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Original Investigation

Analysis of best performances of front crawl swimming: a case study

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Purpose: The aim of this work was to: 1) measure the energy cost of front crawl swimming at various speeds (range .8 -1.8 m·s-1 in elite and medium level swimmers; in addition, 2) estimate the maximal aerobic power and maximal anaerobic capacity from the relationship between overall energy spent and individual best times over distances from 50m to 1500m in one elite athlete. It will also be shown, that 3) the so obtained values are rather close to the actually measured ones.
Methods: Oxygen consumption was measured on 13 medium level and 5 elite swimmers (best time over 100m, 51.50±3.54s), swimming the front crawl in a 25m indoor pool in the speed range .8-1.8 m·s-1. So, the energy cost of front crawl (C_{sw}) could be calculated.
Results: In both groups C_{sw} increased with the speed as a second order polynomial. In the elite group it was ≈ 17 to ≈ 34 % smaller than in medium level swimmers, (P= .005). Knowledge of C_{sw} allowed us to estimate the overall energy expenditure (E_{tot}) during actual competitions as a function of the corresponding performance time (t_r) in one elite swimmer. The results show that (E_{tot}) increased linearly with tr. For $t_r \geq 100s$ the slope and y intercept of the resulting linear regressions yield $\dot{V}O_{2max}$ and maximal anaerobic capacity, respectively. These turned out to be close to the directly determined values.
Conclusions: If the energy cost of swimming as a function of the speed is known, this approach yields reasonable estimates of the swimmers' maximal oxygen consumption and maximal anaerobic capacity.

Keywords: elite swimmers; energy cost; record time; maximal aerobic power; maximal anaerobic capacity.

Introduction

The energy cost of transport (C), i.e. the amount of energy required to cover one unit of distance, is a crucial determinant of performance in any form of human (or animal) locomotion.
In swimming the energy cost (C_{sw}) is generally expressed in kJ·m^{-1} or normalized per unit body surface area kJ/(m·m^2); it has been extensively studied by several authors at sub-maximal[1–4] and maximal speeds.[5–8] These studies have consistently shown that: i) C_{sw} increases with swimming speed; ii) it depends on the swimming style, being lowest in the front crawl and largest in the breast stroke; iii) it is substantially less in elite, as compared to medium level swimmers, and iv) at any given speed it is less in females, as compared to males of medium technical skill. For extensive reviews on these topics see di Prampero[9] and Zamparo et al.[10, 11]
The metabolic power requirement ($\dot{E}$) for swimming at a given speed (v) is the product of the energy cost at that speed (C_{sw}) and the velocity:

$$\dot{E} = C_{sw} \cdot v$$

Rearranging this equation and applying it to maximal performances it becomes immediately apparent that, for any given swimmer, the maximal speed (v_{max}) is determined by the ratio between his/her maximal metabolic power ($\dot{E}_{max}$) and the energy cost of swimming (C_{sw}) at that speed:

$$v_{max} = \frac{\dot{E}max}{Csw}$$

This approach was developed by di Prampero et al.[12] to estimate the individual best performance time for middle-distance running and was later used by Capelli et al.[13] for swimmers and cyclists, and by Buglione et al.[14] for canoeists and kayakers.
In turn, $\dot{E}_{max}$ depends on the subject's maximal aerobic power and the maximum amount of energy derived from the full utilization of anaerobic energy stores, which must be known. In this study, $\dot{E}_{max}$ was not only measured but also calculated on a subject who participated in the Olympic Games (see Theory section for details).
The aim of this work was to: 1) measure the energy cost of front crawl swimming at various speeds (range .8-1.8 m·s^{-1}) in elite and medium level swimmers; in addition, 2) the maximal anaerobic capacity and maximal aerobic power were estimated from the

relationship between overall energy spent and individual best times over distances from 50m to 1500m in one elite athlete. It will also be shown, that 3) the so obtained values are rather close to the measured ones.

Methods

Participants

The experiments were performed on two groups of male subjects whose anthropometric characteristics are reported in Table 1. Group 1 comprised 13 participants of medium technical level who trained three times a week and did not take part in official competitions. Group 2 comprised 5 elite swimmers who trained daily and participated regularly in national and international official competitions. The experimental protocol was approved by the local ethical committee and agreed with the Declaration of Helsinki (1964). The participants were informed on the aim of the tests and gave their written consent.

