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ORIGINAL ARTICLE

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Energetics of swimming at maximal speeds in humans

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Abstract The energy cost per unit of distance (C_s. kilojoules per metre) of the front-crawl. back. breast and butterfly strokes was assessed in 20 elite swimmers. At sub-maximal speeds (v). C_s was measured dividing steady-state oxygen consumption ($\dot{V}O_2$) by the speed (v. metres per second). At supra-maximal v. C_s was calculated by dividing the total metabolic energy (E. kilojoules) spent in covering 45.7. 91.4 and 182.9 m by the distance. E was obtained as: $E = E_{an} + \alpha \dot{V}O_{2max} t_p - \alpha \dot{V}O_{2max} \tau (1 - e^{-(t_p/\tau)})$, where E_{an} was the amount of energy (kilojoules) derived from anaerobic sources. $\dot{V}O_{2max}$ litres per second was the maximal oxygen uptake. α ($= 20.9$ kJ $\cdot$ l O_2^{-1}) was the energy equivalent of O_2, τ (24 s) was the time constant assumed for the attainment of $\dot{V}O_{2max}$ at muscle level at the onset of exercise. and t_p (seconds) was the performance time. The lactic acid component was assumed to increase exponentially with t_p to an asymptotic value of 0.418 kJ $\cdot$ kg^{-1} of body mass for $t_p \geq 120$ s. The lactic acid component of E_{an} was obtained from the net increase of lactate concentration after exercise ($\Delta[La]_b$) assuming that. when $\Delta[La]_b = 1$ mmol $\cdot$ l^{-1} the net amount of metabolic energy released by lactate formation was 0.069 kJ $\cdot$ kg^{-1}. Over the entire range of v. front crawl was the least costly stroke. For example at 1 m $\cdot$ s^{-1}, C_s amounted. on average, to 0.70. 0.84. 0.82 and 0.124 kJ $\cdot$ m^{-1} in front crawl. backstroke, butterfly and breaststroke, respectively: at 1.5 m $\cdot$ s^{-1}, C_s was 1.23. 1.47. 1.55 and 1.87 kJ $\cdot$ m^{-1} in the four strokes. respectively. The C_s was a continuous function of the speed in all of the four strokes. It increased exponentially in crawl and backstroke. whereas in butterfly C_s attained a minimum at the two lowest v to increase exponentially at higher v. The C_s in breaststroke was a linear function of the v. probably because of the considerable amount of energy spent in this stroke for accelerating the body during the pushing phase so as to compensate for the loss of v occurring in the non-propulsive phase.

Key words Energy cost of human locomotion · Swimming · Metabolic power · Maximal oxygen uptake · Lactate

Introduction

The amount of metabolic energy spent in transporting the body mass (m_b) of the subject over a unit of distance has been defined as the energy cost of locomotion (C di Prampero 1986): it is usually given in kilojoules per kilometre or in joules per metre per kilogram and it can be calculated either by including or by subtracting the energy turnover at rest.

The C has usually been assessed from the ratio between steady-state oxygen uptake ($\dot{V}O_2$) and the corresponding speed (v) of progression (di Prampero 1986). This methodology precludes the assessment of C at speeds greater than those corresponding to the subject's maximal O_2 consumption ($\dot{V}O_{2max}$). In a few studies, the lactic acid contribution to the overall metabolic power has also been considered (Capelli et al. 1998), thus extending the range of investigated into those where the use of anaerobically derived energy becomes significant. Some recent studies in running (Hautier et al. 1994; Lacour et al. 1990) and crawl swimming (Ogita et al. 1996) have investigated v which were extended above the range for aerobic metabolism but far below those attained during actual short distance competitions.

The aim of the present study was to determine the energy cost of swimming (C_s) at v ranging from moderate, in which metabolism was completely aerobic, to

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maximal over competition distances (45.7 m, 91.4 m and 182.9 m) and times (from about 24 to about 150 s). In addition, the assessment of C_s was not limited to the front crawl stroke, as has often been the case in the past (Holmér 1974; McArdle et al. 1971; Monpetit et al. 1988; Pendergast et al. 1977; Toussaint et al. 1988; Van Handle et al. 1988), but included also back, breast and butterfly strokes.

Methods

Subjects

This study was performed on 20 elite male college swimmers. The $\dot{V}O_{2\max}$, main anthropometric characteristics of the subjects and average best performance times over several distances in the four strokes are given in Table 1, along with the stroke used by the subject throughout the study. All the subjects were informed about the methods and aims of the study and gave their written consent. Measurements were carried out on three different occasions during the period of the study, September to March, but not all 20 subjects were tested on the same occasion. Of the 20 subjects 3 were evaluated during the month of September, 16 in December of the same year and 1 in the following March. The body surface area of the subjects was obtained from body mass and stature (Dubois and Dubois 1915).

C_s at sub-maximal v and $\dot{V}O_{2\max}$

The C_s at sub maximal v and $\dot{V}O_{2\max}$ were measured using an open circuit method during incremental exercise in an annular pool 2.5-m wide, 2.5-m deep and 60-m in circumference over the swimmer's course. The hoses and the two-way respiratory valve were positioned so as to keep the added drag to a minimum (Toussaint et al. 1990). The swimmers were paced by a platform moving at constant v above the water surface as has been described before (Capelli et al. 1995; di Prampero et al. 1974; Zamparo et al. 1996). The first v of the incremental test depended on the stroke used by the subject and ranged from 0.79 to 0.96 $m \cdot s^{-1}$ from breast to crawl stroke, respectively. Water v was measured by means of an impeller (PT - 301 hand-held probe, MEAD, Riverdale, N.Y., USA) connected to a tachometer (F1-12P portable indicator, MEAD, Riverdale, N.Y., USA) immersed in the water 1.5 m in front of the swimmer and moving with the platform.

