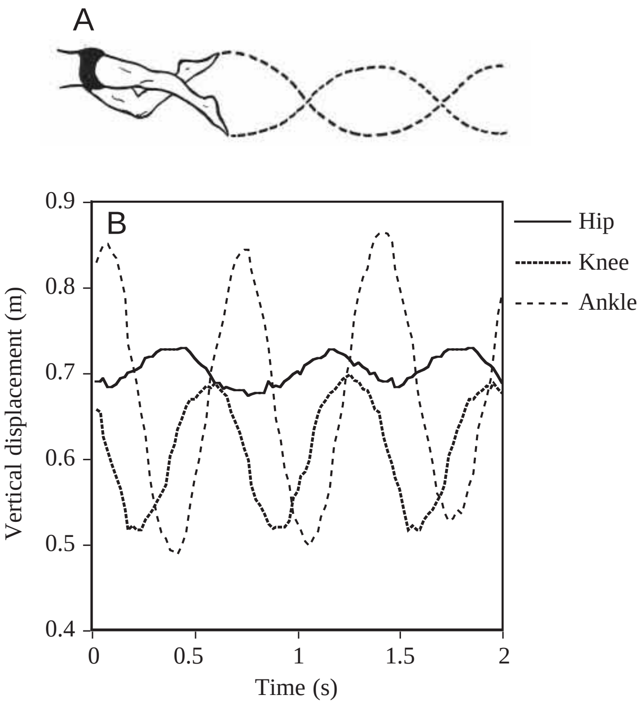

Fig. 2. (A) Schematic representation of the kinematics of the leg (flutter) kick. (B) Vertical displacement of the hip, knee and ankle as a function of time, obtained by video analysis. The kick frequency in A is about half of that shown in B. At variance with walking, where the displacements of these anatomical landmarks are in-phase with each other, when swimming using the leg kick each co-ordinate reaches its minimum/maximum at a phase-shift (Δt) with respect to the others. The distance between the anatomical landmarks (Δl_T, the thigh length; Δl_S, the shank length) divided by the time lag (or phase shift, Δt, in s) gives the velocity of the bending wave along the body ($c=\Delta l_T/\Delta t_T$; $c=\Delta l_S/\Delta t_S$).

mass (see Fig. 2A). A model equation, derived from that proposed for walking by Minetti and Saibene (1992), is proposed in this paper for the calculation of the internal work of the leg kick, based on the values of kick frequency and kick depth.

Materials and methods

The experimental protocol was approved by the Institutional review board and the subjects were informed about the methods and aims of the study and gave their written informed consent prior to participation.

Subjects

The experiments were performed on seven elite college swimmers who were members of a Division I University men's swimming team (State University of New York at Buffalo, NY, USA). Their average body mass was 71.6±7.2 kg, their average stature 1.79±0.69 m and their average age 19.9±1.3 years. The subjects' maximal oxygen consumption $\dot{V}_{O_2max}$ was measured in a separate session by increasing velocity in 0.1 m s^{-1} increments from 0.4 m s^{-1} up to a maximum of 1.3–1.4 m s^{-1}, and ranged from 2.74 to 3.86 l O_2 min^{-1} (3.15±0.38 l O_2 min^{-1}, mean ± S.D.).

Table 1. *Physical characteristics of the fins (Apollo Bio Fin Pro)*

	Fin characteristics					
Fin size	Mass (kg)	Length (m)	Width (m)	Surface area (m^2)	Foot SA (m^2)	Fin/foot SA*
No. 4	1.98	0.50	0.19	0.086	0.026	3.36
No. 5	2.78	0.57	0.22	0.110	0.031	3.53

Fin length, measured from the feet to the trailing edge; fin width, measured at the trailing edge.

The subjects used fins of different sizes depending on their foot dimension (Foot SA: surface area of the foot).

*In both cases fins increase the surface of the 'propeller' of a similar amount (by about threefold).

Fins

Apollo Bio-Fin Pro fins were used in this study. These fins were made of rubber, small in size and highly flexible. This type of fin was shown to be effective in increasing the economy of swimming compared with different types of fins in previous underwater (SCUBA diving) experiments (Pendergast et al., 1996). The subjects used fins of two different sizes; their length, mass and surface area are reported in Table 1. The size of the fins was determined by the foot size of the subjects.

Experimental protocol

The subjects swam (at the water surface) in an annular pool 2.5 m wide, 2.5 m deep and 60 m circumference above the swimmer's path and were paced by a platform moving at constant speed approximately 60 cm above the water surface. The speed of the swimmer was set by means of an impeller type flow meter (PT – 301, Mead Inst. Corp., Riverdale, NY, USA) placed 1.5 m in front of the swimmer and connected to a tachometer (F1-12 P Portable indicator, Mead Inst. Corp., Riverdale, NY, USA). Subjects were requested to swim with the arms hyper-extended over the head and the thumbs joined with the palms down. The forward propulsion was attained by kicking the legs with (LF) or without fins (L).

Active body drag was measured as described by di Prampero et al. (1974). Known masses (0.5–4 kg) were attached to the swimmer's waist 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. This force, defined by di Prampero et al. (1974) as 'added drag' (D_a), leads to a reduction of the swimmer's active body drag (D_b); in our experimental conditions D_a could be better defined as an 'added thrust', since it acts by facilitating the swimmer's progression in water by pulling the subject forward. At constant speed, the ‘added thrust’ is associated with a consequent reduction of $\dot{V}_{O_2}$ and the energy required to overcome D_b becomes zero when D_a and D_b are equal and opposite. At the beginning of the experimental session a load was applied to the pulley system (its mass depending on the speed and/or condition) and the subject was asked to attain the requested speed. After 3 min, once the steady state was attained, expired gas was collected (for approximately 60 s) into an aerostatic balloon through a waterproof inspiratory and expiratory valve-and-hose system supported by the platform. After 1 min the expired gas collection was terminated and the load on the pulley was diminished by approximately 0.5 kg. This procedure was repeated until, in the last step, the subject swam freely (without any added load). During each collection of metabolic data the kick frequency (K_F, Hz) was also recorded. $\dot{V}_{O_2}$ values were determined by means of the standard open circuit method: the gas volume was determined by means of a dry gas meter (Harvard dry gas meter, USA) and the O_2 and CO_2 fractions in the expired air were determined using a previously calibrated gas spectrometer (MGA 1100, Perkin Elmer, CA, USA). The $\dot{V}_{O_2}$ values obtained in the last step (without any ‘added thrust’) were used in the calculations of the energy cost of free swimming: net $\dot{V}_{O_2}$ (above rest, assumed to be 3.5 ml O_2 min^{-1} kg^{-1}) was converted to watts W, assuming that 1 ml O_2 consumed by the human body yields 20.9 J (which is strictly true for a respiratory quotient of 0.96), and divided by the speed v to yield the energy cost of swimming per unit of distance (C) in kJ m^{-1}.

