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ORIGINAL ARTICLE

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An energy balance of front crawl

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Abstract With the aim of computing a complete energy balance of front crawl, the energy cost per unit distance ($C = \dot{E}v^{-1}$, where $\dot{E}$ is the metabolic power and v is the speed) and the overall efficiency ($\eta_o = W_{tot}/C$, where W_{tot} is the mechanical work per unit distance) were calculated for subjects swimming with and without fins. In aquatic locomotion W_{tot} is given by the sum of: (1) W_{int}, the internal work, which was calculated from video analysis, (2) W_d, the work to overcome hydrodynamic resistance, which was calculated from measures of active drag, and (3) W_k, calculated from measures of Froude efficiency (η_F). In turn, $\eta_F = W_d/(W_d + W_k)$ and was calculated by modelling the arm movement as that of a paddle wheel. When swimming at speeds from 1.0 to 1.4 m s^{-1}, η_F is about 0.5, power to overcome water resistance (active body drag $\times$ v) and power to give water kinetic energy increase from 50 to 100 W, and internal mechanical power from 10 to 30 W. In the same range of speeds $\dot{E}$ increases from 600 to 1,200 W and C from 600 to 800 J m^{-1}. The use of fins decreases total mechanical power and C by the same amount (10–15%) so that η_o (overall efficiency) is the same when swimming with or without fins [0.20 (0.03)]. The values of η_o are higher than previously reported for the front crawl, essentially because of the larger values of W_{tot} calculated in this study. This is so because the contribution of W_{int} to W_{tot} was taken into account, and because η_F was computed by also taking into account the contribution of the legs to forward propulsion.

Keywords Swimming · Biomechanics · Energetics · Propelling efficiency · Fins

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Introduction

To compute a complete energy balance of front crawl, two parameters must be known: the energy expended to cover one unit distance and the efficiency with which this energy is transformed into mechanical work.

The energy cost per unit distance (C) is defined as: $\dot{E}\ v^{-1}$, where $\dot{E}$ is the net metabolic power expenditure, and v is the speed of progression.

The mechanical (overall) efficiency (η_O) is defined as: $\eta_O = W_{tot}\ C^{-1}$, where W_{tot} is the total mechanical work per unit distance.

In aquatic locomotion, W_{tot} is the sum of two terms: the work needed to accelerate and decelerate the limbs with respect to the centre of mass (the internal work, W_{int}) and the work needed to overcome external forces (the external work). The latter, in turn, can be further partitioned into: W_d, the work 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) (Alexander 1983; Daniel et al. 1992).

Of the three components of W_{tot}, only the term W_d can be "easily" quantified by using the standard methods to assess active or passive drag reported in the literature. On the other hand, the term W_k is a quantity quite difficult to assess, and we are not aware of methods for calculating W_{int} when swimming the front crawl.

W_{tot} can be calculated also on the basis of measures of propelling efficiency (η_P). Indeed, since η_P is defined as:

$$\eta_P = W_d / W_{tot} \quad (1)$$

once the terms W_d and η_P (for any given speed) are known, W_{tot} can be easily obtained by rearranging Eq. 1. Furthermore, when the terms W_d, W_{int} and W_{tot} (for any given speed) are known, W_k can also be easily calculated. Thus, in order to compute an energy balance of front crawl, the following parameters must be calculated: W_d, W_{int}, C and η_P.

To this aim: (1) we measured W_d and C, (2) we developed a new method to calculate W_{int} based on a three-dimensional (3D) kinematic analysis of the swimming movements, and (3) we revisited a simple model to calculate the η_P of the arm stroke. In this paper we also indicate a simple way to take into account the contribution of the legs to forward propulsion. Thus, we propose here a method to estimate the propelling efficiency of the front crawl as a whole, a parameter that, to our knowledge, has not been computed before.

Those calculations were applied to data collected in subjects swimming the front crawl with and without fins in order to investigate the effects of this locomotory tool on the propelling and overall efficiency of the front crawl and, last but not least, in order to test the sensitivity of our model to different experimental conditions.

Methods

Subjects

The experiments were performed on six elite college swimmers who were members of a Division I University men's swim team (State University of New York at Buffalo, N.Y.). Their average body mass was 71.1 (7.9) kg, their average stature 1.79 (0.08) m, and their average age 20.0 (1.3) years. 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 to participate.

The subjects were asked to swim the front crawl with (ALF) and without fins (AL); the experiments were carried out over a range of speeds (at 1.0, 1.1, 1.2, 1.3 and 1.4 m s^{-1}) that could be accomplished aerobically. Apollo Bio-Fin Pro fins were used in this study. Their characteristics are described in detail elsewhere (Zamparo et al. 2002).

The work to overcome water resistance

The active body drag (D_b) was measured as described in detail elsewhere (di Prampero et al. 1974; Zamparo et al. 2002). Briefly, the subjects swam in an annular pool, and were paced by a platform moving at constant speed above the swimmer's path. Known masses were attached to the swimmer by means of a rope which passed through a system of pulleys fixed to the platform in front of him, thus allowing the force to act horizontally along the direction of movement. This force (D_a) facilitates the swimmer's progression in water by pulling the subject forward and, at constant speed, it is associated with a consequent reduction in rate of oxygen uptake ($\dot{V}O_2$) The energy required to overcome D_b becomes zero when D_a and D_b are equal and opposite. The swimmer's D_b was estimated, at any given speed and condition, by back-extrapolating the $\dot{V}O_2$ versus D_a relationship to resting $\dot{V}O_2$. The power dissipated against drag was calculated from the product of the active body drag times the speed ($\dot{W}_d = D_b\ v$).

During the metabolic data collection (e.g. when the subject was swimming freely, without any added load) the kick frequency (KF, kicks per second, hertz) and the stroke frequency (SF, strokes per second, hertz) were also recorded.

The energy cost of swimming

The energy expenditure was calculated by measuring the steady-state $\dot{V}O_2$ (litres per minute), by a standard open-circuit method when swimming at constant speed (without any added load, $D_a = 0$). Net $\dot{V}O_2$ (above resting values, assumed to be equal to 3.5 ml min^{-1} kg^{-1}) was converted to watts assuming that 1 ml O_2 consumed by the human body yields 20.9 J (which is strictly true for a respiratory ratio of 0.96) and divided by the speed to yield the net energy cost of swimming per unit of distance (C) in kilojoules per minute (di Prampero 1986).