At 3 min after the onset of swimming, the expired gases were collected through a waterproof inspiratory-expiratory valve into an aerostatic balloon (time of collection 60 s). After that, the v was increased by 0.12 $m \cdot s^{-1}$, for front crawl, or by 0.07 $m \cdot s^{-1}$ for all the other strokes and, after 3 min of swimming at the new v, the gas collection was repeated. The v was repeatedly increased by the same increment until the subject was unable to maintain the speed paced by the platform for the required time (2.5 min). The $\dot{V}O_2$ measured during the last complete step was considered to represent the individual's $\dot{V}O_{2\max}$. The expired gasses during the last increment were collected for at least 30 s. The O_2 and CO_2 fractions in the expired air were determined using a previously calibrated paramagnetic O_2 analyser (Beckman C2, Palo Alto, Calif., USA) and an

Table 1 Main anthropometric characteristics and maximal oxygen uptake ($\dot{V}O_{2\max}$) of all the subjects tested. The time of year when the subject was tested and the average best performance times are also given. *BSA* Body surface area, $\dot{V}O_{2\max}$ maximal oxygen consumption including oxygen consumption at rest

Subject	Style	Age (years)	Height (cm)	Body mass (kg)	BSA (m^2)	$\dot{V}O_{2\max}$ ($l \cdot min^{-1}$)	Period (month, year)	Average best performance times (min:s)	Distance (m)	Stroke
DB	Crawl	21	190.5	76.7	2.04	5.05	12, 1993	0:22.2	45.7	Crawl
CB	Crawl	21	187.9	83.1	2.09	4.35	12, 1993	0:49.4	91.4	Crawl
MH	Crawl	18	182.9	69.8	1.91	4.52	12, 1993	1:46.7	182.9	Crawl
DM	Crawl	18	188.0	81.4	2.08	4.23	9, 1993	4:51.1	457.2	Crawl
JP	Crawl	18	182.9	83.7	2.06	4.95	12, 1993	0:54.6	91.4	Backstroke
SS	Crawl	19	177.8	72.6	1.90	4.08	12, 1993	1:54.9	182.9	Backstroke
LJ	Crawl	18	180.3	70.2	1.89	3.62	12, 1993	1:2.2	91.4	Breaststroke
CW	Crawl	19	180.3	76.8	1.96	3.95	12, 1993	2:23.3	182.9	Breaststroke
DH	Backstroke	19	188.0	77.9	2.04	4.96	12, 1993	0:52.4	91.4	Butterfly
KM	Backstroke	18	187.9	68.2	1.93	3.52	12, 1993	1:48.8	182.9	Butterfly
JP	Backstroke	20	182.9	74.6	1.96	3.87	12, 1993			
RA	Breaststroke	18	193.0	75.7	2.05	4.62	12, 1993			
LB	Breaststroke	19	177.8	67.5	1.84	3.27	12, 1993			
ED	Breaststroke	18	185.9	83.3	2.08	4.59	3, 1994			
IS	Breaststroke	19	172.7	68.3	1.81	3.98	12, 1994			
RW	Breaststroke	19	182.9	66.2	1.86	4.12	9, 1993			
MZ	Breaststroke	19	194.3	83.6	2.15	4.80	12, 1993			
KM	Butterfly	19	188.0	88.3	2.15	4.18	12, 1993			
SPN	Butterfly	19	177.8	73.4	1.91	4.03	12, 1993			
JIS	Butterfly	20	180.3	76.6	2.04	4.20	9, 1993			
	Mean	18.9	184.1	75.9	1.99	4.24				
	SD	0.94	5.62	6.44	0.10	0.49				

infrared CO_2 meter (Beckman LB-1, Palo Alto, Calif., USA); the gas volume was measured using a dry gas meter (Harvard Apparatus, South Natick, Mass., USA).

The C_s at v up to $\dot{V}O_{2max}$ was calculated from the ratio between overall $\dot{V}O_2$ (millilitres of oxygen per second) and speed (metres per second). The C_s was converted into kilojoules per meter assuming that the metabolic energy equivalent of one l O_2 standard temperature and pressure, dry amounted to 20.9 kJ (a fact which is strictly true only if the respiratory quotient = 0.98).

