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ORIGINAL ARTICLE

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Effects of age and gender on the propelling efficiency of the arm stroke

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Abstract The propelling efficiency of the arm stroke (η_P) was estimated in a group of 63 male and female subjects (9–59 years of age) of good technical skill, swimming the front crawl at sub-maximal speeds. η_P was calculated on the basis of values of speed (v), stroke frequency (SF) and shoulder-to-hand distance (l, calculated from measures of arm length and elbow angle during the insweep) as proposed by Zamparo et al. (Eur J Appl Physiol 94:134–144, 2005). In both genders, the distance covered per stroke (Ds = v/SF) is similar before puberty, reaches its maximum at about 20 years of age and then steadily declines. l is significantly larger in males than in females and this difference tended to offset the differences in Ds so that η_P is almost the same in male and female swimmers of the same age group and swimming ability: about 0.31 before puberty, 0.38–0.40 at about 20 years of age and about 0.25 in swimmers older than 40 years of age. The development of η_P and Ds during the life span is similar to the changes in muscle strength and power reported in the literature suggesting that these parameters are related to the ability to exert forceful (and hence effective) strokes in water. Since the energy cost of swimming (C) depends essentially on η_P and the hydrodynamic resistance (W_d), these data further suggest that differences in C between genders are mainly to be attributed to differences in W_d, whereas differences across ages can be attributed also to changes in η_P.

Keywords Swimming · Propulsion · Gender difference · Life span

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Introduction

In aquatic locomotion the overall efficiency (η_O) can be calculated from the ratio of total mechanical work (W_{tot}) to the energy cost of swimming (C):

$$\eta_O = \frac{W_{tot}}{C}, \tag{1}$$

where C is calculated from the ratio of the metabolic power input ($\dot{E}$) to the speed ($C = \dot{E}/v$). C is generally expressed in J m^{-1} and represents the energy expended to cover one unit distance (di Prampero 1986).

The useful mechanical work (W_d, the work needed to overcome hydrodynamic resistance) is less than W_{tot} since a fraction of the work produced by the contracting muscles is needed to accelerate water backwards, thus wasting a certain amount of kinetic energy (W_k, Alexander 1983; Toussaint 1990), and to accelerate and decelerate the limbs with respect to the centre of mass (W_{int}, Zamparo et al. 2002, 2005). Since the propelling efficiency (η_P) is defined as the ratio of useful work to total work production:

$$\eta_P = \frac{W_d}{W_{tot}}, \tag{2}$$

by combining Eqs. 1 and 2 it is apparent that, at any given speed and for a specific η_O, an increase in η_P and/or a decrease in W_d leads to a decrease in C allowing the swimmer to spend less energy to cover a given distance (or to cover the same distance at a higher speed):

$$C = \left(\frac{W_d}{\eta_P}\right)\eta_O^{-1}. \tag{3}$$

Both η_P and W_d depend on the anthropometric characteristics of the swimmer and on his/her technical skills. Moreover, η_P and W_d are expected to change during growth (along with body development and training) affecting C in a manner difficult to predict. As an example, the decrease in hydrodynamic resistance associated with an improvement in swimming technique could offset (at least partially) the differences in W_d that could be expected on the basis of the increase in body surface area occurring with age.

Since both η_P and W_d are difficult to quantify (e.g. Wilson and Thorp 2003; Pendergast et al. 2003; Zamparo et al. 2005; Toussaint et al. 2005), the question of whether to minimize C a good technique is more important than a favourable body build or vice versa is far from answered.

Zamparo et al. (2005) recently proposed a simple model to estimate the propelling efficiency for the arm stroke. The model is based on the assumption that the arm is a rigid segment of length l, rotating at constant angular velocity $(\omega = 2\pi \times \mathrm{SF})$ about the shoulder and yields the average efficiency for the underwater phase only, as follows:

$$\eta_p = \left(\frac{v \times 0.9}{2\pi \times \mathrm{SF} \times l}\right)\frac{2}{\pi}, \tag{4}$$

where v is the average speed of the swimmer (multiplied by 0.9 to take into account that, in the front crawl, about 10% of forward propulsion is produced by the legs), SF the stroke frequency and the term l the average shoulder-to-hand distance (which can be calculated trigonometrically by measuring the upper limb length and the average elbow angle during the in-sweep of the arm pull).