The internal work

W_{int} was estimated, in a separate series of experiments, by simulating the swimming movements outside water. In these experiments, the motion of the limbs was "decomposed" into two sub-movements: the leg kick and the arm stroke. The subjects were asked to lie on a swimming bench, to hyper-extend the arms over the head (the hands holding onto a support) and to simulate the leg kick by moving the legs at different frequencies (imposed by means of a metronome) that were selected to match the range of those utilized during actual swimming. A system of pulleys supported the legs via ankle straps in order to simulate the unloading conditions of underwater kicking. Alternatively, the legs (still supported by the pulleys) were fixed together and the subjects were asked to move only the upper limbs in such a way as to simulate the pattern of movement of the arm stroke they would have use during free swimming. Also in this case, the experiments were repeated at different frequencies to match the range of those utilized during actual swimming.

Eighteen reflective markers were put on relevant joints on the subject (nine per side), and a session of video sampling (100 Hz) was recorded at each frequency and condition by a 4-camera motion analysis system (ELITE, BTS, Italy). The 3D coordinates obtained were utilized to calculate the sum of the increases, in 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 (W_{int}) by means of a custom software package (Minetti 1998).

The calculations of internal mechanical power ($\dot{W}_{int}$) are based on the computation of the kinetic energy changes of the body segments with respect to the body centre of mass. The rationale for calculating $\dot{W}_{int}$ resides in the Koenig principle which states that, in a multi-segment system, the total kinetic energy is given by the sum of: (1) the kinetic energy of a point moving with the velocity of the centre of mass, and (2) the kinetic energy associated with the velocity of the particles relative to the centre of mass. It follows that the computation of the internal work is meaningful only if the movement of the two limbs is reciprocal (i.e. if it does not induce a change in the position of the centre of mass). Whereas in the leg kick the movement of the limbs is indeed reciprocal, this is not necessarily true for the arm stroke. Especially at low stroking frequencies, some of the subjects maintained one arm hyper-extended to the front while stroking with the contra-lateral (and vice versa), thus affecting the centre of mass position over time, and increasing the speed oscillations at each stroke.

The variation in the position of the centre of mass over time was therefore computed for both the arm stroke and the leg kick. In the leg kick the centre of mass was found to "move" in a 3D space of less than 1 cm^3, (indicating that this kind of movement is reciprocal, as expected), whereas in the arm stroke, variations in the centre of mass position of as much as 50 cm^3 were observed (mainly due to displacements on the *z* axis). In this study, the data in which the centre of mass position varied more than 5 cm^3 were discarded in the computation of $\dot{W}_{int}$. The discarded data corresponded mainly to low frequencies of movement, the arm stroke becoming more and more reciprocal as the speed (and hence the SF) increases. Hence, if any, care should be taken in calculating $\dot{W}_{int}$ based on measures of SF at slow stroke frequencies, a condition in which $\dot{W}_{int}$ is negligible in any case (see Results and Discussion).

From the relationship between $\dot{W}_{int}$ and KF and between $\dot{W}_{int}$ and SF experimentally determined, the internal work rate during actual swimming was computed based on the values of KF and SF actually measured during free swimming. The data of $\dot{W}_{int}$ due to the movements of the arms and the legs were finally summed together to calculate the internal work rate when swimming the front crawl.

The propelling and the Froude efficiency

A simple method to estimate the propulsion efficiency of the arm stroke was proposed by Martin et al. (1981). An even simpler model is proposed in this paper (described in detail in Appendix 1), which assumes that the arm is a rigid segment of length *l*, rotating at constant angular velocity ($\omega = 2\pi$ SF) about the shoulder, and in which the average efficiency is calculated over half a cycle (only for the underwater phase: from 0 to π). With this simplified model, the propulsion efficiency depends essentially on the ratio between the swimming speed and the stroke frequency (*v*/SF, e.g. the distance per stroke), which are the only variable parameters in the equation (on the assumption of l = constant, see Appendix 1):

$$\eta_{FA} = (v/(2\pi \text{ SF } l))(2/\pi) \tag{2a}$$

In Eq. 2a, *v* is the average forward speed of the swimmer, η_{FA} is the Froude efficiency (defined below) of the arm stroke, and the term *l* is the average shoulder to hand distance. The term *l* was calculated by assuming: (1) an average upper limb length of 0.575 m (as proposed by Martin et al. 1981), (2) an average elbow angle during the in-sweep of 130° (as reported by Payton et al. 1999), and (3) an equal arm and forearm length. From these calculations $l = 0.52$ m.

Two points must be underlined here. (1) When swimming the front crawl, the body is propelled forward by the combined action of legs and arms that contribute, in different proportion, to the progression speed. The contribution of the legs to total propulsion is of about 10–15% in terms of speed or power output (Bucher 1975; Deschodt et al 1999; Hollander et al. 1988). Hence, if the average forward speed of the swimmer is used, the efficiency of the arm stroke is overestimated. Hence, for the arm stroke when swimming the front crawl:

$$\eta_{FA} = ((v0.9)/(2\pi\, SF\, l))(2/\pi) \tag{2b}$$

(2) η_F and η_P are not synonymous. As indicated by Alexander (1983), η_F is the efficiency with which the external work produced by the muscles is transformed into useful work (thrust):

$$\eta_F = W_d/(W_k + W_d) \tag{3}$$

η_P is the efficiency with which the total work produced by the muscles is transformed into useful work (thrust):

$$\eta_P = W_d/(W_k + W_d + W_{int}) = W_d/W_{tot} \tag{4}$$

and hydraulic efficiency (η_H) is defined as:

$$\eta_H = (W_d + W_k)/W_{tot} \tag{5}$$

It is therefore apparent from Eqs. 3, 4 and 5 that the product of hydraulic and Froude efficiency yields the propelling efficiency ($\eta_H\ \eta_F = \eta_P$), and hence that the propelling efficiency will be equal to the Froude efficiency only in the case that $\eta_H = 1$ (e.g. $W_{int} = 0$). It also follows that a decrease in η_H (e.g. an increase in W_{int}) is necessarily associated with a decrease in η_P for any given η_F.