C_s at maximal v

The C_s at v faster than the maximal aerobic v (supra maximal) were obtained in the four strokes as follows. During the 2 days following the test in the annual pool, the subjects swam at their maximal voluntary v in a swimming pool 2, 4 and 8 laps of a 22.9-m lane corresponding to distances of 45.7, 91.4 and 182.9 m. The subjects were allowed to warm up for 5 to 10 min swimming at low v less than 70% of their individual $\dot{V}O_{2max}$, as estimated from the $\dot{V}O_2$ versus v relationship determined during the incremental test. The subjects started from the block but they did not perform a regular turning motion at the end of the lane. Hence, after the turn, they did not push against the end of the pool, but resumed swimming immediately without gliding underwater. The average v (in metres per second) maintained by the subject during the trial was obtained by dividing the distance by the total time (seconds) of the trial measured using the electronic timing system routinely used for competitions. After the trial, the subject sat by the side of the pool. At the 5th and 7th min of recovery, i.e. when the blood lactate concentration ($[La]_b$) after swimming has been shown to reach a peak (di Prampero et al. 1978; di Prampero 1981), blood samples were withdrawn from an antecubital vein and immediately poured into ice-cold 0.6-mol perchloric acid. The samples were analysed for $[La]_b$ (millimol $\cdot$ l^{-1}) using an enzymatic method (Stat-Pack Lactate Test, Behring Diagnostics Inc., Somerveille, N.J., USA) (Gerken 1960). The subject was then allowed to cool down (10 min) and rest for at least 40–60 min before swimming the maximal trial. This recovery interval has been estimated as being sufficient to repay completely the lactic acid oxygen debt (di Prampero 1981). The three distances were covered in series from the shortest to the longest.

The amount of metabolic energy spent during supra maximal swims (E, kilojoules) was assumed to be the sum of three terms (see also Fig. 1):

$$E = E_{an} + \alpha \dot{V}O_{2max} t_p + \alpha \dot{V}O_{2max} \tau (1 - e^{-t_p \tau^{-1}}) \quad (1)$$

where α is the energy equivalent for O_2, assumed to be equal to 20.9 kJ $\cdot$ l^{-1} (see above), τ is the time constant for the attainment of $\dot{V}O_{2max}$ from the onset of exercise. E_{an} is the amount of energy derived from the use of anaerobic energy stores. t_p is the performance time, and $\dot{V}O_{2max}$ (litres per second) includes $\dot{V}O_2$ at rest. Equation 1 has been derived, after marginal transformations, from the original equation proposed by Wilkie (1980) and the theory behind it has been thoroughly explained and discussed elsewhere Capelli et al. 1998 di Prampero et al. 1993; Toussaint and Hollander 1994). The variables appearing in Eq. 1 were either calculated or assumed as follows: $\dot{V}O_{2max}$ was that assessed during the incremental test in the annular pool which, multiplied by α, yielded the maximal aerobic power (MAP, kilowatts) of the subject. The $\dot{V}O_2$ at the muscle level was assumed to attain $\dot{V}O_{2max}$ with a time constant (τ) of 24 s, as has been measured by nuclear magnetic resonance spectroscopy (Binzoni et al. 1992). The E_{an} was the sum of the energies obtained from lactic acid production (see Fig. 1), as estimated from $[La]_b$, plus the energy derived from maximal depletion of phosphocreatine (PCr) in the working muscles:

$$E_{an} = (0.418\,\text{kJ} \cdot \text{kg}^{-1} + \beta [La]_b) m_b \quad (2)$$

where E_{an} is in kilojoules, m_b (in kilograms) is the body mass of the subject. β is the energy equivalent of La accumulation in the blood, which has been assumed to be equal to 0.0689 kJ $\cdot$ kg^{-1} $\cdot$ $mmol^{-1}$ (di Prampero 1981), and $[La]_b$ is the peak blood lactate concentration after exercise above resting (assumed = 1 mmol $\cdot$ l^{-1}). In turn, 0.418 kJ $\cdot$ kg^{-1} in Eq. 2 corresponds to the net splitting of 18.5 mmol of phospocreatine (PCr) per kilogram of wet muscle in a maximally working muscle mass equal to 30% of the overall body mass (Corresponding to 22.8 kg in our subjects). Since this value strictly applies only within the age range 21–30 years, in younger athletes, it has been adjusted for age (Cerretelli et al. 1968): in subjects aged 18–19 years, it amounted to 0.393 kJ $\cdot$ kg^{-1}, and in 20 year-old athletes it equalled 0.407 kJ $\cdot$ kg^{-1}. Finally, the actual amount of energy derived from PCr splitting at the onset of exhausting exercise was assumed to increase with the exercise duration with a time constant (τ_{al}) of 23.4 s, as has been described by Medbø and Tabata (1993).

The values of E calculated for each individual maximal swim were then divided by the distance covered (d, metres) to yield (kilojoules per metre).