The swimmer’s D_b was estimated, at any given speed and condition, by extrapolating the $\dot{V}_{O_2}$ *versus* D_a relationship to resting $\dot{V}_{O_2}$. The power dissipated against drag was then calculated from the product of the active body drag times the speed ($\dot{W}_d=D_bv$).

The experiments were carried out over a range of speeds (N=5) that could be accomplished aerobically. The range of speeds depended on the condition selected: 0.6–1.0 m s^{-1} (L), 0.7–1.1 m s^{-1} (LF). Each subject participated in several experimental sessions, each corresponding to 1–3 swims at a given speed and/or condition; the swims were separated by at least 15–20 min of rest.

Kinematic analysis

During the experiments, video recordings were taken at a sampling rate of 50 Hz (Handy Cam Vision, Sony, Japan) while the subjects passed in front of an underwater window. Black tape markers were applied on selected anatomical landmarks in order to facilitate the following video analysis. The distance between the hip (great trochanter) and the knee (lateral epicondyle) was measured and recorded for each subject and each experimental session and was utilized as a calibration factor.

After the experiments, the data were downloaded to a PC and digitized using a commercial software package (Peak Motus, Co, USA). The 2-D coordinates of selected anatomical landmarks were utilized to calculate the trunk inclination, the kick depth, the Froude efficiency and the internal work. Only the data collected during steady state free swimming were analyzed.

Trunk inclination (T_I, degrees) was measured with the leg proximal to the camera fully extended (see Fig. 2A), from the angle between the shoulder (acromion process) and the hip (great trochanter) segment and the horizontal. In the same frame, kick depth (K_D, m) was measured from the vertical distance between the ankles (lateral malleolous). Finally, in this same frame the 2-D coordinates of the hip and the knee (lateral epicondyle) markers were recorded in order to obtain the calibration factor (for each subject, speed and condition). 1–3 passes of the swimmer were filmed for each condition and speed; data for T_I and K_D reported in the text are the mean of all the values measured in all the passes (in each subject and for each condition and speed).

*The internal work (*W*int)*

The internal work of the leg kick, with and without fins, was computed from video analysis during free swimming (without any added drag) on two subjects according to the method originally proposed by Cavagna and Kaneko (1977). To measure W_{int} the locations of nine anatomical landmarks (wrist, elbow, shoulder, neck, hip, knee, ankle, heel, toe tip) were digitized over one complete swimming cycle. On the assumption that bilateral swimming movements are symmetrical, the 2-D coordinates obtained from the body side proximal to the camera were duplicated (shifted half a cycle) and the swimming cycle was reconstructed for the whole body (see Fig. 2A). The 3-D coordinates obtained and standard anthropometric tables (Dempster, 1959) allowed us to calculate the position and the linear and angular speed of each body segment, from which the position of the body centre of mass was also derived. When swimming with fins, the extra mass of the fins was taken into account in order to compute the segment mass/total mass fraction of each body segment. The sum of the increases, over the time course, of absolute rotational kinetic energy and of relative (with respect to the body centre of mass) linear kinetic energy of adjacent segments over one cycle were then computed by a custom software package (Minetti, 1998) in order to calculate W_{int}.

As shown by Minetti and Saibene (1992) the mechanical internal work rate when walking ($\dot{W}_{int}$, in W) could be described by the following equation:

$$\dot{W}_{int} = kv^2f\,, \tag{4}$$

where k is related to the inertia parameters of the moving body segments, v is the average progression speed (m s^{-1}) and f is the stride frequency (Hz). When swimming using the leg kick, $\dot{W}_{int}$ is probably similar to that of walking, as the legs move with a sinusoid-like mechanism in both cases. In contrast to walking, in swimming using the leg kick the relative linear speed of the limbs is not constrained to the average progression speed and the vertical and horizontal oscillations of the body centre of mass are kept to a minimum, similar to cycling (Minetti et al., 2001). The term v^2, which expresses the dependency of $\dot{W}_{int}$ on the translational and kinetic energy of the moving segments, is therefore more correctly related (for swimming) to the speed of the vertical movement of the legs (s, m s^{-1}) rather than to the average horizontal speed. Whereas in cycling the displacement of the lower limb (i.e. the kick depth) is constrained by the biomechanical arrangement of the subject–bicycle system, this is not the case for the leg kick (by analogy with the step length in walking) and, hence, to calculate s both the kick depth (K_D, m) and the kick frequency (K_F, Hz) should be measured. Hence the model equation proposed by Minetti and Saibene for walking (1992) was modified as follows:

$$\dot{W}_{int} = k(2K_D)^2K_F^3\,, \tag{5}$$

where $(2K_D)K_F$ is the vertical speed of the legs (s) and the term $2K_D$ takes into account the fact that K_D is analogous to step length (the distance covered in half a cycle), whereas K_F was calculated over one complete cycle (by analogy with the stride frequency in walking).

This model equation was utilized to estimate k (Systat 5, USA) in the two conditions (k_L and k_{LF}) by means of a multiple non-linear regression.

The Froude efficiency (η_F) and the kinetic energy (W_k)

The Froude efficiency η_F of swimming with (LF) and without fins (L) was calculated from the values of average forward speed (v) and from the velocity of the backward wave (c) on the same two subjects. c (m s^{-1}) was measured as indicated by Ungerechts (1983) and Sanders et al. (1995) from the 2-D coordinates of the hip, knee and ankle joints. As shown in Fig. 2B, each coordinate reaches its minimum/maximum displacement with a phase-shift represented by the time lag (Δt). The distance between the anatomical landmarks Δl_T (the thigh length) and Δl_S (the shank length) divided by the corresponding time lag between the waves minima gives the velocity of the wave along the body ($c=\Delta l_T/\Delta t_T$ and $c=\Delta l_S/\Delta t_S$). From the values of c, the Froude efficiency was calculated according to Equation 1 and the term W_k was calculated according to Equation 3.

Statistics

The regressions between $\dot{V}_{O_2}$ and D_a for each condition were calculated by the sum of the least-squares linear analysis model. The differences in the measured variables (e.g. C, D_b, W_{int}) as determined in the L and LF conditions were compared by the paired Student's t-test at matched speeds (from 0.7 to 1.0 m s^{-1} only, N=28).

Results

The results of a typical experiment are reported in Fig. 3 for the LF condition in one subject. The regression between D_a and oxygen consumption ($\dot{V}_{O_2}$), obtained from 4–5 observations, was linear for all subjects at all speeds (mean r^2=0.959±0.042; range=0.775–1.000, N=70). From these relationships the individual values of active body drag (D_b=D_a, at $\dot{V}_{O_2rest}$) and of net energy cost (C=$\dot{V}_{O_2net}/v$, at D_a=0) were calculated.