Accordingly, both anthropometric factors and differences in technical skill can influence η_P. As indicated by Eq. 4, lower values in SF, for a given speed, lead to higher values in η_P. The ratio v/SF is the distance covered per stroke (Ds), an improvement of which is generally related to a more forceful and effective stroke. Higher values of η_P are also associated with a shorter shoulder-to-hand distance (l). This could occur for anthropometric reasons (differences in upper limb length among subjects) or for technical reasons (differences in the kinematics of the stroke which can affect the average elbow angle during the in-sweep). The model hence "suggests" that swimming with a closer elbow angle should improve η_P and that subjects with a shorter arm length are naturally endowed with a better "swimming technique" with respect to those with longer upper limbs (whilst taller swimmers have, generally, longer distances per stroke).

This paper is focused on the effects of age and gender on the propelling efficiency of swimming the front crawl with the aim of determining the relative importance of anthropometric factors and technical abilities on the development of η_P (and hence of C). To do so, the propelling efficiency was estimated according to the simple model described by Zamparo et al. (2005) in a group of 63 male and female swimmers of 9–59 years of age.

Materials and methods

The subjects

The experiments were carried out on 63 subjects (32 males and 31 females) whose principal anthropometric characteristics are reported in Table 1. All subjects trained regularly (for at least 2 years in the cases of M-11 and F-10) and their swimming technique was ranked from medium to good by their own coaches. Subjects of the M-16 and F-16 groups were competing at national Italian level. The subjects were informed about the methods and aims of the study and gave their written informed consent to participate; parental consent was obtained for underage subjects.

Experimental procedure

The experiments were performed in a 50 m long swimming pool. The subjects were asked to swim a pool length at constant speed and stroke rate and to repeat the swim at three to four different, incremental speeds (self-selected by the subjects). During these experiments the speed maintained by the subject during each trial (v, m s^{-1}) was measured from the time taken to cover the middle 30 m of each 50 m lap and the average stroke frequency (SF, cycles s^{-1}) was computed by averaging the time taken to complete five strokes in the 30 m intermediate lap. The distance per stroke (Ds, m) was

Table 1 Anthropometric characteristics of the subjects (M males, F females) grouped by age

	N	Age (years)	Body mass (kg)	Stature (m)	Arm length (m)
M-11	4	11.3 ± 1.7	39.0 ± 5.5	1.48 ± 0.02	0.48 ± 0.01
M-14	4	13.8 ± 0.5	53.5 ± 9.1	1.68 ± 0.10	0.56 ± 0.04
M-16	5	15.8 ± 0.8	65.4 ± 4.7	1.76 ± 0.06	0.61 ± 0.01
M-23	7	22.7 ± 2.8	90.4 ± 22.0	1.81 ± 0.11	0.63 ± 0.03
M-37	5	36.8 ± 4.8	78.2 ± 10.7	1.81 ± 0.08	0.60 ± 0.03
M-54	7	54.3 ± 4.9	78.3 ± 5.7	1.83 ± 0.09	0.61 ± 0.05
F-10	4	9.8 ± 0.5	40.0 ± 7.1	1.44 ± 0.01	0.47 ± 0.02
F-12	5	12.2 ± 0.4	50.8 ± 16.8	1.59 ± 0.05	0.54 ± 0.02
F-16	6	15.5 ± 1.0	56.4 ± 3.8	1.67 ± 0.05	0.57 ± 0.02
F-23	6	22.7 ± 2.7	65.0 ± 10.4	1.72 ± 0.04	0.57 ± 0.01
F-33	4	33.0 ± 2.6	60.8 ± 3.0	1.73 ± 0.04	0.57 ± 0.01
F-45	6	45.2 ± 4.8	66.7 ± 17.6	1.66 ± 0.05	0.55 ± 0.02