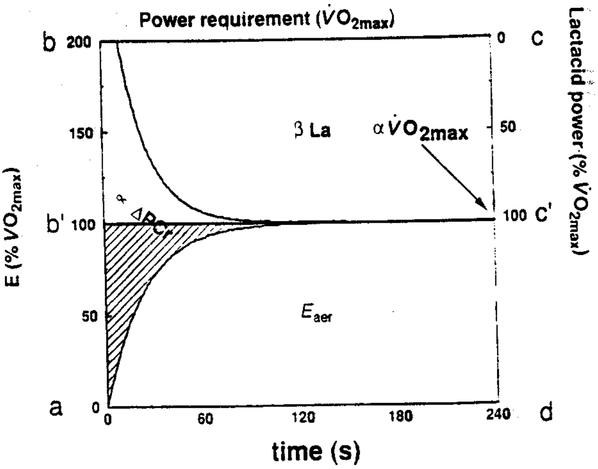

Fig. 1 Diagram of the energetics of hypothetical supra-maximal exercise the intensity of which is assumed to be 200% maximal oxygen intake ($\dot{V}O_{2max}$). *Upper horizontal line* is the power required to swim the distance at a given speed v. Thus, the overall energy spent during the swim (E see Eq. 1 in text) is given by the rectangle *a b c d*. The oxygen uptake ($\dot{V}O_2$) increases rapidly at the onset of the swim to attain $\dot{V}O_{2max}$ monoexponentially with a time constant $\tau \approx 24$ s. The energy derived from aerobic sources E_{aer} is given by the rectangle *a b' c' d*, adjusted for the *hatched area*. This is expressed mathematically by the 3rd term of Eq. 1 in text. The energy derived from net lactate production (βLa) and that obtained from net phosphocreatine (PCr) breakdown ($\alpha \Delta PCr$) are also indicated. The latter lies *to the left of the curves* indicating the $\dot{V}O_2$ and La production rates at the onset of exercise: it is indicated mathematically by the 1st term of Eq. 2 in text. Finally, the sum of βLa and ΔPCr yields the overall energy obtained from anaerobic sources E_{an} in Eq. 1 in text). The time delay with which La production sets in as well as its time course, are largely hypothetical

Statistics

Regressions were calculated by means of a least-squares-methods provided by a graphical and statistical package (Systat, Evanston, Ill., USA). The differences among peak $[La]_b$ assessed at the end of maximal trials were evaluated using a two-way ANOVA and the *post-hoc* test of Bonferroni (Box et al. 1978). Differences among the exponents and the coefficients of the exponential regressions were analysed using an analysis of covariance after their linearisation (Armitage 1971).

Results

The average v and C_s measured during the tests in the annular pool for v up to that yielding $\dot{V}O_{2max}$ are reported in Table 2 for the four strokes.

Table 2 Energy cost of swimming (C_s) in all the subjects and all the strokes measured during the tests in the annular pool at speeds up to maximal oxygen uptake ($\dot{V}O_{2max}$). *n* Number of subjects. Speed *speed* maintained during the swim. At speeds below $\dot{V}O_{2max}$, the standard deviation of the speed (SD) was nil since the subjects swam at the same speed as that imposed by the platform. C_s Gross energy cost of swimming

Stroke	*n*	Speed ($m \cdot s^{-1}$)		C_s ($kJ \cdot m^{-1}$)	
		Mean	SD	Mean	SD
Crawl	8	0.96		0.75	0.107
		1.14		0.80	0.127
		1.24		0.91	0.164
		1.34		0.99	0.169
		1.42	0.048	1.04	0.116
Backstroke	3	0.86		0.78	0.051
		0.93		0.81	0.117
		1.00		0.84	0.117
		1.07		0.90	0.085
		1.14		0.95	0.025
		1.21		0.99	0.097
		1.32	0.040	1.09	0.188
Breastsroke	6	0.79		1.02	0.107
		0.86		1.09	0.112
		0.93		1.16	0.094
		1.00		1.29	0.120
		1.09	0.084	1.35	0.142
Butterfly	3	0.86		0.98	0.069
		0.93		0.90	0.060
		1.00		0.84	0.104
		1.07		0.92	0.089
		1.14		0.96	0.089
		1.27	0.069	1.09	0.104

The average values of v, $[La]_b$ and C_s obtained during the supra-maximal trials are reported for each d and for all subjects in Table 3 together with the contribution to the overall metabolic power output (kilowatts) of the aerobic, anaerobic lactic acid and anaerobic alactic acid energy sources. The average $[La]_b$ at the end of the shortest trial turned out to be significantly less [9.30 (SD 2.37) mmol · l^{-1}, $P < 0.05$] than those measured at the end of the two longer swims, which amounted, on average, to 12.6 (SD 2.35) and to 13.1 (SD 3.39) mmol · l^{-1} respectively. The estimated percentages of the overall metabolic energy output obtained:

1. From the amount of O_2 taken up from the environment (E_{aer}, %)
2. From anaerobic glycolysis (E_{anlac}, %) and
3. From the splitting of the high energy phosphate of the muscles (E_{analac}, %) are also reported in Table 4.

The average metabolic power output maintained by the subjects during maximal trials in the four strokes was calculated from the ratio of Eq. 1 to t_p and amounted to 129.4 (SD 6.79)% of individual MAP for an average swimming time of 137.2 (SD 10.60) s, to 169.3 (SD 21.38)% for an average time of 58.8 (SD 8.26) s and to 204.4 (SD 38.45)% for an average time of 26.7 (SD 3.56) s.

The average anaerobic contribution to the overall metabolic power output calculated during the maximal trials amounted to 2.82 (SD 0.21) kW, 1.63 (SD 0.41) kW, and 0.71 (SD 0.13) kW in the four distances of 45.72, 91.44, and 182.88 m, respectively. These values were the sum of the E_{anlac} contribution [1.67 (SD 0.52) kW, 1.11 (SD 0.35) and 0.44 (SD 0.14) kW] plus that from the PCr splitting [1.15 (SD 0.21), 0.52 (SD 0.09) and 0.24 (SD 0.04) kW]. This implied that 24.6 (SD 3.88)%, 43.0 (SD 8.56)% and 54.2 (SD 9.74)% of the total power output was derived from E_{anlac} sources.