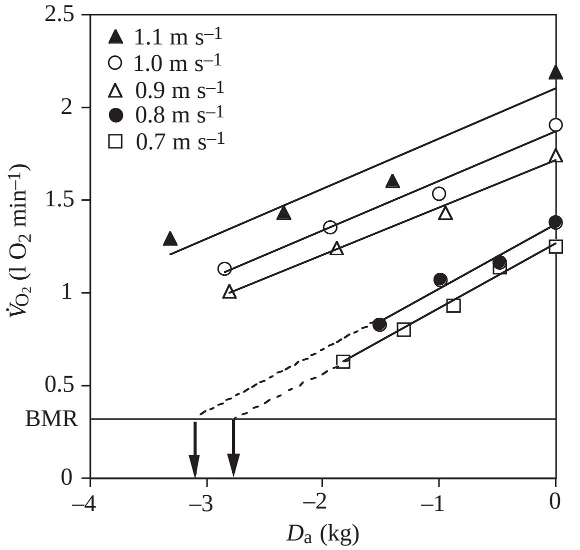

Fig. 3. The linear relationships between added drag (D_a) and rate of oxygen consumption ($\dot{V}_{O_2}$) obtained from a subject swimming with fins at the indicated speeds. Active body drag D_b was estimated, at each speed, by extrapolating the D_a *versus* $\dot{V}_{O_2}$ relationship to $\dot{V}_{O_2rest}$ (basal metabolic rate, BMR) as indicated by the dotted lines and the arrows pointing downwards. D_a=0 corresponds to free swimming (see text for details).

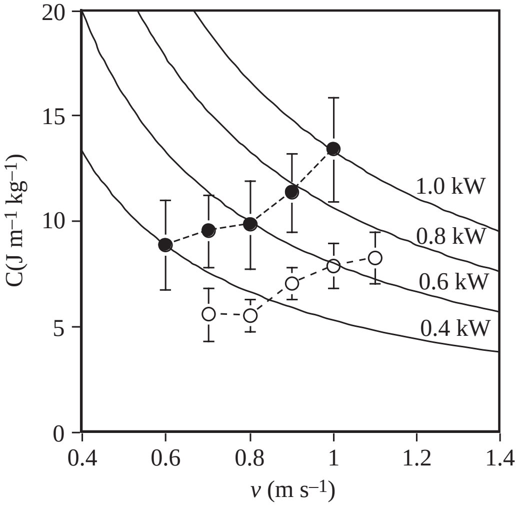

Fig. 4. Energy cost of swimming using the leg kick (C) as a function of the speed (v), measured with fins (open circles) or without (closed circles). The descending curves represent iso-metabolic power hyperbolae (as calculated for a 'standard' subject of 75 kg body mass) of 0.4, 0.6, 0.8 and 1.0 kW (from bottom to top). Fins decrease the energy cost of swimming by approximately 40 % at comparable speeds and, for any given metabolic power, fins increase the speed of progression by approximately 0.2 m s^{-1}.

The energy cost of the swimming leg kick is reported in Fig. 4 as a function of the speed for both L and LF conditions. At paired speeds, the energy cost when swimming with fins was 42±2 % lower than when swimming without (LF–L=–4.5±2.5 J m^{-1} kg^{-1}, $P<0.001$). When compared at the same metabolic power, the decrease of C brought about by the use of fins allowed an increase of progression speed of approximately 0.2 m s^{-1}.

Average values of kick depth, kick frequency, active body drag and trunk inclination are reported in Table 2. Fins only slightly decrease (14 %) the kick depth (at the ankle level) but cause a large reduction (43 %) in the kick frequency. No significant differences in active body drag and trunk inclination were observed between the two conditions at comparable speed.

Froude efficiency (η_F), calculated by Equation 1 in two subjects, was found to be 0.61±0.02 (N=39) when swimming with the legs only and 0.69±0.02 (N=24) when swimming with fins. No differences were found in the time lag (Δt) between the data calculated from the hip-knee or knee-ankle coordinates within both L and LF conditions. As shown in Fig. 5, the wave speed (c, m s^{-1}) was found to increase linearly with the kick frequency (K_F, Hz). The strength of this relationship (r^2=0.911) suggests that η_F can be accurately estimated from individual values of kick frequency and speed assuming a wavelength of 2.33 m. Using this simplified method the average values of η_F (N=35) were found to be 0.61±0.01 when swimming with the legs only and 0.70±0.04 when swimming with fins, i.e. a 16 % increase at comparable speeds (see Table 3).

From the individual data of $\dot{W}_d$ (W) ($\dot{W}_d=D_b v$) and η_F, the term $\dot{W}_k$ (W) could be estimated using Equation 2. $\dot{W}_k$ increased with swimming speed in both conditions and was 32 % smaller in LF than in L at comparable speeds (see Table 4).

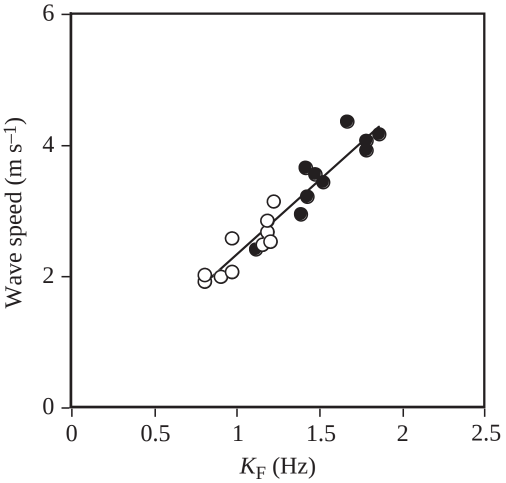

Fig. 5. In some types of aquatic locomotion, bending waves can be observed moving along the body in a caudal direction (e.g. the ondulatory movements of slender fish). Similar waves were observed in this study in subjects swimming using the leg kick (see also Fig. 2). The velocity of the wave travelling along the body (wave speed: c, m s^{-1}) increases linearly with the kick frequency (K_F, Hz) with fins (LF, open circles) and without fins (L, closed circles). The relationship between c and K_F is well described by $c=2.33K_F$ (r^2=0.911, N=20), the slope of which is the wavelength (λ, m).