Data are averages ± 1 SD; *N* number of subjects calculated by dividing the average speed by the corresponding stroke frequency. During the experiments video records were taken, with a sampling rate of 50 Hz, by means of a video-camera (Panasonic, USA) positioned in a waterproof cylinder about 0.5 m below the water surface, frontally to the swimmer's direction. After the experiments, the data were downloaded to a PC and digitized using a commercial software package (Twin pro, SIMI, G). The elbow angle was measured at the end of the in-sweep (when the plane of the arm and forearm is perpendicular to the camera) for both sides (right and left arms) and for different arm cycles (2–6). These data were averaged to yield the subject's average elbow angle (EA, degrees) on the basis of which the shoulder-to-hand distance (l) was calculated. Arm length was measured in a standing position as the distance between the acromion and the centre of the hand's palm. The average values of EA are reported in Table 1; the average values of l are reported in Table 2.

Statistics

Average values are reported ±1 SD. Differences in the values of v, SF, Ds, L and η_P among males and females of the same age group (e.g. M-16 vs. F-16) were evaluated by means of an unpaired Student's t test. The level of significance was set at $P \leq 0.05$.

Results

The average values of v, SF and Ds are reported in Table 2 for each group of subjects: children swam at slower speeds and with lower values of Ds with respect to more mature swimmers who, on the other hand, can reach higher speeds with lower SF (and higher Ds) than their elderly counterparts. The average values of Ds are also reported in Fig. 1 as a function of age for males (full circles) and females (open circles): Ds increases as a function of age during childhood and, before puberty (M-11 and M-14, F-10 and F-12), is essentially the same in male and female swimmers. Ds reaches its maximum at about 20 years of age with male subjects showing values about 15% larger than for females ($P < 0.05$); after this age Ds decreases steadily in both groups to reach, in the elder groups of swimmers (M-54 and F-45), values similar to those observed in children (M-11 and F-10).

Differences among the groups were also observed as a function of age with regard to the elbow angle, as indicted in Fig. 2. Children and mature swimmers tended to maintain the upper limb straighter than competitive swimmers (who bend the elbow to a larger extent), without any clear-cut difference between genders ($P > 0.1$ for all age groups). The differences in elbow angle are, however, not so important in determining the differences in the shoulder-to-hand distance which is essentially determined by the anthropometric characteristics of the subjects. Indeed both l and the arm length increase as a function of age during childhood and, before puberty, are essentially the same for males (full circles) and females (open circle) (see Fig. 3, Tables 1, 2). After puberty, male subjects reach values of l that are about 10% longer ($P < 0.05$) than for female swimmers (M-23 and F-23), a difference which is maintained through the following years.

The average values of propelling efficiency are reported in Fig. 4 as a function of age for males (full circles) and females (open circles): in association with the data reported in Fig. 1 (Ds vs. age) η_P increases during childhood and is maximal at about 20 years of age in both genders. After this age, η_P decreases steadily in both groups to reach, in the elder groups of swimmers (M-54 and F-45), values that are even lower than those observed in children (M-11 and F-10). At variance with the data reported in Fig. 1 there are no clear-cut differences in η_P between males and females (but for the M-16 and F-16 groups), the differences in Ds being offset by the differences in l.