Table 3 *Distance, Speed*, blood lactate concentration ($[La]_b$), energy cost of swimming C_s, together with the contribution of aerobic (E_{aer}), anaerobic lactic acid (E_{anlac}), and anaerobic alactic acid (E_{analac}) energy sources to the overall metabolic power output for all subjects during maximal trials. *Distance* Distance covered during maximal trials, *n* number of subjects. *Speed* average speed maintained during maximal trials. $[La]_b$ gross peak lactate concentration assessed in the recovery phase after maximal swim. C_s overall energy cost of swimming

Distance (m)	Stroke	*n*	Speed ($m \cdot s^{-1}$)		$[La]_b$ mmol · l^{-1}		C_s ($kJ \cdot m^{-1}$)		E_{aer} (kW)		E_{anlac} (kW)		E_{analac} (kW)	
			mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
45.7	Crawl	8	1.97	0.07	9.9	2.16	2.25	0.199	0.56	0.053	1.94	0.428	0.83	0.091
	Backstroke	3	1.73	0.05	11.1	1.05	2.37	0.146	0.56	0.103	1.93	0.253	0.75	0.062
	Breaststroke	6	1.50	0.10	7.7	2.98	1.79	0.389	0.65	0.073	1.09	0.392	0.69	0.100
	Butterfly	3	1.85	0.08	9.3	0.35	2.39	0.276	0.54	0.026	1.85	0.215	0.83	0.081
		20	1.75	0.20	9.3	2.37			0.58	0.074	1.67	0.523	0.78	0.105
91.4	Crawl	8	1.75	0.05	10.5	2.74	1.73	0.16	0.90	0.089	1.29	0.260	0.53	0.048
	Backstroke	3	1.64	0.03	12.4	0.81	1.64	0.194	0.88	0.157	1.05	0.155	0.48	0.041
	Breaststroke	6	1.34	0.09	11.9	5.18	1.67	0.350	0.99	0.110	0.81	0.423	0.40	0.070
	Butterfly	3	1.63	0.11	14.1	2.37	1.84	0.145	0.88	0.044	1.26	0.083	0.51	0.053
		20	1.59	0.19	13.1	3.39			0.92	0.105	1.10	0.349	0.48	0.075
182.9	Crawl	8	1.62	0.05	11.4	1.60	1.28	0.113	1.19	0.128	0.48	0.079	0.27	0.026
	Backstroke	3	1.52	0.03	13.9	1.34	1.34	0.192	1.15	0.205	0.55	0.100	0.24	0.021
	Breaststroke	6	1.23	0.09	13.1	3.38	1.54	0.210	1.24	0.152	0.41	0.127	0.19	0.038
	Butterfly	3	1.41	0.01	13.5	1.67	1.43	0.066	1.18	0.054	0.52	0.093	0.23	0.007
		20	1.45	0.19	11.9	2.76			1.20	0.134	0.47	0.060	0.24	0.042

Table 4 Percentage contribution of aerobic (E_{aer}), anaerobic lactic acid (E_{anlac}) and anaerobic alactic acid sources (E_{analac}) of energy to the overall energy expenditure for all subjects during maximal trials. *Distance* Distance covered during maximal trials. *n* number of subjects. *Speed* average speed maintained during maximal trials

Distance (m)	Stroke	*n*	Speed (m · s^{-1})		E_{aer} (%)		E_{anlac} (%)		E_{analac} (%)	
			mean	SD	mean	SD	mean	SD	mean	SD
45.7	Crawl	8	1.97	0.07	15.3	6.06	58.9	8.36	25.8	4.16
	Backstroke	3	1.73	0.05	17.4	3.10	59.4	3.81	23.1	0.74
	Breaststroke	6	1.50	0.10	27.1	2.86	43.7	8.10	29.3	5.59
	Butterfly	3	1.85	0.08	16.9	1.50	57.3	1.40	25.9	0.20
		20	1.75	0.20	19.4	6.64	54.2	9.74	26.4	4.37
91.4	Crawl	8	1.75	0.05	33.3	2.30	47.2	4.61	19.6	2.51
	Backstroke	3	1.64	0.03	36.4	2.69	43.6	1.96	20.0	1.31
	Breaststroke	6	1.34	0.09	46.5	8.06	34.8	11.16	18.7	3.61
	Butterfly	3	1.63	0.11	33.3	1.13	47.5	2.67	19.2	2.29
		20	1.59	0.19	37.7	7.47	43.0	8.56	19.3	2.59
182.9	Crawl	8	1.62	0.05	61.5	2.46	24.7	2.81	13.8	0.20
	Backstroke	3	1.52	0.03	59.2	0.97	28.2	0.53	12.6	1.21
	Breaststroke	6	1.23	0.09	67.9	4.21	21.7	4.39	10.4	1.29
	Butterfly	3	1.41	0.01	61.1	4.13	26.6	4.10	12.3	0.04
		20	1.45	0.19	63.0	4.48	24.6	3.88	12.4	1.81