Table 2. *Kick frequency* (K_F)*, kick depth* (K_D)*, active body drag* (D_b) *and trunk inclination* (T_I) *as measured when swimming at the indicated speeds* (v) *with or without fins*

	v (m s^{-1})	K_F (Hz)	K_D (m)	D_b (N)	T_I (degrees)
L	0.6	1.29±0.14	0.34±0.08	20.0±7.8	–18.2±2.2
	0.7	1.44±0.05	0.33±0.04	23.6±5.8	–15.9±3.7
	0.8	1.58±0.22	0.34±0.04	29.5±4.6	–14.8±3.2
	0.9	1.73±0.15	0.37±0.03	38.9±8.8	–12.6±3.4
	1.0	1.90±0.07	0.36±0.04	42.1±9.9	–13.9±3.3
LF	0.7	0.73±0.14	0.30±0.04	28.3±10.8	–17.1±4.9
	0.8	0.92±0.17	0.30±0.07	22.9±5.4	–18.1±4.9
	0.9	0.98±0.20	0.31±0.06	41.8±13.5	–14.6±3.1
	1.0	1.18±0.15	0.29±0.05	41.9±10.3	–14.6±3.3
	1.1	1.29±0.16	0.33±0.05	54.1±6.6	–10.7±3.7
LF–L	Abs.	–0.71±0.04 *	–0.05±0.02*	0.16±4.9	–1.8±1.1
(LF–L)/L	%	–43±5 %	–14±5 %	1±18 %	13±8 %

LF, with fins; L, without fins.

Values are means ±1 S.D.; Student's t-test for paired data (N=28).

*$P<0.001$.

The last two rows report the differences between the L and LF conditions at comparable speeds (Abs., absolute difference; %, percentage difference).

The internal work rate ($\dot{W}_{int}$, W kg^{-1}), as measured in two subjects during actual swimming, is reported in Fig. 6 as a function of the speed (v, m s^{-1}). $\dot{W}_{int}$ was found to increase with the speed in both conditions. In these two subjects $\dot{W}_{int}$ was found to range from 13 to 43 W in the L condition (N=10) and from 9 to 18 W in the LF condition (N=10).

The constant k, as obtained from the multiple non-linear regression, was found to be 13.93 (k_L, N=10, r^2=0.976) in the L condition and 25.55 (k_{LF}, N=10, r^2=0.832) in the LF

Table 3. *Average values (for all subjects and all speeds) of the efficiencies measured in this study with and without fins*

	Efficiencies				
	η_M	η_P	η_H	η_F	η
L	0.11±0.02	0.36±0.01	0.59±0.01	0.61±0.01	0.04±0.01
LF	0.13±0.02	0.58±0.03	0.82±0.03	0.70±0.02	0.08±0.01
(LF–L)/L (%)	9±7	62±8	40±6	16±3	77±21

LF, with fins; L, without fins.

η_M, mechanical efficiency; η_P, propelling efficiency; η_H, hydraulic efficiency; η_F, Froude efficiency; η, performance efficiency (see text and Fig. 1 for details).

The parameters reported in this table are related as follows: $\eta_M \times \eta_P = \eta$ and $\eta_P = \eta_H \times \eta_F$.

The last row reports the percentage difference between the L and LF conditions at comparable speeds.

Table 4. *Average values of the power needed to overcome frictional forces ($\dot{W}_d$), to impart kinetic energy to the water ($\dot{W}_k$) and to overcome inertial forces ($\dot{W}_{int}$), total mechanical power ($\dot{W}_{tot}$) and net metabolic expenditure $\dot{E}$, as measured when swimming at the indicated speeds* (v) *with or without fins*

	v ($\mathrm{m\,s^{-1}}$)	$\dot{W}_d$ (W)	$\dot{W}_k$ (W)	$\dot{W}_{int}$ (W)	$\dot{W}_{tot}$ (W)	$\dot{E}$ (kW)
L	0.6	12.0±4.7	8.0±3.5	13.3±3.9	33.3±9.5	0.39±0.12
	0.7	16.5±4.0	10.8±2.8	18.8±5.0	46.1±8.4	0.48±0.11
	0.8	23.6±3.7	15.0±2.2	24.9±7.2	63.5±5.2	0.57±0.15
	0.9	35.0±7.9	22.1±4.9	39.6±10.3	96.7±12.8	0.74±0.18
	1	42.0±9.9	26.6±6.5	48.5±10.9	117.1±10.9	0.97±0.26
LF	0.7	19.8±7.6	7.9±3.5	4.1±2.0	31.8±11.4	0.28±0.06
	0.8	20.6±4.8	8.5±3.4	6.9±3.3	36.0±10.3	0.32±0.04
	0.9	37.6±12.1	15.6±6.0	10.3±5.4	63.5±19.5	0.45±0.04
	1	41.7±10.3	19.5±5.8	13.7±2.5	77.0±16.8	0.56±0.07
	1.1	59.5±7.2	27.4±3.5	23.7±10.3	110.6±15.0	0.65±0.07
LF–L	Abs.	0.6±2.9*	–5.7±1.9*	–24.2±9.4 *	–29.3±11.6*	–0.29±0.09*
(LF–L)/L	%	3±14 %	–32±8 %	–74±3 %	–36±5 %	–42±2 %

LF, with fins; L, without fins.

Student's *t*-test for paired data (N=28); *P<0.001.

Total mechanical power ($\dot{W}_{tot}$)=($\dot{W}_d$+$\dot{W}_{int}$+$\dot{W}_k$) (see text for details).

The last two rows report the differences between the L and LF condition at comparable speeds (Abs., absolute difference; %, percentage difference).

condition. The good coefficients of determination suggest that $\dot{W}_{int}$ can be accurately estimated from individual values of kick frequency and depth and from the estimated values of k (e.g. by applying Equation 5). The so-calculated average values of $\dot{W}_{int}$ (N=35 in L and LF) are reported in Table 4: $\dot{W}_{int}$ increased with swimming speed in both conditions and was 74 % smaller in LF than in L at comparable speeds.

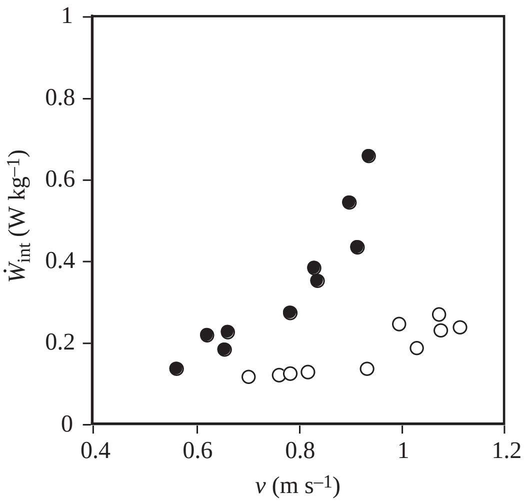

Fig. 6. Internal work rate ($\dot{W}_{int}$, $\mathrm{W\,kg^{-1}}$), measured in two subjects as a function of the speed (v, $\mathrm{m\,s^{-1}}$). W_{int} increases with the speed in both conditions: with fins (FL, open circles) or without (L, closed circles). At paired speeds, $\dot{W}_{int}$ is larger when swimming without fins than when swimming with them. The differences in $\dot{W}_{int}$ are mainly attributable to differences in kick frequency (about 40 % lower when fins are used; see text for details).