Hence, the efficiency obtained by using Eq. 2a and 2b is a Froude and not a propelling efficiency since the contribution of the internal work to total work production is not taken into account. Moreover, this is the Froude efficiency of the arm stroke only. To estimate the overall η_F in the front crawl, the contribution of the legs should be taken into account. As described in Appendix 2, if the swimmer is modelled as a system with two engines/propellers working in parallel, the overall Froude efficiency (η_{FAL}) of legs and arms together can be computed as:

$$\eta_{FAL} = \eta_{FL} 0.1 + \eta_{FA} 0.9 \quad (6)$$

where η_{FA} is the efficiency of the arm stroke (calculated according to Eq. 2b), and η_{FL} is the efficiency of swimming by using the leg kick only. The Froude efficiency of the leg kick (η_{FL}) was measured in a previous study (Zamparo et al. 2002) and found to be 0.60 when swimming without fins and 0.71 when swimming with fins, and to be unaffected by the speed (from 0.6 to 1.0 m s^{-1}). It is assumed here that these values still apply at the speeds investigated in this study (from 1.0 to 1.4 m s^{-1}).

The propelling efficiency, the total work and the mechanical efficiency

Once the terms η_F and W_d for the front crawl are known (for any given speed) it is easy to calculate W_k (rearranging Eq. 3). Once the term W_k for the front crawl is obtained, it can be added to the terms W_{int} and W_d to calculate W_{tot} for any given speed. Once the term W_{tot} is calculated, the propelling and hydraulic efficiencies can be computed (see Eqs. 4 and 5), and the mechanical efficiency of swimming the front crawl can finally be obtained.

Statistics

The regressions between $\dot{V}O_2$ and D_a for each condition were calculated by the sum of the least square linear analysis model. The differences in the measured variables (e. g. C, D_b, W_{int}...), as determined in the AL and ALF conditions at comparable speeds, were compared by the paired Student's t-test at matched speeds ($n = 30$ throughout). Values given are means (SD).

Results

C and KF and SF are reported in Figs. 1 and 2 as a function of the speed in both conditions (with and without fins). As shown in Fig. 1, fins decrease the energy cost of swimming the front crawl by about 10% at comparable speeds [ALF−AL = −0.070 (0.014) kJ m^{-1}, $P < 0.001$). The improvement in the economy of swimming is much lower than the 40% decrease in C as obtained when swimming by using fins compared with swimming with the leg kick alone (Zamparo et al. 2002).

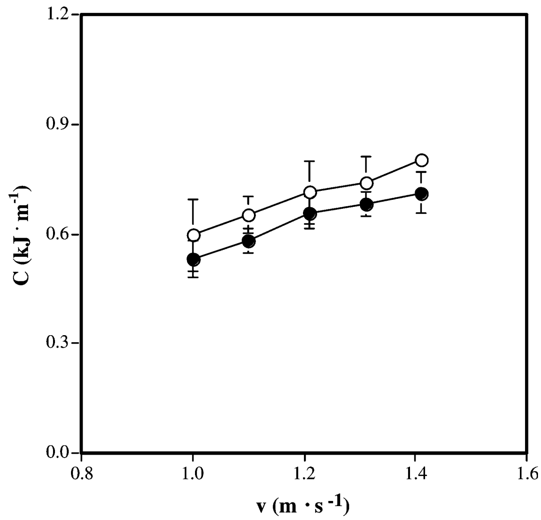

Fig. 1 Energy cost (C, kilojoules per metre) as a function of the speed (v, metres per second) when swimming the front crawl with (*open circles*) and without (*filled circles*) fins

As shown in Fig. 2, the use of fins decrease the KF [ALF−AL = −0.24 (0.04) Hz, $P < 0.001$) as well as the SF (ALF−AL = −0.06 (0.02) Hz, $P < 0.001$) when swimming the front crawl (about 20% in both cases). In comparison, the decrease in KF is larger (about 40%) when swimming by using fins compared with swimming with the leg kick alone (Zamparo et al. 2002). No differences in W_d were observed when swimming the front crawl at comparable speeds due to the use of fins ($P = 0.4$) as previously found for the leg kick alone (Zamparo et al. 2002).

The values of $\dot{W}_{int}$ as obtained in the simulated experiments outside water are reported in Fig. 3 as a function of the KF or SF (where $\dot{W}_{int}$ is in watts, and KF and SF are in hertz). The relationship between $\dot{W}_{int}$ and

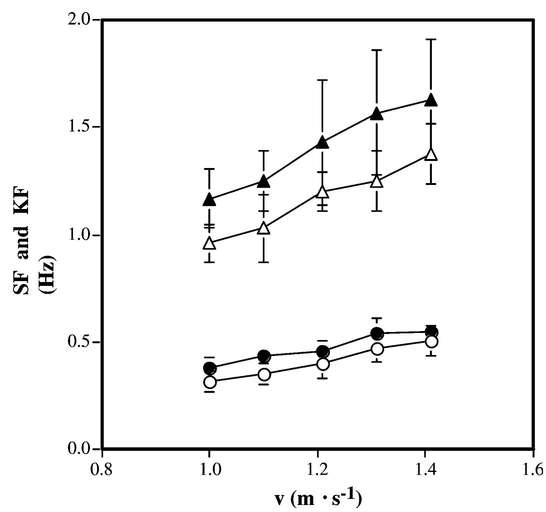

Fig. 2 Kick (*KF*, *triangles*) and stroke (*SF*, *circles*) frequency (hertz) of swimming the front crawl with (*open symbols*) and without (*filled symbols*) fins