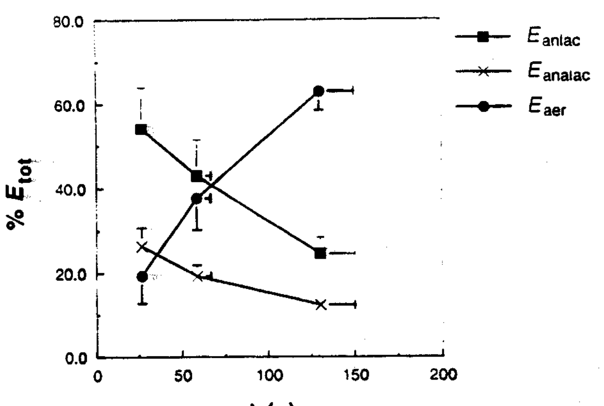

Fig. 2 The percentages of the total metabolic power output (%E_{tot}) derived from aerobic, anaerobic alactacid acid and anaerobic lactic acid energy sources are represented as a function of the average time (t) necessary to swim maximal voluntary trials. Points have been obtained by pooling individual values regardless of the stroke utilised by the subject. For other definitions see Tables 3 and 4

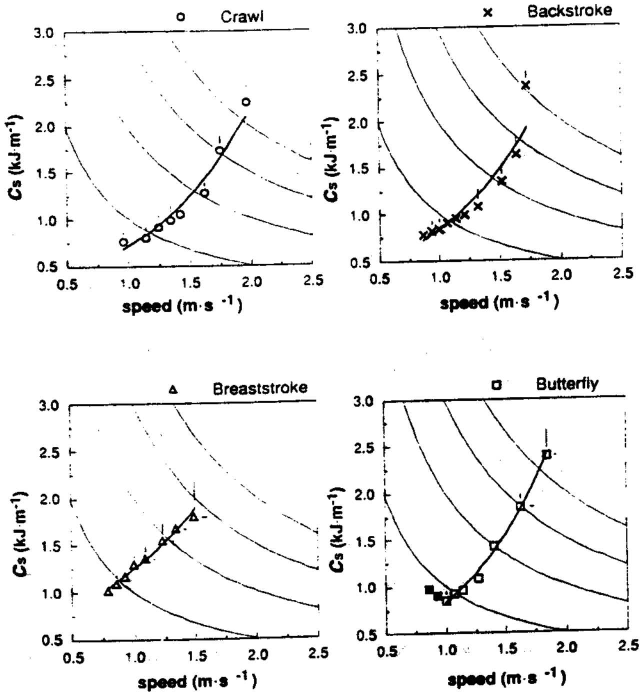

Fig. 3 Average values of the energy cost of swimming (C_s) in the four strokes as a function of the speed. Regressions were calculated from all individual values with the exception of the butterfly stroke where only the *unfilled symbols* were used. Front crawl: $y = 0.228\ 10^{0.488x}$, $r^2 = 0.960$; Backstroke: $y = 0.270\ 10^{0.491x}$, $r^2 = 0.922$; Breaststroke: $y = 0.548\ 10^{0.355x}$, $r^2 = 0.981$; Butterfly: $y = 0.234\ 10^{0.547x}$, $r^2 = 0.993$). The *curves* in each diagram are isopleths corresponding to constant values of metabolic power equal to 1, 2, 3 and 4 kW (*from bottom to top*)

whereas 12.4 (SD 1.81)%, 19.3 (SD 2.59)% and 26.4 (SD 4.37)% were obtained from the splitting of the high energy phosphate from the longest to the shortest trial, respectively (see Fig. 2).

The amount and the fraction of the overall metabolic power provided by aerobic sources increased with the d covered. They amounted to 0.583 (SD 0.074) kW and to 19.4 (SD 6.64)% in the shortest trial (45.72 m), to 0.92 (SD 0.105) kW and to 37.7 (SD 7.47)% in the middle distance (91.44 m) and to 1.20 (SD 0.134) kW and to 63.0 (SD 4.48)% in the longest (182.88 m; see Fig. 2).

The average values of C_s are plotted as a function of the average speed in Fig. 3 for the four strokes tested. Data were interpolated using exponential functions to give an empirical description of the possible relationship between the variables. Regressions were significantly different in terms of exponent, but not in terms of coefficient. Tables 2, 3 and 4 and Fig. 3 show that the most economical swimming stroke was front crawl followed by back, butterfly and breast strokes. In addition, in the front crawl, back and breast strokes C_s increased monotonically with the swimming v, whereas, in the butterfly stroke, C_s reached a minimum at a v of about $1\ m \cdot s^{-1}$ and increased exponentially at higher v.

Discussion

In the present study the C_s was estimated in the front crawl, back, breast and butterfly strokes at v ranging from those employing sub-maximal aerobic metabolism to those usually attained during competitions by elite athletes.

In the past, C_s has been assessed at v substantially slower than those actually attained during competitions over the shortest d in the four strokes (Holmér 1974; McArdle et al. 1971; Pendergast et al. 1977; Toussaint et al. 1990; Van Handle et al. 1988). Even Holmér (1972, 1974), in the extended series of measurements of his seminal studies, has measured the $\dot{V}O_2$ necessary to swim using the four strokes within a range of steady v markedly lower than those attained by our subjects during maximal swims. To our knowledge, the only attempt to estimate energy expenditure using the front crawl stroke at maximal competition v was that accomplished by di Prampero (1986) applying a series of calculations, more or less like those used in the present study. His estimate of C_s was $2.20\ kJ \cdot m^{-1}$ using the front crawl stroke at $2.0\ m \cdot s^{-1}$. However, his calculations referred to good, but not elite, swimmers and did not include the energy metabolism at rest. As such, a direct comparison with his swimmers is difficult to make.