Discussion

The data reported in this paper indicate that the propelling efficiency of the arm stroke depends essentially

Table 2 Average values (±1 SD) of speed (v), stroke frequency (SF), distance per stroke (Ds), shoulder-to-hand distance (l) and propelling efficiency (η_P) for male (M) and female (F) subjects, grouped by age

	N	v (m s^{-1})	SF (Hz)	Ds (m)	l (m)	η_P
M-11	13	0.91 ± 0.11	0.60 ± 0.12	1.56 ± 0.21	0.45 ± 0.02	0.32 ± 0.04
M-14	16	**1.29 ± 0.10**	0.65 ± 0.10	**2.02 ± 0.26**	**0.51 ± 0.04**	0.36 ± 0.03
M-16	21	1.30 ± 0.15	**0.55 ± 0.09**	**2.39 ± 0.25**	**0.55 ± 0.03**	**0.40 ± 0.04**
M-23	27	1.32 ± 0.20	0.56 ± 0.13	**2.40 ± 0.31**	**0.57 ± 0.04**	0.38 ± 0.06
M-37	20	**1.29 ± 0.19**	0.65 ± 0.17	2.04 ± 0.27	**0.53 ± 0.05**	0.36 ± 0.08
M-54	25	**0.88 ± 0.13**	0.56 ± 0.12	**1.59 ± 0.16**	**0.58 ± 0.05**	0.25 ± 0.04
F-10	15	0.93 ± 0.09	0.66 ± 0.09	1.44 ± 0.15	0.44 ± 0.03	0.30 ± 0.04
F-12	20	**1.22 ± 0.09**	0.68 ± 0.09	**1.80 ± 0.20**	**0.47 ± 0.03**	0.35 ± 0.04
F-16	22	1.23 ± 0.08	**0.64 ± 0.12**	**1.99 ± 0.18**	**0.52 ± 0.03**	**0.35 ± 0.03**
F-23	24	1.25 ± 0.11	0.59 ± 0.09	**2.14 ± 0.22**	**0.51 ± 0.02**	0.38 ± 0.04
F-33	16	**1.17 ± 0.10**	0.59 ± 0.10	2.00 ± 0.17	**0.50 ± 0.01**	0.36 ± 0.03
F-45	24	**0.73 ± 0.06**	0.54 ± 0.07	**1.37 ± 0.16**	**0.51 ± 0.04**	0.25 ± 0.03

Bold characters indicate significant differences ($P < 0.05$) between males and females of the same age group (unpaired Student's t test)
N number of observations

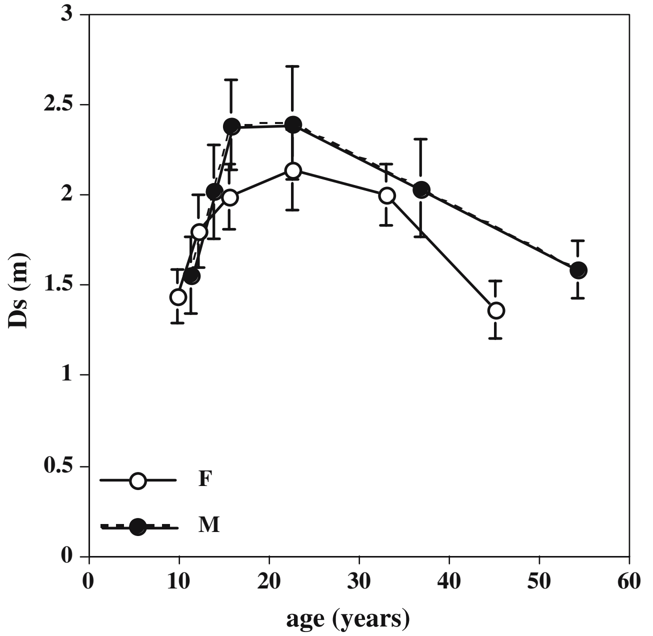

Fig. 1 Distance per stroke (Ds, m) as a function of age (years) in male (*full circles*) and female (*open circles*) swimmers. Data are means ± 1 SD