Experimental Design

All tests were performed in a 25m indoor pool with a constant water temperature of 25 °C. The tests were carried out in the fasting state, at least three hours after the last meal and 48 hours after the last training session. Before the start of the study, all subjects were familiarized with the equipment and the experimental procedures. The protocol consisted of a standardized warm-up: the subjects swam 4 pool lengths at .8 $m \cdot s^{-1}$ with a passive recovery of 10 seconds after each pool length. Before the warm-up resting oxygen, consumption was measured in all subjects in water, with hands on the edge of the pool. After completing the warm-up each subject swam 10 pool lengths at constant speeds of .8, 1.0, 1.2, 1.4 and 1.6 $m \cdot s^{-1}$ for the medium level and 1.0, 1.2, 1.4, 1.6 and 1.8 $m \cdot s^{-1}$ for the elite swimmers with a passive recovery of 10 seconds after each pool length. In all cases, the swimming style was the front crawl with free stroke frequency. At the beginning and end of each lap, the subjects were resting in the water, with their hands on the edge of the pool; to begin swimming, they extended their legs, slowly pushing their feet against the wall, and at the end of each lap, they stopped and put their hand on the edge of the pool.

Table 1. Anthropometric characteristics participants

Participants groups	N°	Age (yr)	Body Mass (kg)	Stature (m)	Body Surface Area (m^2)	Best Time 100m (s)
Group 1 (medium level)	13	25.3 ± 6.9	71.7 ± 10.9	1.77 ± 0.09	1.88 ± 0.17	
Group 2 (elite level))	5	22.9 ± 5.9	81.8 ± 2.5	1.85 ± 0.04	2.05 ± 0.05	51.50 ± 3.54

Note: All data are expressed as mean/SD.

The speed was set by a system of lights, positioned on the bottom of the pool, managed by a dedicated software (AQVATECH Engineering srl Torino, Italy, patent N.0001399260 of 20/09/2009).

The actual distance covered at each speed was measured subtracting 17.94± .84m (10 · 1.79± .08) from the total nominal of 250m (25 · 10). Indeed, the distance covered by the centre of mass of the swimmer is less than the nominal distance by an amount equal to about one body length per pool travelled.

Instruments

Gas exchange and blood lactate measurement

Oxygen consumption was measured by means of a portable metabolic device (VO2000; MedicGraphics, USA), the reliability and accuracy of which have been validated by Byard and Dengel[15]. This system was modified, with a snorkel and a flexible plastic tube attached to the breathing valve, using the method proposed and validated by Pinna et al.[16] Before the test the device was calibrated according to the manufacturer's instructions. The additional dead space of the plastic tube was taken into account by modifying the pre-set parameters of the metabolimeter. This system allowed us to assess single breath oxygen uptake without interfering with the swimming technique.[17] The oxygen uptake was measured continuously during each series and in the following six minutes as proposed by Buglione et al.[14] and Buglione and di Prampero.[18]

Direct assessment of the energy cost of swimming

The front crawl's energy cost (Csw) was determined by dividing the total metabolic energy expended above resting levels (E, measured in joules) by the distance covered (d, in meters). The value of E was derived from the combined contributions of aerobic (Aer), anaerobic alactic (AnAl), and anaerobic lactic (AnLa) energy expenditures. Specifically, Aer was assessed by integrating the net $\dot{V}O_2$ from the start of exercise (t= 0) to the completion of the test, with the net $\dot{V}O2$ calculated by subtracting pre-exercise resting values (measured before warm-up) from the recorded data. Meanwhile, anaerobic alactic (AnAl) energy expenditure was estimated based on $\dot{V}O_2$ kinetics observed in the initial six minutes of recovery.