Along with the mean values of $\dot{W}_{int}$ and $\dot{W}_k$ the values of $\dot{W}_d$ and $\dot{W}_{tot}$ are also reported in Table 4 as well as the values of $\dot{E}$ (in kW, i.e. the net metabolic power). $\dot{W}_{tot}$ increased with the speed in both conditions and was significantly reduced (36 %) by the use of fins at comparable speeds. The contribution of $\dot{W}_k$ and $\dot{W}_{int}$ to $\dot{W}_{tot}$ were found to be speed-independent within both conditions. The contribution of $\dot{W}_k$ to $\dot{W}_{tot}$ is approximately the same in the L and LF condition (24±1 %, mean ± S.D. at all speeds). On the contrary, whereas $\dot{W}_{int}$ is a major determinant of $\dot{W}_{tot}$ in the L condition (40±1 % of $\dot{W}_{tot}$, average at all speeds), its contribution is reduced to a half in the LF condition (18±3 % of $\dot{W}_{tot}$, average at all speeds).

As shown in Fig. 7, at comparable speeds fins reduce $\dot{W}_k$ by 32 %, $\dot{W}_{int}$ by 74 % and $\dot{W}_{tot}$ by 36 % (whereas $\dot{W}_d$ is unchanged). The decrease in $\dot{E}$ brought about by the use of fins (42 %) is proportional to the decrease in $\dot{W}_{tot}$ (36 %), so that the mechanical efficiency of swimming (η_M: $\dot{W}_{tot}/\dot{E}$) is only slightly higher when swimming with fins: it ranges from 0.08 to 0.12 in the L condition and from 0.11 to 0.17 in the LF condition. On average (all subjects at comparable speeds), fins increase the mechanical efficiency of swimming by about 10 % compared to use of legs alone (see Table 3).

Discussion

Energetics of swimming

Existing data on the energetics of fin swimming refer mainly to underwater swimming (SCUBA diving) (see Pendergast et al., 1996), and show that the effects of different fins on the energy requirements of swimming depend on the type of fin used. Large, rigid fins are energetically demanding but improve

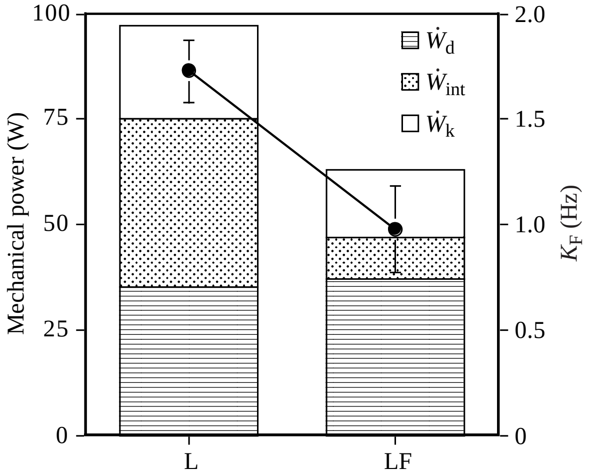

Fig. 7. Mean values of the power (W, left vertical axis) to impart 'useless' kinetic energy to the water ($\dot{W}_k$) and to overcome frictional ($\dot{W}_d$) and inertial forces ($\dot{W}_{int}$) as measured without fins (L) and with fins (LF) at a speed of $0.9\,m\,s^{-1}$. The mean (± 1 S.D.) kick frequency at the same speed is also reported in the two conditions (K_F, Hz, closed circles, right vertical axis).

the maximal attainable speed, whereas flexible (small sized) fins improve the economy of swimming at submaximal 'cruising' speeds (Lewis and Lorch, 1979; McMurray, 1977; Pendergast et al., 1996). Whereas fish can self-adjust the stiffness of the tail according to their needs (Lewis and Lorch, 1979; Alexander, 1977), humans must select the fin design according to the task to be performed. In accordance with these observations, the flexible fins used in this study were found to decrease the energy cost of swimming by approximately 40 % at sub-maximal speeds of progression compared to using legs alone. As indicated in Fig. 4, at any given metabolic power the reduction in C brought about by the use of fins is associated with an increase in the speed of progression of approximately $0.2\,m\,s^{-1}$ (the descending curves representing iso-metabolic power hyperbolae). Thus the effect of using fins on economy of water locomotion is similar to that observed for passive locomotory tools in land locomotion (Minetti et al., 2001).

Substantial variation in the energy cost of swimming using the leg kick was observed in the L condition (Fig. 4). The differences in economy of swimming in subjects of comparable skill (assumed here) and at comparable speeds are attributed to the anthropometric characteristics that determine the subject's position in water. These differences can be quantified by measuring the underwater torque (T′, a measure of the tendency of the feet to sink) by means of an underwater balance. T′ was indeed found to be a major determinant of the energy cost of swimming at low to moderate speeds (see Pendergast et al., 1977). At moderate speeds, T′ (a static measure of the subject's position in water) relates to the subject's dynamic position in water (e.g. the trunk inclination, T_I). Hence T_I can also be expected to be a determinant of C. When speed increases, hydrodynamic lift acts on the body, which assumes a more streamlined position in the water and the difference between static and dynamic position (T′ and T_I) lessens.

C and T_I were found to be linearly related (the larger T_I, the larger C) in the L condition, with an average correlation coefficient (for the five speeds considered) of 0.759±0.082 (range: 0.710–0.881, $N=7$ for each regression, $P<0.05$ except for $0.7\,m\,s^{-1}$). This suggests that part of the variability of C observed in the L condition is indeed attributable to differences in anthropometric characteristics of the subjects. In contrast, even if no differences in T_I were found between the L and LF conditions, the relationships between C and T_I were not significant in the LF condition, which indicates that other factors more strongly influence the energy cost of locomotion when fins are used.

Work components and efficiency of swimming

As previously discussed for land locomotion (Minetti et al., 2001), an improvement in economy does not imply, *per se*, a parallel improvement in the efficiency of locomotion. The effects of the use of fins on the efficiency of the leg kick can be investigated only by measuring all the components of the total mechanical work.