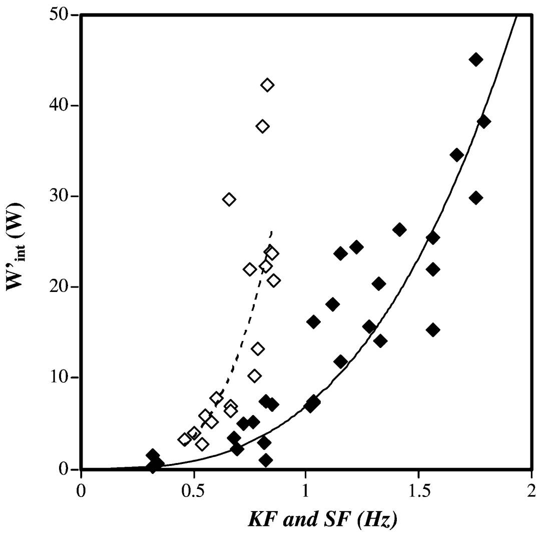

Fig. 3 The internal work rate ($\dot{W}_{\rm int}$, watts) as measured in the experiments of simulated swimming as a function of SF or KF frequency) for the arm stroke (*open diamonds*) and the leg kick (*filled diamonds*). The *continuous line* ($\dot{W}_{\rm int} = 6.9\ \mathrm{KF}^3$) indicates the relationship between $\dot{W}_{\rm int}$ and KF as measured during actual kick swimming. The *dashed line* interpolates the data of the simulated arm movements ($\dot{W}_{\rm int} = 38.2\ \mathrm{SF}^3$)

KF is well described by an equation of the form: $\dot{W}_{\rm int} = 6.9\ \mathrm{KF}^3$ (continuous line) and between $\dot{W}_{\rm int}$ and SF by: $\dot{W}_{\rm int} = 38.2\ \mathrm{SF}^3$ (dashed line). On the basis of these equations, $\dot{W}_{\rm int}$ during actual swimming was computed based on the values of KF and SF as measured during the swimming experiments. Overall $\dot{W}_{\rm int}$ was finally calculated as the sum of $\dot{W}_{\rm int}$ due to the leg kick and $\dot{W}_{\rm int}$ due to the arm stroke (see Table 1). As indicated in this table, the use of fins was found to reduce the internal work rate of front crawl swimming by about 40% (at comparable paired speeds). Due to the lower frequencies of the stroke as compared to the kick, the contribution of the arms movement to $\dot{W}_{\rm int}$ turned out to be rather small: only 4 W on average in the investigated frequency range.

The values of $\eta_{\rm FA}$ are reported in Table 2, along with the values of $\eta_{\rm FL}$ and the values of $\eta_{\rm FAL}$. Table 2 shows that there are no major differences among the values of Froude efficiency calculated by taking into account the contribution of the legs ($\eta_{\rm FAL}$) or not ($\eta_{\rm FA}$) to forward propulsion, provided that a correction is made for the speed of progression (that $\eta_{\rm FA}$ is calculated according to Eq. 2b and not according to Eq. 2a). Data reported in Table 2 also show that the use of fins improves not only $\eta_{\rm FL}$ but also $\eta_{\rm FA}$, so that $\eta_{\rm FAL}$ increases by about 15% when fins are used (at comparable paired speeds).

The values of power to give water kinetic energy ($\dot{W}_{\rm k}$), power to overcome water resistance ($\dot{W}_{\rm d}$), $\dot{W}_{\rm int}$ and total mechanical power ($\dot{W}_{\rm tot}$), as well as of $\dot{E}$ and C, measured / calculated at all speeds and in both conditions are reported in Table 3. From these data all the efficiencies can be computed, and their averages over the range of speeds investigated in this study are reported in Table 4. $\eta_{\rm FAL}$ and $\eta_{\rm P}$ were found to increase with the use of fins (by 17% and 22%, respectively), whereas $\eta_{\rm H}$ and $\eta_{\rm O}$ were found to be almost unaffected by the use of fins (differences of 5% and −6%, respectively).

The values of overall (mechanical) efficiency for the front crawl (with and without fins) are also reported in Fig. 4, along with the values of $\eta_{\rm O}$ as measured in a previous study (Zamparo et al. 2002) in subjects swimming by using the leg kick (with and without fins). In absolute terms, the values of $\eta_{\rm O}$ were found: (1) to increase with the speed, (2) to be about twice that measured when swimming by using the leg kick alone, and (3) to reach values comparable to those observed for human locomotion on land.

Discussion

In this paper a complete energy balance for front crawl swimming was attempted by considering the contribution of both the upper and lower limbs to forward

Table 1 Values of kick (*KF*) and stroke frequency (*SF*) at the investigated speeds (*v*) when swimming the front crawl with (*ALF*) and without fins (*AL*). The values of $\dot{W}_{\rm int}$ for the arm stroke ($\dot{W}_{\rm int}A$) and the leg kick ($\dot{W}_{\rm int}$L) were calculated as indicated in the text. The values of $\dot{W}_{\rm int}$ for the front crawl ($\dot{W}_{\rm int}AL$) are the sum of $\dot{W}_{\rm int}$L and $\dot{W}_{\rm int}$A

	v (m s^{-1})	KF (Hz)	SF (Hz)	$\dot{W}_{\rm int}$A (W)	$\dot{W}_{\rm int}$L (W)	$\dot{W}_{\rm int}$AL (W)
AL	1.0	1.17	0.38	2.0	11.0	13.0
	1.1	1.25	0.44	3.3	13.5	16.8
	1.2	1.43	0.46	3.6	20.3	23.9
	1.3	1.57	0.54	6.0	26.8	32.8
	1.4	1.63	0.55	6.3	29.9	36.2
ALF	1.0	0.96	0.32	1.2	6.1	7.3
	1.1	1.03	0.35	1.6	7.6	9.2
	1.2	1.20	0.40	2.5	11.9	14.4
	1.3	1.25	0.47	3.9	13.6	17.5
	1.4	1.38	0.51	4.9	18.2	23.1

Table 2 Values of Froude efficiency for the arm stroke (η_{FA}), the leg kick (η_{FL}) and the front crawl (η_{FAL}) at the investigated speeds while swimming with (ALF) and without (AL). See text for details. *SF* Stroke frequency, *SL* Stroke length (or distance per stroke), *v* average speed

Condition	*v* (m s^{-1})	SF (Hz)	SL (m)	$\eta_{\rm FA}$ (Eq. 2a)	$\eta_{\rm FA}$ (Eq. 2b)	$\eta_{\rm FL}$	$\eta_{\rm FAL}$
AL	1	0.38	2.67	0.52	0.47	0.60	0.48
	1.1	0.44	2.49	0.48	0.44	0.60	0.45
	1.2	0.46	2.63	0.51	0.46	0.60	0.48
	1.3	0.54	2.41	0.47	0.42	0.60	0.44
	1.4	0.55	2.56	0.50	0.45	0.60	0.46
ALF	1	0.32	3.16	0.61	0.55	0.71	0.57
	1.1	0.35	3.14	0.61	0.55	0.71	0.57
	1.2	0.40	2.99	0.58	0.52	0.71	0.54
	1.3	0.47	2.78	0.54	0.49	0.71	0.51
	1.4	0.51	2.77	0.54	0.48	0.71	0.51