The net $\dot{V}O_2$ values obtained from the 4th to 6th minute of recovery were linearly interpolated. Back extrapolation of the so obtained function to recovery time zero allowed us to estimate, by subtraction, the fast component the alactic O_2 debt payment, the integral of which yielded AnAl.[14, 18]

The anaerobic lactic (AnLa) contribution to total energy expenditure was determined based on the net accumulation of blood lactate ([La]b) following exercise, exceeding the resting level (assumed to be 1 mM). This calculation used an energy equivalent of 3 ml $O_2 \cdot kg^{-1} \cdot mM^{-1}$.[19,20] of [La]b accumulation in the blood. The total energy expenditure (E), comprising aerobic (Aer), anaerobic alactic (AnAl), and anaerobic lactic (AnLa) components, was then divided by the distance traveled to obtain C_{sw}, expressed in joules per meter. This estimation assumes that 1 ml of O_2 in the human body produces 20.9 J, which holds true specifically when the respiratory quotient is .96. Body surface area was calculated according to DuBois and DuBois.[21]

Theory

As originally proposed by Scherrer and Monod[22] and subsequently modified by Wilkie[23] the maximal metabolic power that can be sustained at a constant level until exhaustion is a decreasing function of the exhaustion time (t_e), as described by:

$$\dot{E}_{max} = AnS \cdot t_e^{-1} - [MAP \cdot \tau (1 - e^{-te/\tau})] \cdot t_e^{-1} + MAP \quad (1)$$

where $\dot{E}_{max}$ is the maximal metabolic power, AnS is amount of energy that can be derived from complete utilization of the anaerobic (alactic + lactic) stores; MAP is the subject's maximal aerobic power (proportional to $\dot{V}O_{2max}$ above resting); t_e is the exhaustion time; and τ is the time constant with which $\dot{V}O_{2max}$ is reached at the onset of exercise. Thus, the second term on the right side of equation 1 is the amount of anaerobic energy corresponding to the so-called Oxygen Deficit incurred in the time elapsed between work onset and the attainment of $\dot{V}O_{2max}$.[23] It should be pointed out here that equation 1 can be reasonably

applied for t_e values longer than about 50 s, but shorter than about 15 min. Indeed, on the one side, 50s is the shortest time necessary for complete utilization of the anaerobic energy stores and, on the other, 15 minutes is the longest time allowing MAP to the maintained at 100% level. Hence, it can be assumed that, within this time domain both AnS and MAP are constant.

It follows from equation 1 that the maximal amount of energy (E_{tot}) that any given subject can utilize in the time t_e is the product of equation 1 and t_e itself:

$$E_{tot} = \dot{E}_{max} \cdot t_e = AnS - [MAP \cdot \tau (1- e^{-te/\tau})] + MAP \cdot t_e \quad (2)$$

On the other side, the total energy requirement (E_{req}) for swimming any given distance is the product of the energy cost of swimming and the distance itself:

$$E_{req} = C_{sw} \cdot d \quad (3)$$

where, obviously enough, C_{sw} is a function of the speed itself.

To effectively cover any given distance in the shortest possible time, the maximal amount of energy that the athlete can utilize in the time t_e (E_{tot}, eq. 2) must be equal to the energy required to cover the distance in question at the appropriate speed (E_{req}, eq. 3). Thus, replacing t_e with the record time (t_r), and rearranging, equation 2 becomes:

$$E_{tot} = E_{req} = AnS - [MAP \cdot \tau (1- e^{-tr/\tau})] + MAP \cdot t_r \quad (4)$$

At work onset $\dot{V}O_{2max}$ is reached with a the time constant (τ) of 10 - 23s,[13,23] and since an exponential attains its asymptote in a time $\geq 4\ \tau$, for $t_r \approx 100$ s, MAP is essentially equal to $\dot{V}O_{2max}$. In addition, after about 100 s also the term in square brackets becomes constant, since for $t_r \geq 4\ \tau$, the quantity $e^{-tr/\tau}$ becomes vanishingly small. Therefore, replacing MAP with $\dot{V}O_{2max}$, equation 4 becomes:

$$E_{tot} = E_{req} = AnS - \dot{V}O_{2max} \cdot \tau + \dot{V}O_{2max} \cdot t_r \quad (5)$$

This equation shows that $E_{tot} = E_{req}$ can be expected to increase linearly with t_r, its slope yielding $\dot{V}O_{2max}$, and its intercept on the y axis yielding the quantity $AnS - \dot{V}O_{2max} \cdot \tau$.

Statistical analysis

All results are expressed as Means ± Standard Deviation (SD). The assumption of normality
was verified through the Shapiro-Wilk test. Non-Parametric Paired and Independent *t*-test was used to verify the differences between groups energy cost. Data analysis was carried out with the SPSS statistical package version 20.0 (IBM Armonk, New York, USA). Statistically significance was considered at *P*-value < .05. Regression analysis was performed between energy cost and speed in participant D.L.