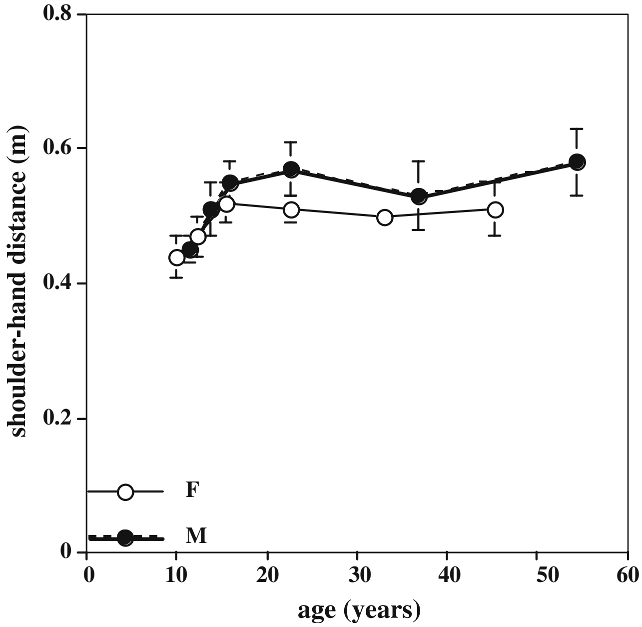

Fig. 3 Shoulder-to-hand distance (m) as a function of age (years) in male (*full circles*) and female (*open circles*) swimmers. Data are means ± 1 SD. This parameter was calculated on the basis of measurements of upper limb length and elbow angle (see text for details)

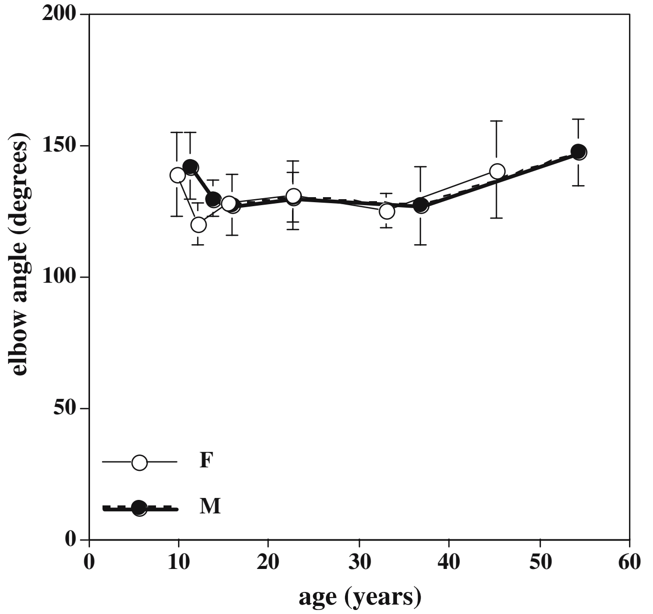

Fig. 2 Elbow angle (degrees) as a function of age (years) in male (*full circles*) and female (*open circles*) swimmers. Data are means ± 1 SD. Elbow angle was measured at the end of the in-sweep phase (see text for details)

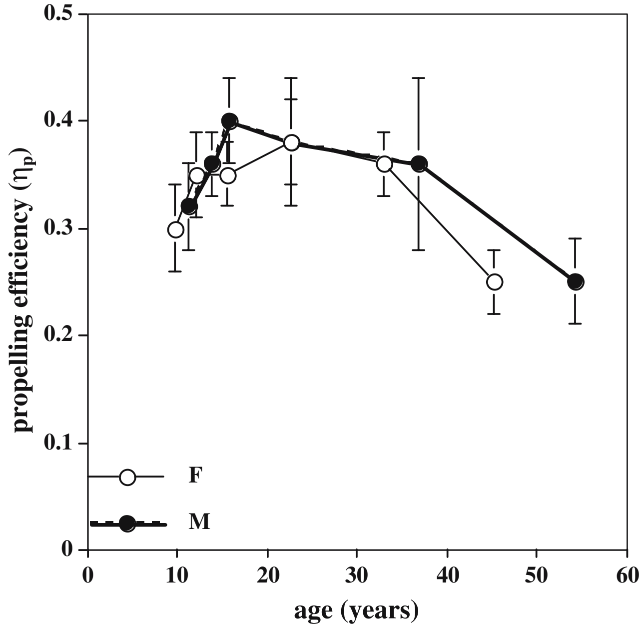

Fig. 4 Propelling efficiency (η_P) as a function of age (years) in male (*full circles*) and female (*open circles*) swimmers. Data are means ± 1 SD. The values reported here refer to the propelling efficiency of the arm stroke only (see text for details)

on the distance covered per stroke whereas the shoulder-to-hand distance (and its determinants) play a minor role in determining η_P (and hence *C*).