Table 3 Average values of the power needed to overcome frictional forces ($\dot{W}_d$), to impart "unuseful" kinetic energy to the water ($\dot{W}_k$) and to overcome inertial forces ($\dot{W}_{int}$) when swimming ALF and AL at the indicated speeds (v). Data of total mechanical power ($\dot{W}_{tot}$), net metabolic expenditure ($\dot{E}$) and net energy expenditure per unit distance (C) are also reported. The last row reports the percentage differences between the AL and ALF condition

Condition	v (m s^{-1})	$\dot{W}_d$ (W)	$\dot{W}_k$ (W)	$\dot{W}_{int}$ (W)	$\dot{W}_{tot}$ (W)	$\dot{E}$ (W)	C (J m^{-1})
AL	1.0	52.5	56.8	13.0	122.3	595	597
	1.1	54.8	66.3	16.8	137.9	721	655
	1.2	73.6	81.3	23.9	178.8	857	714
	1.3	88.6	112.6	32.8	233.9	966	743
	1.4	96.9	112.3	36.2	245.4	1126	804
ALF	1.0	47.6	36.1	7.3	91.1	529	531
	1.1	57.5	44.0	9.3	110.8	639	581
	1.2	73.3	61.9	14.4	149.6	791	659
	1.3	89.3	86.0	17.5	192.8	888	683
	1.4	114.4	110.9	23.2	248.5	998	713
(ALF−AL)/AL	–	3 (10)%	−24 (13)%	−43 (4)%	−15 (10)%	−10 (2)%	−10 (2)%

propulsion. By taking into account all the three components of W_{tot}, values of mechanical efficiency of about 0.20 were calculated. The larger values of overall efficiency (η_O) (and hence the higher values of W_{tot} for a given C, see Eq. 1) obtained in this study with respect to previously published data are to be attributed to the three factors:

1. The term W_d was calculated by measures of active body drag instead of passive drag
2. For the first time the contribution of the internal work was taken into consideration in the computation of W_{tot}
3. The contribution of the leg kick to forward propulsion was also taken into account

The work to overcome drag resistance

The values of hydrodynamic resistance reported in this paper are larger than those reported in the literature and obtained by using different methods. The drag forces created when the swimmer is moving through water are higher than those that can be measured in a static position (as shown by Thayer, as reported by Maglischo 2003, by using an hand–arm model) and this could explain the difference between these values and passive drag measurements. Active drag can be measured by means of the measure active drag (MAD) system (e.g. Toussaint 1990; Toussaint et al. 1990) from measures of the force exerted by the swimmer on instrumented fixed pads positioned at the water surface. In the MAD set up, however, the legs are supported by a pull buoy and fixed together, thus reducing the frontal area of the swimmer, and reducing the effect of the movements of the lower limbs to the overall hydrodynamic resistance. This could explain why the values reported here are higher than those measured by means of the MAD system.

However, the method utilized in this paper is not free of criticism due to the fact that: (1) the subjects are swimming in an annular pool (and not in a straight line), and (2) the values of active body drag are obtained indirectly by measures of $\dot{V}O_2$.

(1) The annular pool has a radius of 9.55 m at the swimmer's path. For a subject of 70 kg body mass, the centripetal force will range from 7.3 N at 1 m s^{-1} to 14.4 N at 1.4 m s^{-1}, i.e. about 17% of the active body

Table 4 Average values (all subjects and all speeds) of the efficiencies measured in this study when swimming the front crawl with (*ALF*) and without (*AL*) fins. The last row reports the percentage difference between the AL and ALF conditions. η_O overall efficiency, η_P propelling efficiency, η_H hydraulic efficiency, η_F Froude efficiency

Condition	η_O	η_P	η_H	η_F
AL	0.21 (0.02)	0.40 (0.02)	0.87 (0.02)	0.46 (0.02)
ALF	0.20 (0.03)	0.49 (0.03)	0.92 (0.01)	0.54 (0.03)
(ALF−AL)/AL	-6 (12)%	22 (5)%	5 (1)%	17 (6)%

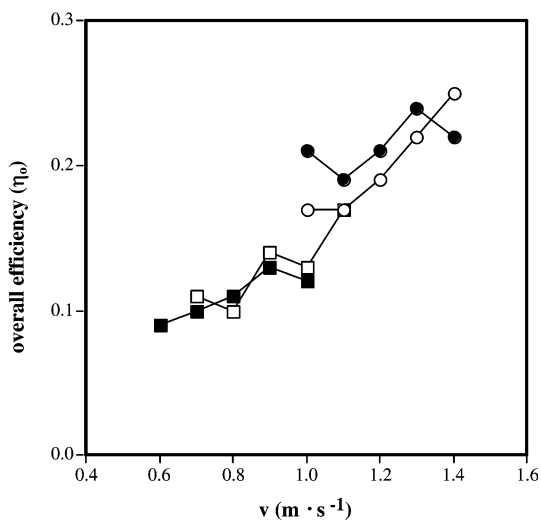

Fig. 4 Overall (mechanical) efficiency as a function of the speed (v) when swimming the front crawl with (*open circles*) and without (*filled circles*) fins. Data collected when swimming the leg kick with (*open squares*) and without (*filled squares*) fins are reported as a reference

drag at the same speed (50.1 N and 75.4 N, respectively, see Table 3). Centrifugal force points outward in the same plane as the drag force vector and is perpendicular to it. The resulting, overall force can be calculated to range from 50.6 N at 1 m s^{-1} to 76.8 N at 1.4 m s^{-1} i.e. about 1.5% larger than the drag force. Thus the difference between swimming in an annular pool or swimming in a straight line is indeed rather small.

(2) It can be debated whether the decrease of $\dot{V}O_2$ observed as a consequence of adding masses to the pulley system has to be attributed to changes in $\dot{W}_d$ 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 KF and SF: the higher D_a, the lower KF and SF. The observed reduction of $\dot{V}O_2$ for any given D_a has therefore to be also attributed to a decrease in $\dot{W}_{int}$ and $\dot{W}_k$ (both proportional to KF and SF). Since the contribution of these factors to total $\dot{V}O_2$ is large at $D_a = 0$ (during free swimming) and smaller 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 not affecting the determination of D_b.