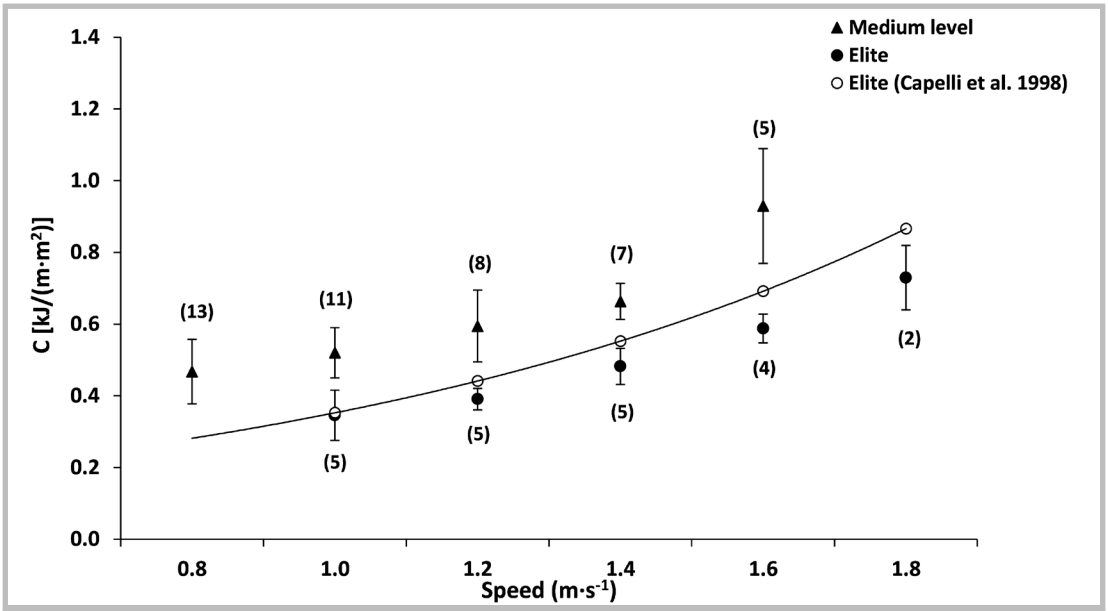

Figure 1. The Energy Cost of Frontal Crawl (kJ/(m · m²) (± 1SD, vertical bars) is plotted as a function of the average speed (m·s⁻¹) in medium level (▲) and elite swimmers (●). Number of subjects in brackets. Data on elite swimmers from Capelli et. al.[5] are indicated by circles (○).

Results

In the medium level group C_{sw} amounted to .47± .09, .52± .07, .59± .10, .66± .05, .93± .16 kJ/ (m·m²) at .8, 1.0, 1.2, 1.4, and 1.6 m·s⁻¹, respectively. The elite swimmers were ≈ 17 to ≈ 34 % more economical (*P*= .005), their C_{sw} values amounting to .35± .07, .39± .03, .48± .05, .59± .04, .73± .11 kJ/(m·m²) at 1.0, 1.2, 1.4, 1.6 and 1.8 m·s⁻¹, respectively (see Figure 1).

The maximal O_2 consumption of our best elite subject (D.L., 84 kg, 1.90m) as measured at a speed of 1.8 m·s⁻¹ amounted to 5096 ml·min⁻¹ (60.7 ml·kg⁻¹·min⁻¹), resting included and the maximal value of the fast component of the alactic oxygen debt, as measured after the test at 1.8 m·s⁻¹, amounted to 3972 ml O_2. The maximal blood La concentration above resting observed at the end of an actual competition over 400m in this same subject amounted to 14 mM, corresponding to an O_2 equivalent of 3528 ml, the maximal capacity of the anaerobic stores amounting therefore to: 3972 + 3528 = 7500 ml O_2.

Discussion

The results of this study show that the energy cost of front crawl (C_{sw}), increases with the speed; however, at any given speed, C_{sw} in the elite swimmers it is significantly less than observed in the medium level ones (see Figure 1), in agreement with numerous previous studies.[1, 6, 9, 10]

Furthermore, the present data in the elite group are on the same order as reported by Capelli et al.[5] for front crawl swimming in top class athletes (Figure 1).