The evolution of η_P and Ds as a function of age and gender closely resembles the changes in muscle strength and power along the life span as reported in the literature (e.g. Astrand et al. 2003; Margaria et al. 1966) and suggests that these two parameters are related to the ability to exert forceful (and hence effective) strokes in water. Indeed, in analogy with the development of muscle strength and power, Ds and η_P increase in both genders before puberty, reach a maximum at about

20–30 years of age and then steadily decline. Moreover, no major differences in Ds are observed between males and females during childhood, whereas, after puberty, the values observed in males become larger than those for females and this difference is maintained through the following years. Finally, the differences in Ds between genders tend to disappear when the data are "normalized" for the anthropometric characteristics of the subjects (the upper limb length, or the shoulder-to-hand distance, in the calculations of η_P).

In the following sections the sample and the model to estimate the propelling efficiency will be briefly discussed; the results of this study will then be compared with similar data reported in the literature

About the subjects

At variance with other sport activities (e.g. cycling) where minimal differences in efficiency are observed among subjects with different technical abilities (Nickleberry and Brooks 1996), training and skill deeply influence the efficiency (and hence the energy cost) of swimming (e.g. di Prampero 1986).

Since the major aim of this study was to investigate the effects of age and gender on η_P, the subjects were selected as to be comparable for swimming technique and training intensity/duration. These factors were quantified by each subject's coach and verified, a posteriori, by checking whether, or not, the individual values of Ds were comparable to those of the other subjects of that group. When this was not the case (e.g. because of differences between biological and chronological age or because of differences in training status) the subject's data were disregarded. This selection reduced the number of data points but allowed an evaluation of more homogeneous groups.

It goes without saying that the data reported here are the result of a cross-sectional and not a longitudinal study; as such it is possible that factors independent of age changes per se may contribute to this observation.

About the model

The model proposed by Zamparo et al. (2005) assumes that the arm is a rigid segment of length l, rotating at constant angular velocity about the shoulder. The average propelling efficiency is calculated over half a cycle (only for the underwater phase: from 0 to π) according to Eq. 4, which indicates that η_P can range from 0 to $2/\pi$ (i.e. from 0 to 0.63). Maximum efficiency hence occurs when the tangential speed of the hand ($2\pi \times \mathrm{SF} \times l$) equals the forward speed of the swimmer ($0.9 \times v$) whereas η_P decreases the larger the tangential speed with respect to the forward speed.

As shown by Zamparo et al. (2005), Eq. 4 can be used to estimate the propelling efficiency of the arm stroke even if the contribution of the internal work (W_{int}) to total work production ($W_{\mathrm{tot}} = W_k + W_d + W_{\mathrm{int}}$) is not taken into account. Indeed, the efficiency calculated by means of Eq. 4 is not, properly speaking, a propelling efficiency [$\eta_P = W_d/(W_k + W_d + W_{\mathrm{int}})$] but a Froude efficiency [$\eta_F = W_d/(W_k + W_d)$]. The difference between the two depends on the amount of work that has to be expended to accelerate and decelerate the upper limbs with respect to the centre of mass (W_{int}), which is proportional to the frequency of the limb's movement. As shown by Zamparo et al. (2005) W_{int} is rather low in the arm stroke (at least in the range of speeds utilized in this study) and could be neglected so that, as a first approximation, $\eta_F \sim \eta_P$ (see Zamparo et al. 2005 for a detailed discussion of this point).