It must be pointed out that the high values of mechanical efficiency calculated in this study strongly depend on the correct determination of D_b (*ceteris paribus*, a decrease of $\dot{W}_d$ of 50% leads to a decrease of η_O of the same amount). Therefore, until a more precise method to measure the active drag in aquatic locomotion is developed, the exact determination of the overall efficiency in water remains an open question.

The internal work rate

In a previous paper (Zamparo et al. 2002), the internal work rate of the leg kick was described by a model equation of the form: $\dot{W}_{int} = k(2\mathrm{KD})^2\ \mathrm{KF}^3$ (where KD is the kick depth and k is a value related to the inertia parameters of the moving body segments). In that previous study, a two-dimensional kinematic analysis was carried out to determine KD for each subject, speed and condition. The data analysis was simple and straightforward since the leg kick is a movement carried out essentially on the sagittal plane. Video data were also collected in this study, but, when swimming the front crawl, the subjects rolled so much that it was not possible to measure KD (a 3D kinematic analysis should have been done instead). In the previous study, it was however shown that, for practical purposes, a simpler equation of the form $\dot{W}_{int} = k\ \mathrm{KF}^3$ (where $k = 6.9$, $\dot{W}_{int}$ is in watts and KF in hertz) was accurate enough to calculate $\dot{W}_{int}$ at different speeds and in different conditions (with and without fins) because KD is almost unaffected by the speed (it can be included in the constant k), and the increase in speed is obtained essentially by an increase in KF. This relationship between $\dot{W}_{int}$ and KF^3 is indicated in Fig. 3 by the continuous line, while the diamonds represent the values of $\dot{W}_{int}$ as measured in this study by means of the ELITE system. This figure indicates that the experiments outside water reproduce the actual swimming condition well enough, at least for the leg kick. In the same figure the data obtained when simulating the arm stroke outside water are also reported, the dashed line interpolating the data is well described by an equation of the form: $\dot{W}_{int} = k\ \mathrm{SF}^3$ (where $k = 38.2$, $\dot{W}_{int}$ is in watts and SF in hertz). The pattern of movement in the arm stroke is similar, if any, to the circular motion of cycling, a case in which $\dot{W}_{int}$ is indeed related to f^3 (the cube of the cycling frequency) (Minetti et al. 2001).

The data of $\dot{W}_{int}$ reported in this study indicate the following. (1) The contribution of the internal work to $\dot{W}_{tot}$ due to the arm stroke is rather small (in the range of speeds investigated in this study). (2) The contribution of the internal work to $\dot{W}_{tot}$ due to the leg kick cannot be neglected, and it is responsible for the differences between Froude and propelling efficiency calculated in this study for the front crawl.

Hence, the kicking of the legs is the major determinant of the ''un-optimal'' hydraulic efficiency of the front crawl (η_H is about 0.9 when swimming with or without fins, see Table 4). This observation gives a quantitative explanation of the general understanding in swimming practice that it is better to use the leg kick as little as possible, i.e. for stabilizing the body and improving the propulsion of the upper limbs, rather than for obtaining an increase in propulsion directly from the action of the legs. The last statement obviously applies to ''non-sprint'' swimming races, where the efficiency of locomotion, rather than the power output, is the parameter to be maximized.

The propelling efficiency of the front crawl

All the methods proposed so far to measure η_P measured indeed the efficiency of the arm stroke. Toussaint and coworkers (1990, 1991, 1992) report values of propelling efficiency in the 0.45–0.75 range, not far from the (corresponding) values of η_{FA} reported here, i.e. 0.42–0.55 when swimming the front crawl with or without fins (see Table 2). In contrast, the values of efficiency reported by Martin and co-workers (1981) are much lower (about 0.20) than those reported here. This could be attributed to the fact that in their paper they did not take into account the average elbow angle during the in-sweep phase, but (implicitly) assumed a constant elbow angle of 180°. In this paper, we assumed an average elbow angle during the in-sweep of 130° (as reported by Payton et al. 1999), and hence we calculated an l value smaller that that reported by Martin and co-workers (1981). As indicated by Eq. 2a and 2b, lower values of l necessarily mean higher values of efficiency.

In the model presented in this paper, the forward speed of the swimmer is assumed to be constant, and the arm is assumed to move with a constant angular speed about the shoulder. Over a stroke cycle, propulsion and drag are unsteady and this obviously affects the Froude efficiency in different phases of the arm stroke. An analysis of the variations in drag and propelling efficiency during a stroke cycle was not included in the aims of this paper, and we preferred to use a steady-state approach by taking into account the net effect of these factors on the propelling efficiency of the front crawl, i.e. by utilizing the average values of v and SF over several cycles in the computation of η_F. Moreover, in the front crawl, the stroke is more symmetrical and the intracyclic variations in speed are rather small compared to other strokes (Craig and Pendergast 1979).

Eq. 2a and 2b indicates that an increase in propelling efficiency is associated with an increase in the distance per stroke. The notion that better swimmers distinguish themselves from the poorer ones by a greater distance per stroke (by a lower stroke frequency for a given speed) has been suggested and discussed by several authors (Craig and Pendergast 1979; Craig et al. 1985; Toussaint and Beek 1992). Both the model presented in this study and the model proposed by Martin and coworkers (1981) (which is based on the same theory of swimming propulsion) have the advantage of pointing out at the direct relationship between these two parameters.

The effect of using fins when swimming the front crawl

The results of this study confirm data and conclusions previously reported regarding the effects of passive locomotory tools in human locomotion (Minetti et al. 2001; Zamparo et al. 2002). For the same "gait" (e.g. bicycling, swimming the leg kick, swimming the front crawl), the improvement in the economy of locomotion due to the use of "tools" is not due to an increase in the (overall) efficiency of locomotion. It depends, rather, on a reduction of the overall work performed per unit distance. Indeed, the reduction in the energy demands due to the use of fins ($\dot{E}$, about 10%) is brought about by a proportional reduction in $\dot{W}_{tot}$, (about 15%) (see Table 3 and Eq. 1) so that the overall efficiency ($\eta_O = \dot{W}_{tot}/\dot{E}$) is the same when swimming with or without them.