As shown by the flow diagram in Fig. 1 (adapted from Daniel, 1991) the efficiency of aquatic locomotion is determined by three factors. (1) The efficiency with which muscles use oxygen to generate work. This efficiency is usually defined as mechanical or musculo–skeletal efficiency ($\eta_M=\dot{W}_{tot}/\dot{E}$). (2) The efficiency with which the work done by the muscles produces a useful movement (i.e. that fraction of the work that gives kinetic energy to the fluid). This component takes into consideration the fact that some of the contractile energy 'is lost' in accelerating the mass of the lower limbs, in deforming parts involved in thrust production (e.g. the fin's blade) and in overcoming viscous damping in the tissues; this efficiency is called hydraulic efficiency (η_H) (Alexander, 1983). Whereas the contribution of the elastic and viscous factors is difficult to assess, the contribution of the inertial factors can be estimated by measuring the internal work of swimming (W_{int}). Hydraulic efficiency is given by:

$$\eta_H = (\dot{W}_k + \dot{W}_d) / \dot{W}_{tot} . \tag{7}$$

(3) The efficiency with which the work done in moving fluid goes to useful thrust (W_d); this is the Froude efficiency (η_F) and is given by:

$$\eta_F = \dot{W}_d / (\dot{W}_k + \dot{W}_d) . \tag{8}$$

The product of hydraulic efficiency (η_H) and Froude efficiency (η_F) gives the propelling efficiency ($\eta_P=\dot{W}_d/\dot{W}_{tot}$); the product of mechanical efficiency (η_M) and propelling efficiency (η_P) gives what can be called performance efficiency ($\eta=\dot{W}_d/\dot{E}$) and can be checked by dimensional analysis, as reported by Daniel (1991) and Webb (1971b).

In the computation of $\dot{W}_{tot}=\dot{W}_k+\dot{W}_d+\dot{W}_{int}$, the elastic and viscous terms were considered negligible and the terms $\dot{W}_d$ and $\dot{W}_{int}$ were directly measured. The term $\dot{W}_k$ was obtained from the values of Froude efficiency.

In the following paragraphs the measured/calculated values of the above mentioned parameters will be discussed separately. The average values of all the efficiencies indicated in this figure are reported in Table 3.

The power needed to overcome drag ($\dot{W}_d$)

The term $\dot{W}_d$ was calculated as proposed by di Prampero et al. (1974) and was found to be unaffected by the use of fins, at comparable speeds.

It can be debated whether the decrease of $\dot{V}_{O_2}$ observed as a consequence of adding masses to the pulley system (D_a, see Fig. 2) is attributed to changes in W_d only. We found that the added thrust (D_a) not only reduced the swimmer's active body drag (and hence $\dot{W}_d$) but also affected the frequency of the kick: the higher D_a, the lower K_F. The observed reduction of $\dot{V}_{O_2}$ for any given D_a has therefore to be attributed to a decrease in $\dot{W}_{int}$ and $\dot{W}_k$ (both proportional to K_F). Since the contribution of these factors to total $\dot{V}_{O_2}$ is large at D_a=0 (during free swimming) but negligible at the highest D_a, it can be shown that these factors affect only the slope of the relationship between D_a and $\dot{V}_{O_2}$ and not the point at which the regression crosses the D_a axis, thus they do not affect the determination of D_b.

Thus, even if the procedure to determine active body drag is based on several assumptions, this is still, in our opinion, the best method proposed so far to estimate resistive forces to aquatic locomotion in humans.

The internal work rate ($\dot{W}_{int}$)

To our knowledge, no data for $\dot{W}_{int}$ have been reported before (nor even considered as a source of energy expenditure) for swimming humans. The internal work rate when swimming using the leg kick accounts for approximately 40 % of $\dot{W}_{tot}$ in the L condition and for about 20 % of $\dot{W}_{tot}$ in the LF condition (its contribution to $\dot{W}_{tot}$ being almost independent of the speed). Hence, fins halve the contribution of inertial factors to energy expenditure in aquatic locomotion. In absolute terms, $\dot{W}_{int}$ increases more than threefold over the selected speed range in both conditions and can account for up to 50 W at the higher K_F observed. Not considering this parameter could therefore lead to a severe underestimation of the overall swimming efficiency.

In this paper the model equation proposed Minetti and Saibene (1992) for walking was adapted to describe the relationship between $\dot{W}_{int}$, kick frequency and kick depth when swimming. The value of k, a constant which takes into account the inertial parameters of the moving segments, turned out to be comparable to that calculated by Minetti and Saibene (1992) for walking (k=21.64). In the L condition, k was found to be half of that calculated for walking (k_L=13.93), in agreement with the fact that only the lower limbs are moving and the oscillation amplitude is smaller. The larger value of k in the LF condition (k_{LF}=25.55) reflects the effect of the added fin mass on the inertial parameters of the lower limbs.

KF was found to be the main determinant of $\dot{W}_{int}$ in swimming. Indeed, as shown in Table 2, values of K_D increase only slightly, whereas large variations in K_F are observed with speed in both conditions. Moreover, fins only slightly decrease the amplitude of the kick but cause a large reduction in the kick frequency. Hence, as a first approximation, the term $(2K_D)^2$ in Equation 5 can be considered as constant and $\dot{W}_{int}$ can be calculated from $\dot{W}_{int}=kK_F^3$. When the $\dot{W}_{int}$ data as directly measured in the two subjects in both conditions were pooled, the equation became $\dot{W}_{int}=6.9K_F^3$ (N=20, r^2=0.789; where $\dot{W}_{int}$ is in W and K_F in Hz). The coefficient of determination is only slightly lower than the one obtained with the model equation (r^2=0.841, see above) suggesting that this approximate version of the equation can be safely utilized to estimate $\dot{W}_{int}$ when data for K_D are not available.

There is some debate about whether external and internal work have to be separately calculated and summed in walking (assuming no energy transfer between the two) or jointly computed, allowing for any possible transfer, but in cycling (Minetti et al., 2001) and swimming the lower limb movement minimally affects the movement of the centre of mass. Moreover, in swimming, limb movement occurs in an orthogonal axis with respect to progression and the vertical and horizontal oscillations of the centre of mass are kept to a minimum.

The Froude efficiency (η_F)

In this paper the Froude efficiency was estimated by applying the equation proposed by Lighthill (1975) and Alexander (1977) for animal locomotion in water (Equation 1) to human swimming. This method is based on the calculation of the speed of the bending waves that move along the body (of the swimmer or the fish) in a caudal direction.