In this study the elbow angle was measured at the end of the in-sweep and was assumed to represent the average EA maintained by the subject during the underwater phase. As calculated by Payton et al. (1999) in male competitive front crawl swimmers (21 years of age), elbow flexion changes by about 45° between the start and the end of the in-sweep. Hence, the average EA during the underwater phase should be somewhat higher than that reported in Table 1. Even if the term l could be calculated with better accuracy, data reported in Fig. 2 indicate that inter-individual differences in EA are rather small and data reported in Tables 1 and 2 show that this term is essentially determined by the anthropometric characteristics of the subjects (by the upper limb length). As such increasing the elbow flexion seems not to be a determinant for increasing η_P.

No significant differences were found between the right and left elbow angles and no differences of EA were found as a function of the speed in both genders and at all ages. This is mainly attributable to the large variability of this parameter among cycles, as already pointed out by several authors (e.g. Payton et al. 1999).

A comparison with data of η_P reported in the literature

The data of η_P reported in the literature refer, mainly, to male swimmers competing at national or international level (e.g. Toussaint et al. 1990; Zamparo et al. 2005), whereas we are unaware of studies that investigate the propelling efficiency in children, master athletes or in subjects with less than good swimming technique.

As indicated in Fig. 4, in children, as well as in mature swimmers, of "average" swimming skills, the efficiency of propulsion can be as low as 0.20–0.30 indicating that almost 70–80% of the swimmer power output is wasted in giving water un-useful kinetic energy. On the other hand, the values reported here for male competitive swimmers (of about 0.40) indicate that a substantial fraction of the subject's energy expenditure is bound to be wasted even in well-trained swimmers with above-average technical skills.

As a comparison, values of η_P of 0.42–0.47 were reported for competitive US swimmers by Zamparo et al. (2005) using the same model utilized in this study. Toussaint et al. (1990) report data of η_P of 0.44 ± 0.03 and 0.61 ± 0.06 for highly trained triathletes and competitive swimmers (as measured with the MAD system). In a group of swimmers of both genders and with different technical skills, Berger et al. (1997) reported values of η_P of 0.35 ± 0.03 (as measured by a kinematic approach) and 0.56 ± 0.05 (as measured with the MAD system).

Stroking characteristics in children and adults

Although studies on propelling efficiency are scanty, several papers investigated the differences in stroking characteristics between children and adults and between male and female swimmers.

Kjendlie et al. (2004b) report higher stroke frequency in children (11.1 ± 0.8 years) than in adults (21.4 ± 3.7 years) for any given (sub-maximal or maximal) speed. The values of Ds for children (about 1.75 m) and adults (about 2.5 m) are close to those found in this study for subjects of comparable age and gender (M-11, Ds = 1.56 ± 0.21 m; M-23, Ds = 2.40 ± 0.31 m). Adjusting for body size does not reduce the difference in Ds between children and adults; hence, the authors conclude that swimming technique (and possibly propelling size, e.g. the hand surface) must be the factor responsible for the differences in performance (making the adults more effective swimmers than children).

Vorontsov and Binevsky (2003) measured SF and Ds in a group of 225 male subjects (11–16 years of age) swimming the 100 m distance at maximal speed: they found that Ds increases from about 1.1 m at 11 years to about 1.65 m at 16 years. Whereas these values are somewhat lower than those reported in this study, the percentage increase over the same age range is comparable (Ds increases by about 50% from 11 to 16 years of age). Also in this case the differences in Ds are thought to be related to improvements in swimming technique, rather than to changes in body size. Moreover, these authors underline the parallel increase, in this age range, of muscle mass and power suggesting (as is the case of this study) that these factors play a major role in the development of Ds (and hence of η_P).

Pelayo et al. (1997) have investigated the relationship between swimming performance (maximal speed over 50 m) and stroking characteristics (Ds and SF) on a large number (2,058) of non-skilled pupils aged 11–17 of both genders (swimming training amounting to just 6 ± 2 h year^{-1}). On the basis of their data of v and SF (and on the basis of the values of l reported in this study for the same age and gender) propelling efficiency can be calculated to range from 0.21 (at 11 years) to 0.24 (at 17 years) in both male and female subjects. With due caution, these values could be taken to represent the lower limits of η_p in young, unskilled, swimming humans.