Thus, fins reduce the energy requirements of swimming the front crawl mainly because they reduce the total mechanical work in water locomotion (internal and kinetic, the work against drag being unaffected by the use of fins). The use of fins is indeed associated with a slight increase in the hydraulic efficiency (about 5%, from 0.87 to 0.92, without and with fins, respectively), which is brought about by a 40% decrease in $\dot{W}_{int}$ when fins are used. Using fins also reduces the term $\dot{W}_k$ by about 20%, a reduction that is brought about by an equal increase in propelling efficiency.

It is interesting to note that the use of fins in the front crawl induces not only a decrease in the kick frequency, but also a decrease in the stroke frequency. The decrease in SF due to the use of fins is a necessary consequence of the fact that in the front crawl SF and KF are coupled (about 3:1 in these subjects). This indicates that this locomotory tool not only improves the propulsion efficiency of the lower limbs (Zamparo et al. 2002) but also influences, to some extent, the propulsion efficiency of the arms. As indicated in Table 4, when fins are used the propelling efficiency of the front crawl increases of about 20%, e.g. about twice the increase in efficiency that can be obtained by using hand paddles (Toussaint et al. 1991).

The effect of leg action in enhancing the overall propulsive force by improving the propulsive action of the arms has also been suggested by others. As an example, Deschodt and co-workers (1999) showed that not only the leg kick (in the full stroke) allows for a 10% increase in maximal speed in a 25 m sprint (in comparison with swimming with arms alone), but also that the leg kick directly influences the kinematics of the arm stroke modifying the wrist trajectory and increasing the stroke length (as found in this study).

The overall efficiency of swimming

Data presented in this study show: (1) that the front crawl (with or without fins) is indeed a more efficient way of moving in water than the leg kick (with or without fins) as indicated by other studies (Adrian et al 1966; Pendergast et al. 2003), (2) that the overall efficiency of the front crawl can be substantially higher than previously reported (di Prampero et al. 1974; Toussaint 1990; Toussaint et al. 1990), but (3) that it does not reach an optimum since η_O increases almost continuously from the slower speeds attainable with the leg kick to those attainable in the front crawl (see Fig. 4). As shown by Pendergast and coworkers (2003), the overall efficiency in water locomotion can reach optimal values (0.25–0.35) only at the speeds and loads attainable with hulls and boats.

The higher mechanical efficiency in the front crawl, with respect to the leg kick, is essentially attributable to a larger total mechanical output for an almost identical energy input ($\eta_O = \dot{W}_{tot}/\dot{E}$). Indeed $\dot{E}$ ranges from 0.3 to 1.0 kW in both cases, whereas $\dot{W}_{tot}$ ranges from 30 to 100 W in the leg kick (Zamparo et al. 2002), and is about two times larger, at any given speed, in the front crawl (present study). Due to the higher speeds attainable with the front crawl, similar values of $\dot{E}$ implies lower values of the energy expended to cover one unit distance ($C = \dot{E}/v$) with respect to the leg kick. Hence the economy of the front crawl is higher than that of the leg kick. In addition, in the front crawl, this energy is more effectively transformed into work per unit distance because higher loads can be produced and sustained. Hence the efficiency of the front crawl is higher that that of the leg kick. These data confirm previous hypotheses that the efficiency in swimming it is limited by the amount of force that can be applied to the water (Pendergast et al. 2003; Zamparo et al. 2002).

Conclusions

In this paper we proposed an energy balance for front crawl by considering the contribution of both the upper and lower limbs to forward propulsion. The larger values of η_O obtained in this study with respect to previous studies are to be attributed to the three factors: (1) the term W_d was calculated by measures of active body drag, (2) the contribution of W_{int} was taken into consideration in the computation of W_{tot}, (3) the contribution of the leg kick to forward propulsion was taken into account.

The model of arm propulsion proposed in this study is based on the Newtonian principle of action–reaction, and is a simplified version of that proposed by Martin and coworkers (1981). Even if this model can be considered too simple for describing the complex pattern of movement of the arm stroke, it gives values of propelling efficiency comparable to those reported in the literature, and obtained with far more complex calculations and set ups. Moreover, it has the advantage of pointing out at the direct relationship between the propelling efficiency and the ratio v/SF (i.e. the distance per stroke), a parameter that is largely utilized in common practice to assess swimming performance.

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Appendix 1

In subjects swimming by using the leg kick, η_F can be assessed by means of methods usually applied to the study of undulating fish (Zamparo et al. 2002), e.g. from measures of the speed of the backward wave travelling along the body and of the forward speed (Alexander 1983; Daniel et al. 1992; Lighthill 1975). The mode of propulsion of the arm stroke is, in contrast, more similar to the one adopted by "rowing" animals that move in water by producing power strokes, during which an appendage is accelerated backwards, and recovery strokes, during which the appendage returns to its original position moving forward (Alexander 1983; Daniel et al. 1992). Rowing animals proceed in water with oscillating speed, i.e. they accelerate in the power stroke and decelerate in the recovery stroke. However, as a first approximation, these oscillations can be considered negligible and the body can be assumed to move forward at constant speed (v) while the appendages move forward and backward with a velocity u relative to the body. As indicated by Alexander (1983) the ratio v/u is proportional to the theoretical (or Froude) efficiency (η_F).

The ratio v/u is directly (or inversely) proportional to the theoretical efficiency in all fluid machines: pumps, turbines, propellers, fans, water wheels and paddle wheels. As an example, the theoretical efficiency of a water wheel can be calculated from the ratio of the tangential velocity of the paddles (the rim speed, u) to the velocity of the headwater stream (v). In this case u is less than v because only a fraction of the kinetic energy of the water (and hence of the power input) goes into shaft power output. On the other hand, the theoretical efficiency of a paddle wheel can be calculated from the ratio of the average velocity of the boat itself (v) to the tangential velocity of the blades (the rim speed, u). In this case v is less than u because only part of the shaft power input goes into "useful" motion, whereas the remaining fraction is wasted in giving "un-useful" energy to the water. Generally speaking, in all turbo-machines, the theoretical (Froude) efficiency depends (among the others) on the velocity components of the fluid and rotor at the inlet and outlet sections (Fox and McDonald 1992).