As shown in Fig. 5, wave speed (c, m s^{-1}) increased linearly with the kick frequency (K_F, Hz). Since kick frequency is the reciprocal of the wave period (T, s), the slope of the above linear relationship is the wavelength (λ, m). As shown by the high determination coefficient, the wavelength was found to be quite constant for different subjects, speeds and conditions (λ=2.34±0.18 m, N=20) and similar to the values measured by Sanders et al. (1995) in male swimmers using the butterfly stroke (2.24±0.25 m). The good agreement between the average values of wavelength measured in the different studies, the small standard deviation and the high determination coefficient (r^2), suggest that the linear relationship between wave speed and K_F described above can be utilized to predict the Froude efficiency of swimming using the leg kick from measurements of kick frequency (K_F) and average speed (v).

That c depends essentially on K_F while the wavelength of the propulsive wave (λ) is almost constant at different swimming speeds was also observed and reported by Webb for the rainbow trout *Salmo gairdneri* (1971a). Fish with similar body forms are characterized by similar specific wavelenghts (λ/L, where L is the fish length). Depending on the fish swimming type, λ is larger (carangiform mode) or smaller (angulliform mode) than L (Webb, 1971a). The data reported above (λ=2.3 m and hence λ>body length) are compatible with the morphological observation that humans are relatively thicker for their length and resemble, if we can risk such a comparison, a trout rather than an eel.

The values of Froude efficiency measured in this study are not far from those measured in the rainbow trout by Webb (according to the method proposed by Lighthill), who reported a range of values for η_F of 0.61–0.81 at speeds between 0.1 and 0.52 m s^{-1} (Webb, 1971b).

The kinetic work rate not useful for thrust production ($\dot{W}_k$)

The data for $\dot{W}_k$ were obtained according to Equation 3 and using the measured/calculated values of $\dot{W}_d$ and η_F. $\dot{W}_k$ data for swimming humans are scarce; the only other values reported in the literature were obtained by means of the MAD system. With this method $\dot{W}_k$ is calculated as $\dot{W}_k=\dot{V}_{O_2eqFREE}-\dot{V}_{O_2eqMAD})/\eta$, where $\dot{V}_{O_2eqFREE}$ is the energy expended when swimming freely (expressed in W), $\dot{V}_{O_2MAD}$ (W) is the energy expended when swimming on the MAD system and η is the efficiency of swimming (as obtained by graphical analysis). In those conditions (arm stroke only with the legs floating), $\dot{W}_k$ was found to range from 16 to 64 W at speeds of 1.0–1.3 m s^{-1} (Toussaint et al., 1988). Since the values of $\dot{W}_k$ increase with speed, it is reasonable that the values found in the present study (9–31 W in both conditions) are lower than those reported at higher speeds using the arm stroke. The two sets of data are not, however, directly comparable. In fact, the term $\dot{W}_k$ as defined by Toussaint et al. is given by the sum $\dot{W}_k+\dot{W}_{int}$ since it was obtained from values of $\dot{W}_{tot}$ and $\dot{W}_d$ only (indeed, they correctly defined their efficiency as ‘propelling’).

For values of Froude efficiency ranging from 0.50 to 0.75 (a reasonable range for human locomotion in water), the power wasted when imparting kinetic energy to the water ($\dot{W}_k$) is bound to range from $\dot{W}_k=\dot{W}_d$ (η_F=0.5) to $\dot{W}_k=1/3\dot{W}_d$ (η_F=0.75). Not taking into account this parameter can therefore lead to an underestimation of the overall swimming efficiency, as discussed above for $\dot{W}_{int}$ and previously emphasized by Toussaint et al. (1988). Indeed $\dot{W}_k$ accounts for approximately 25 % of $\dot{W}_{tot}$ (for both conditions and at all speeds).

Hydraulic efficiency (η_H) and the propelling efficiency (η_P)

From the data reported in Table 4, the hydraulic efficiency can be calculated as: $\eta_H=(\dot{W}_k+\dot{W}_d)/\dot{W}_{tot}$);$\eta_H$ was found to be 0.59 in L and 0.82 in LF conditions, corresponding to a 40 % difference at comparable speeds (see Table 3). As indicated by Alexander (1983) the efficiency of a propeller is given by the product of $\eta_H\times\eta_F$ (or, in other terms, $\eta_P=\dot{W}_d/\dot{W}_{tot}$). The propelling efficiency turned out to be 0.36 in the L and 0.58 in the LF condition, i.e. 62 % larger in LF than L at comparable speeds (see Table 3). In both cases the LF–L difference was found to be independent of the swimming speed.

Propelling efficiency has also been estimated, in competitive swimmers, by means of the MAD system when swimming using the arm stroke, and it was found to be comparable to that calculated in this study: 0.53 (Toussaint et al., 1988) and 0.56 (Berger et al., 1997) at speeds between 0.9 and 1.35 m s^{-1}.

All these values can be compared to the values of propelling efficiency of other locomotory devices for aquatic locomotion. As reported by Abbott et al. (1995), human-powered vehicles with drag-device propulsion (such as boats propelled by poles, oars and paddles) are characterized by propelling efficiencies of about 0.65–0.75. Even though these values are larger than those reported for swimming, about one third of the subject’s power output is bound to be wasted using these locomotory devices. Human-powered propeller-driven boats, which can reach greater propelling efficiencies, have been developed since the 1890s for practical transportation purposes (Abbott et al., 1995). Their development almost completely ceased when gasoline-driven outboard motors were introduced; propellers with efficiencies exceeding 90 % are currently in use on human-powered watercrafts of recent development (e.g. the flying fish; Abbott et al., 1995).

The efficiency of a propeller is higher if a large mass of fluid is accelerated to a low velocity than if a small mass is accelerated to a high velocity (Alexander, 1977). Since fins increase the propelling surface they would be expected also to increase propelling efficiency (as experimentally determined). The increase in η_P observed in this study (62 %) can be compared to the increase of propelling efficiency (7 %) obtained by the use of hand paddles when swimming the arm stroke (Toussaint et al., 1991). The increase in η_P with fins compared to without fins or between fins and hand paddles may be partially explained by the higher propelling surface of fins compared to feet (fin/foot surface area: 3.5; see Table 1) and hand paddles (hand paddles/hand surface area: 0.026/ 0.018 m^2=1.45).

Mechanical efficiency (η_M)

The mechanical efficiency of swimming with and without fins, at a given speed, was calculated from the ratio of total mechanical power ($\dot{W}_{tot}=\dot{W}_k+\dot{W}_d+\dot{W}_{int}$) to total metabolic power ($\dot{E}$). Mechanical efficiency ranged from 0.08 to 0.17 in both conditions and at all speeds (0.11 and 0.13 for L and LF, respectively; mean for all subjects at comparable speeds). These values are higher than those reported for swimming humans. In those studies, however, any contributions of internal and/or kinetic work were neglected. When internal and kinetic work are not accounted for, efficiency values ($\eta=\dot{W}_d/\dot{E}$) range from 0.03 to 0.05 (in the L condition), which is comparable to that reported by others for front crawl swimming 0.05–0.08 (Toussaint et al., 1988), 0.03–0.09 (Pendergast et al., 1977) and 0.04–0.08 (Holmer, 1972) and compatible with the fact that the leg kick is a less effective way of moving in water than the arm stroke (e.g. Adrian et al., 1966).