Differences in η_P and C between genders and across ages

Women have a lower energy cost than men, particularly in swimming events over long distances (e.g. Lavoie and Montpetit 1986; Pendergast et al. 1977). This higher economy is traditionally attributed to a smaller hydrodynamic resistance due to their smaller size, larger percentage fat and more streamlined position in comparison to male swimmers (e.g. Zamparo et al. 1996). Since there are no major differences in propelling efficiency between male and female swimmers of the same age and technical skill (but for the competitive groups F-16 and M-16, see Table 2) it follows that the differences in C between genders are, indeed, to be mainly attributed to differences in hydrodynamic resistance (see Eq. 3). This conclusion is supported by Montpetit et al. (1988) who found no differences in C between male and female swimmers when matched for age, body size and swimming experience.

Tanaka and Seals (1997) have investigated the effect of ageing on swimming performance. They have shown that, in both men and women, peak performance occurs at about 35 years of age and that the rate and magnitude of the decline in performance with advancing age is larger in female than in male swimmers. Data reported in Fig. 4 could at least partially explain this finding since the rate and magnitude of the decline in propelling efficiency seems to be larger in female than in male swimmers. Hence, as indicated by Eq. 3, with advancing age the C of female swimmers must increase, and their performance decrease, to a larger extent in comparison with male swimmers, as actually found by Tanaka and Seals (1997).

It is more difficult to predict differences in C between children and adults since η_P changes during growth (hence the changes in C could be either due to changes in η_P or W_d). Indeed, children were found to be either more or less economical than adults: C was found to be higher in children (14.5 ± 1.9 years) of good competitive level than in elite swimmers (Zamparo et al. 2000), the difference being explained on the basis of differences in swimming technique (and hence of η_P). On the other hand Kjendlie et al. (2004a) report lower values of C in children (11.8 ± 0.8 years) than in adults (21.4 ± 3.7 years), the difference being explained on the basis of differences in body size and hydrodynamic resistance between the two groups.

The determinants of swimming performance

The differences in η_p observed in this study can help in explaining the differences in performance reported in the literature among subjects with different technical skill, age and gender. It must be pointed out, however, that swimming performance (as determined by the shortest time needed to cover a given distance) depends not only on η_p and W_d (Eq. 3) but also on the maximal aerobic–anaerobic power of the subjects. Indeed, maximal speed ($v_{\max}$) is given by the ratio:

$$v_{\max} = \frac{\dot{E}_{\max}}{C}, \tag{5}$$

where $\dot{E}_{\max}$ is the maximal metabolic power derived from both the aerobic and anaerobic energy sources (e.g. di Prampero 1986; Zamparo et al. 2000). It necessarily follows that a subject with a good propelling efficiency (and a lower C) will not necessarily outrun a subject with a poor η_{p} (and a higher C) but with an outstanding $\dot{E}_{\max}$. Since both the maximal aerobic and anaerobic power change with age, gender and training they ''also'' contribute to the development of performance along with the changes in η_{p} (and W_{d}).

Conclusions

Data reported in this paper indicate that the propelling efficiency of the arm stroke depends essentially on the distance covered per stroke whereas the shoulder-to-hand distance (and its determinants) plays a minor role in determining η_{P}. The development of η_{P} and Ds as a function of age and gender closely resembles the changes in muscle strength and power along the life span as reported in the literature suggesting that these two parameters are related to the ability to exert forceful (and hence effective) strokes in water. Since the energy cost of swimming depends essentially on η_{P} and the hydrodynamic resistance (W_{d}) and since η_{P} changes with age but not with gender, these data further suggest that differences in C between males and females are mainly to be attributed to differences in W_{d}, whereas differences across ages can also be attributed to changes in η_{P}.

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