Hence, the results presented in this study extend our knowledge of the bioenergetics of swimming to v very close to, or even overlapping, those actually attained during competitions in the four classical competition strokes by elite athletes.

Estimates of metabolic power expenditure

Average respiratory gas exchange ratio at $\dot{V}O_{2max}$ was 1.07 (SD 0.04); a value which indicated that our subjects exercised indeed at, or very close to, their MAP (see Londeree 1986). Hence, we do not consider that any underestimation of C_s at supra-maximal v was due to the inaccuracy with which $\dot{V}O_{2max}$ was measured.

To calculate E, we assumed that $\dot{V}O_{2max}$ was attained at the onset of maximal exercise according to a first order kinetic function with a τ equal to 24 s. The assumption of a larger value of τ would have led, for given values of E_{an} to a decrease of E, and hence to lower values of C_s, whereas the opposite would have been true for a smaller τ. However, this possible source of error would have had a role only in the two longer distances, since the contribution of the third term of equation 1 to the overall metabolic power was only a minor fraction (6.3, 4.5 and 4.2%) from the shortest to the longest trial.

The E_{an} contributed substantially to E at all distances (see Results section above). Thus, systematic errors in estimating and/or in assuming one or both the components of E_{an} may have brought about large errors in calculating E, and, as a consequence, C_s.

In this study, we assumed that the maximal amount of energy derived from the complete utilisation of PCr stores of the active muscles was $0.418\ kJ \cdot kg^{-1}$ in subjects aged 21–30 years and slightly less in younger subjects: $0.408\ kJ \cdot kg^{-1}$ and $0.393\ kJ \cdot kg^{-1}$ at 20 and 18–19 years, respectively. Assuming that the muscle mass involved in swimming was 30% of the m_b of our subjects, i.e. about 23 kg, this corresponded to, on average, an overall decrease of PCr concentration at exhaustion of 18.5, 18.1 and $17.4\ mmol \cdot kg^{-1}$ of wet muscle mass. These values are close to the decline of PCr that has been measured by other authors (Bangsbo et al. 1990; Sahlin et al. 1979) immediately after exhausting exercise. As such, we think the assumed values are reasonable estimates of the maximal amount of energy that can be derived from maximal PCr splitting. We also assumed that the amount of PCr used at the onset of exhausting exercise increases with the exercise duration following a first order kinetic function with a time constant of 23.4 s (see Medbø and Tabata 1993).

Therefore, the energy from PCr splitting would have been fully available only for the longer supra-maximal swims the average duration of which was 137 s. Indeed, for the two shorter supra-maximal swims, the amount of energy derived from PCr splitting would have amounted to about $0.286\ kJ \cdot kg^{-1}$ and to $0.384\ kJ \cdot kg^{-1}$ in the oldest subjects. Assuming a faster or slower time course for the use of PCr at the onset of supra-maximal exercise would yield values of 0.314, 0.398 and $0.418\ kJ \cdot kg^{-1}$ for $\tau_{al} = 19.2$ s and to 0.253, 0.363 and $0.414\ kJ \cdot kg^{-1}$ for $\tau_{al} = 26.8$ s (for the oldest group from the shortest to the longest distance, respectively). This would result in a 3.8%, 0.77% and 0.77% error for $\tau_{al} = 19.2$ s, and 3.02%, 1.10% and 0.77% error for $\tau_{al} = 28.8$ s in calculating C_s. Different τ_{al} values for PCr splitting would also have affected the relative contribution of all energy sources to the overall E.

The fraction of E_{an} derived from the production of lactate obviously depends on the assumed equivalent used to convert it into metabolic energy from peak $[La]_b$ assessed after maximal swims. The energy equivalent of La assumed in this study ($0.068.9\ kJ \cdot mmol^{-1} \cdot kg^{-1}$) was originally calculated by Margaria et al. (1963, 1971) during supra-maximal running the duration of which was similar to our maximal trials. Moreover, in spite of the fact that the energy equivalent of La has been questioned on several grounds (Gastin 1994), Medbo et al. (1988) have recently confirmed it by evaluating with an independent method the lactic acid component of oxygen deficit and comparing it to the $[La]_b$ at the end of exhausting running.

Given the numerous assumptions involved in the estimate of the amount of energy obtained from the anaerobic metabolism, the values of the total anaerobic capacity estimated in this study should be compared with that determined in swimmers of the same level. The anaerobic capacity in oxygen equivalent estimated in this investigation from peak $[La]_b$ and from the energy deriving from PCr breakdown amounted, in crawl swimmers, to 51.7 ml $O_2 \cdot kg^{-1}$ (SD 10.24; range: 72.5–32.3). This value is close to that determined in elite crawl swimmers using the accumulated oxygen deficit method (Ogita et al. 1996) which amounted to 50.2 ml $O_2 \cdot kg^{-1}$. It is smaller (about 30%), however, than the average value reported by Toussaint and Hollander (1994) which amounted in high level athletes to 1452 $J \cdot kg^{-1}$, i.e. to 69.5 ml $O_2 \cdot kg^{-1}$.

We have therefore concluded that the set of values for the alactic acid component and the method for estimating the lactic acid contribution to the E were not affected by major errors. Hence, we think that the inaccuracy in the estimate of E, and hence of C_s, was small and, as such it did not invalidate the quantitative conclusion drawn from this study. We would also like to point out that all methods used so far to estimate energy turnover during supra-maximal exercise are affected by substantial drawbacks: they are either experimentally demanding, making them difficult to apply routinely in large groups of subjects, or imply a substantial number of assumptions, making them liable to inaccuracy and imprecision. However, in our opinion:

1. The method proposed in this paper has sound physiological bases and
2. The data obtained in the present study agree fairly well with those reported by others.