Locomotory (mechanical) efficiency is generally investigated to get insight into how muscles (the actuators) work *in situ*. The challenge is to compute all the components of the external and internal work (as well as taking into account the contribution of elastic energy storage and release, viscous damping in the tissues and so on...) in order to obtain the best possible estimate of muscle efficiency.

By taking $\dot{W}_k$ and $\dot{W}_{int}$ into consideration in the computation of $\dot{W}_{\mathrm{tot}}$, a better estimate of η_{M} in swimming humans was obtained than in previous studies. The values are still lower than those expected from the thermodynamics of muscle contraction (0.25–0.35 at optimal contraction speeds; Woledge et al., 1985), however. The 'gap' between the measured values of η_{M} and the optimal values of muscle efficiency could arise from an underestimation of $\dot{W}_{\mathrm{tot}}$, from an overestimation of $\dot{E}$ and (obviously enough) from muscle inefficiency itself.

Among the factors that might contribute to an overestimation of $\dot{E}$ (the metabolic power above resting conditions) is an underestimation of 'basal metabolic rate' (which was not measured in this study but assumed to be $3.5\,\mathrm{ml\,min^{-1}\,kg^{-1}}$), e.g. because a larger fraction of $\dot{E}$ is utilized for thermoregulation in water in respect to land locomotion. Moreover, as previously pointed out by Gaesser and Brooks (1975) for humans and Stevens and Dizon (1982) for warm-bodied fish, basal metabolic rate increases with progression speed/work rate. If this can be accounted for, higher values of η_{M} would result mainly at the higher investigated speeds.

Among the factors that can contribute to an underestimation of $\dot{W}_{\mathrm{tot}}$ (particularly in the case of LF) is the work done in deforming parts involved in thrust production. These are expected to be higher in LF (the fins' blade) than in L (the foot's sole).

As far as muscle efficiency itself is concerned, inefficiency should arise when the muscles are not working in the optimal range of either their force/length and/or force/speed relationships.

The leg kick is quite an ineffective way of using the lower limb muscles. The range of motion of the hip and knee joints is more restricted than in walking and cycling (an appreciable bending is observed only in the recovery, almost passive, phase of the cycle, see Fig. 2A) so that the leg extensors probably do not contract at their optimal length (maximal force of the knee extensors occurs at a knee angle of about 110 °; e.g. Narici et al., 1988).

The other factor that is known to affect muscle efficiency (and hence mechanical efficiency) is the contraction speed at which the muscles are working. From studies of muscle physiology, it is known that only at a given contraction velocity is the maximum efficiency reached (Woledge et al., 1985). While we did not directly measure the contraction speed of the lower limb extensor muscles, it is reasonable to assume that the kick frequency is strongly associated to it. Frequencies of about 1.0 Hz have been suggested as the optimum one for Type I fibres (in cycling; Sargeant and Jones, 1995). Fins decrease the kick frequency from 1.59 ± 0.25 Hz in L to 1.02 ± 0.25 Hz in LF conditions (average at all speeds and for all subjects) and hence are expected to increase η_{M} by allowing the muscles to work more efficiently (as found in this study and for other locomotory tools on land; see Minetti et al., 2001).

Performance efficiency (η)

The rate of useful work production divided by total rate of energy expenditure has been used as a measure of performance for many biological systems (Daniel, 1991). In the step diagram of Fig. 1, performance efficiency is defined as the ratio of useful power (necessary to generate thrust) to total energy expenditure ($\dot{W}_{\mathrm{d}}/\dot{E}$). This concept is useful for briefly summarizing the results found in this study.

Since fins do not affect $\dot{W}_{\mathrm{d}}$ (at comparable speeds), the increase in economy (42 %) observed when fins are used must produce an increase in performance; the ratio $\dot{W}_{\mathrm{d}}/\dot{E}$ is equal to 0.03–0.05 in L and 0.07–0.09 in LF and corresponds to a 77 % difference at comparable speeds. This increase is almost completely explicable on the basis of the observed increase of propelling efficiency (66 %). Of the increase in η_{P}, one third has to be attributed to an increase in η_{F} (13 %) and two thirds to an increase of hydraulic efficiency (40 %). The increase in η_{P} is obtained essentially through a 43 % decrease in K_{F} (which leads to a 74 % decrease of $\dot{W}_{\mathrm{int}}$) and through an increase in the propelling surface (3.5 times higher with fins), which allows for the acceleration of larger masses of fluid at lower speeds (Alexander, 1977).

Conclusions

A complete energy balance during swimming using the leg kick, with and without fins, was attempted by combining methodologies previously applied to human and fish swimming. From the combination of these techniques, the economy (C), total mechanical work (W_{tot}), propelling efficiency (η_{F}) and mechanical efficiency (η_{M}) of swimming were computed. While the breakdown of the individual components of performance efficiency helps in understanding why swimming with fins represents an advancement in human powered locomotion in water, the overall gain in propulsion is far from being commensurate with what muscles are expected to produce based on their performance in land locomotion. Despite the lowering of energy expenditure and an increase of $0.2\,\mathrm{m\,s^{-1}}$ in swimming speed at equivalent metabolic power, other solutions with different locomotory devices should be pursued to increase Froude efficiency (e.g. to decrease $\dot{W}_{\mathrm{k}}$), hydraulic efficiency (e.g. to decrease $\dot{W}_{\mathrm{int}}$) and muscle efficiency in order to further improve swimming performance in humans.

List of symbols

c	velocity of the backward wave
C	energy cost of swimming
D_{a}	added drag/added thrust
D_{b}	active body drag
E	total metabolic power
f	stride frequency
K_{D}	kick depth
K_{F}	kick frequency
$\mathrm{l_S}$	shank length
$\mathrm{l_T}$	thigh length
L	swimming without fins
L	fish length
LF	swimming with fins
Re	Reynolds number

s	speed of vertical movement of legs
t	time
T	wave period
T_I	trunk inclination
T'	underwater torque
v	average forward speed
$\dot{V}_{O_2}$	oxygen consumption
W_d	work needed to overcome drag that contributes to useful thrust
W_{ext}	external work
W_{int}	internal work
W_k	work needed to overcome drag that does not contribute to thrust
W_{tot}	total work
η	performance efficiency
η_F	Froude efficiency
η_H	hydraulic efficiency
η_M	mechanical efficiency
η_P	propelling efficiency
λ	wavelength

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