Humans can be considered as "fluid machines" that obtain the thrust necessary to proceed at a given speed (v) by using two engines: the legs and the arms. As indicated above, for subjects swimming by using the leg kick alone, the term u can be obtained from measures of the speed of the backward wave travelling along the body (as in the case of slender fish). The problem is how to calculate u in the arm stroke. The simplest way to do so is to model the movement of the upper limbs as that of a paddle wheel, a case in which the term u can be easily calculated/estimated from measures of rim speed.

The model presented in this paper is a simplified version of the model proposed by Martin et al. (1981) and considers the arm as a rigid segment rotating at constant angular velocity about the shoulder (see Fig. 5). The model assumes that the body is moving through the water with a constant speed v (metres per second), and that the arms rotate with a stroke rate SF (hertz). As proposed by Martin et al. (1981), it is also assumed that the two arms are 180° out of phase, and that one arm enters the water when the other completes its stroke. Hence, the angular position of the arm is α (α

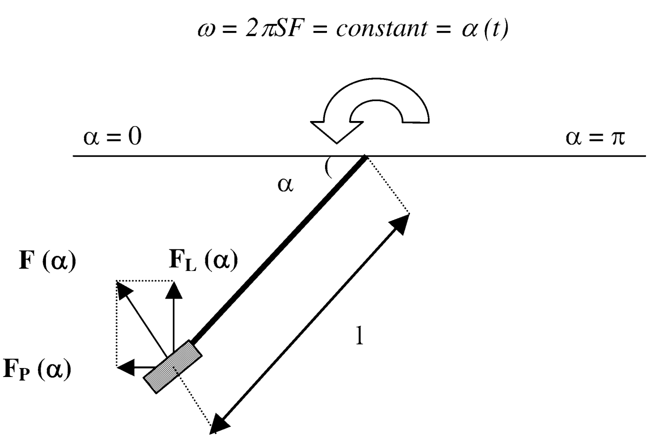

Fig. 5 Schematic representation of the arm stroke modelled in analogy to the movement of a paddle wheel (see text for details)

ranges from 0 to π), and the angular speed is: $\omega = \alpha(t) = 2\pi \mathrm{SF}$ (constant through the cycle), where t is time. The efficiency of this form of propulsion can be calculated as the ratio of useful work rate to total work rate. The useful work rate is given by the product of the propelling force (F_p) times the swimmer's velocity. In turn, F_p is the horizontal component of the force at the hand ($F(\alpha)$):

$$F_P(\alpha)v = F(\alpha)\ \sin\alpha\ v$$

From Newton's second law ($\Sigma F = m\dot{v}$), this force (the thrust) should be equal and opposite to the drag force:

$$F_p(v) - F_d(v) = m\dot{v}$$

where m is the mass of the swimmer and $\dot{v}$ his/her acceleration, that is assumed to be zero at constant speed (at steady state). Hence $F_p(v) = F_d(v)$.The total work rate can be calculated from the product of the moment about the shoulder ($F(\alpha)$ l) and ω:

$$F(\alpha)l\omega = F(\alpha)l2\pi\ \mathrm{SF}$$

The instantaneous efficiency is therefore:

$$\eta[\alpha(t)] = \frac{F(\alpha)\sin\alpha\ \ v}{F(\alpha)2\pi\ \mathrm{SF}\ l} = \frac{v\ \sin\alpha}{2\pi\ \mathrm{SF}\ l}$$

Over one "underwater cycle" (from 0 to π), the average efficiency is:

$$\overline{\eta} = \frac{v}{2\pi\ \mathrm{SF}\ l}\left(\frac{1}{\pi}\right)\int\limits_{\alpha=0}^{\alpha=\pi}(\sin\alpha)\mathrm{d}\alpha = \frac{v}{2\pi\ \mathrm{SF}\ l}\left[\frac{2}{\pi}\right]$$

which is equivalent to Eq. 2a reported in the text.In this last equation, the term ($v/2\pi$ SF l) is the ratio of forward speed to rim speed (v/u), whereas the term $2/\pi$ indicates that only half a cycle (the pushing phase) is made underwater, whereas the recovery phase is made on air. At variance with swimming humans, paddle wheels and water wheels "rotate" outside water and exert a force (at the rim) which is always tangential to the direction of the water stream. In those two cases, the Froude efficiency is indeed given by the ratio v/u. The term $2/\pi$ (0.637) indicates that the maximal Froude efficiency of the arm stroke should be less than 1 ($\eta_F = v/u$ 0.637) since the force exerted by the swimmer has both a horizontal (tangential to the water stream) and a vertical component (not useful for propulsion).

Appendix 2

To estimate the overall efficiency in the front crawl, the combined efficiency of the upper and lower limbs should be computed. This could be done by modelling the swimmer in analogy to a system with two engines/propellers working in parallel: the arms (A) and the legs (L). Since the two engines are not equal, each one will be characterized by its own efficiency (η), power output (PO) and power input (PI):

for legs $\eta_L = \mathrm{PO_L}/\mathrm{PI_L}$
for arms $\eta_A = \mathrm{PO_A}/\mathrm{PI_A}$
since $\eta_{AL} = \mathrm{PO_{AL}}/\mathrm{PI_{AL}}$
$\mathrm{PO_{AL}} = (\mathrm{PO_A} + \mathrm{PO_L})$
$\mathrm{PI_{AL}} = (\mathrm{PI_A} + \mathrm{PI_L})$
then $\eta_{AL} = [(\mathrm{PI_L}/\mathrm{PI_{AL}})\eta_L] + [(\mathrm{PI_A}/\mathrm{PI_{AL}})\eta_A]$
for $\mathrm{PI_L}/\mathrm{PI_{AL}} = k$
then $\eta_{AL} = \eta_L k + \eta_A(1-k)$

In these equations, PI and PO stand for mechanical power input and output (the efficiency here is a Froude efficiency) and the effects of a positive/negative influence–interaction between the "two engines/propellers" are not taken into consideration. However, this factor is likely to be partially accounted for by the partitioning in the total propulsion of arms ($1-k = 0.9$) and legs ($k = 0.1$), as experimentally determined by several authors on the basis of independent methods (Bucher 1975; Deschodt et al. 1999; Hollander et al. 1988).

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