This makes the present approach suitable for the routine estimate of C_s in swimmers at competition speeds.

Metabolic power requirement

The $\dot{V}O_{2max}$ and C_s were not evaluated at the same time of year in all the subjects. Hence, their swimming technique and their physiological characteristics might have been less homogeneous than assumed, a possibility that would have made the pooling of the data questionable. It must be pointed out, however, that only 3 out of 20 subjects were studied early in the season. In all the others, the measurements were carried out after competitions had been running for at least 4 months and thus the beneficial effects of training on technical skill would probably have occurred. Hence, the values of C_s and $\dot{V}O_{2max}$ obtained in the present study do describe the swimming economy and the physiological status of a homogeneous group of elite athletes.

The total d and times of maximal trials were not adjusted for the d covered and the intervals of time spent by the subjects gliding after the start. Applying the equations that have been used by Toussaint and Hollander (1994) for calculating them, it can be calculated that our approach may have lead to a maximal underestimation of C_s close to 7%. However, as these equations refer only to the front crawl stroke and are average descriptions of these two phenomena, we think that their application to individual cases should be made with care.

The average values of C_s assessed at sub-maximal v in front crawl swimming were in good agreement with those that have been reported by other authors at comparable speeds (Chatard et al. 1990; Toussaint et al. 1988), but they were about 13% lower, on average, than those reported by Holmer (1974) in elite front crawl swimmers (see also Monpetit et al. 1983; Pendergast et al. 1977). Comparisons for the other three strokes are not possible as the C_s for these strokes had not been measured systematically. The average values of C_s measured at sub-maximal speeds in back and breaststroke were about 20% lower than those obtained at comparable speeds (1.0, 1.2 and 1.32 $m \cdot s^{-1}$ in backstroke and 0.8 and 1.00 $m \cdot s^{-1}$ in breaststroke by Holmér (1974).

Earlier studies have rarely extended the range of the v investigated beyond those employing aerobic metabolism (see Toussaint and Hollander 1994 for an extended review of the published papers). In two cases, however, $\dot{V}O_2$ has been measured using the back-extrapolation technique (Costill et al. 1985; Lavoie et al. 1983) in front crawl swimmers after 400-yards and 400-m maximal swims. The values of C_s at $\dot{V}O_{2max}$, assessed during the incremental test in the annular pool, were therefore compared with the values obtained in these studies.

From the mean anthropometric characteristics of the subjects that have been studied by Lavoie, et al. (1983), their average $\dot{V}O_{2max}$, the mean value of v maintained over 400 m (1.45 $m \cdot s^{-1}$) and assuming an overall anaerobic capacity of 1420 $J \cdot kg^{-1}$ of m_b and a value of the oxygen stores equal to 125.4 $J \cdot kg^{-1}$ of m_b, a C_s of 1.21 $kJ \cdot m^{-1}$ can be calculated. This value is about 14% greater than that found in the front crawl stroke at maximal aerobic speed (1.42 $m \cdot s^{-1}$) in our study which was equal, on average, to 1.04 $kJ \cdot m^{-1}$ (see Table 2). The same applies to the data presented by Costill et al. (1985) who have reported an average C_s of 1.16 $kJ \cdot m^{-1}$ (about 10% smaller) at 1.42 $m \cdot s^{-1}$ in elite front-crawl stroke male swimmers. These slight differences may possibly be due to the different technical level of the groups of subjects.

All the mean data, regardless of the v were well interpolated using continuous functions in all the strokes with the exception of the butterfly stroke where C_s reached a minimum at about 1.0 $m \cdot s^{-1}$ to increase at higher v. Moreover, the C_s in breaststroke appeared to show a linear increase over the entire range of v. The metabolic requirement per unit of distance in swimming has been described to be a result of the energy spent in overcoming drag, in moving water for propulsion, in accelerating the body and of mechanical efficiency (Toussaint and Hollander 1994). Moreover, it has been considered that a considerable fraction of the overall energy at low v may be spent in opposing gravity (Lavoie and Monpetit 1986).

The high values of C_s at low v using the butterfly stroke may by caused by the need to counteract the tendency of the body to sink which, at slow v and in this symmetrical stroke, is not opposed by an appropriate upward lift. As the v increases, the upward force increases, and the relative contributions of the several sources of energy dissipation may change, bringing about a temporary decrease of C_s. In the breaststroke, another symmetrical stroke, wide intracycle variations in v occur as the athlete compensates, in the accelerating phase, for the deceleration occurring in the non-propulsive phase of the cycle. Hence, the energy required to accelerate the body is large and probably makes up a large fraction of the overall C_s. This, as has already been hypothesised by Holmér (1974), may be an explanation for the different increase of C_s with v occurring in the breaststroke in comparison with the other strokes.

In conclusion, the approach adopted in this study made it possible to assess the C_s in four common strokes at v close to those attained by the athletes during actual competitions. The results confirmed the findings reported in previous studies at lower speeds which showed that front-crawl was the most economic stroke to make possible the attainment of the fastest absolute speeds.

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