Knowledge of the energy cost of swimming as a function of the

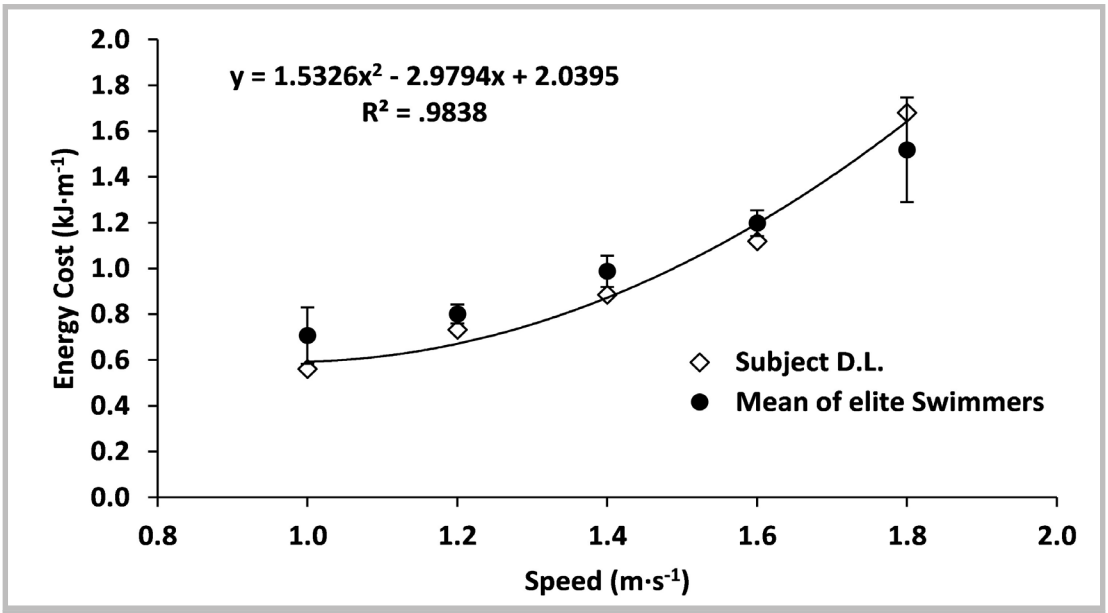

Figure 2. The Energy Cost of Frontal Crawl (kJ·m-1), of one elite swimmer (subject D.L., ◊) and the mean of all elite swimmers of our study (●), is plotted as a function of the average speed (m·s-1). Regression describes the relationship between energy cost and speed in subject D.L. (y = 1.53×2 – 2.98× + 2.04 R² = .98).

speed allows one to estimate the maximal anaerobic capacity and maximal aerobic power of any given athlete provided that his/her best performance times over a given set of distances is also known. The paragraphs that follow are devoted to making these calculations explicit, along the lines described in more detail in the theory section.

The best performance times over 50, 100, 200, 400, 800, 1500m, and hence the corresponding average speeds, were available for one of the elite swimmers (subject D.L., stature 1.90 m, body mass 84 kg), who participated at the Olympic Games; they amounted to 2.22, 2.04, 1.88, 1.78, 1.70, 1.66 m·s^{1}, respectively. The relationship between the energy cost of swimming and the speed for this specific athlete was also known (see Figure 2). Thus, equation 3 (see Theory section) allowed us to estimate the overall energy spent to cover each of the above-mentioned distances. In addition, in this same subject, the maximal aerobic power and maximal anaerobic capacity (lactic and alactic) were also measured (see Results).

The paragraphs that follow are devoted to assessing, in this specific subject, AnS and $\dot{V}O_{2max}$ and to compare the so obtained data with the directly measured ones.

Energy requirement (E_{req}) for subject D.L. is reported as a function of tr in Figure 3 which shows that, for tr ≥ 100 s, the regression between the two variables is indeed linear, as described by: y = 195.5 + 1.97 tr. Thus $\dot{V}O_{2max}$=1.97 kW (=5.65 l O_2·min^{-1}). In addition, since the y intercept of this regression yields the quantity AnS – $\dot{V}O_{2max}$ · τ (see above), AnS can also be obtained by simple algebra as: AnS= 195.5 + 1.97 · τ = 215.5 to 240.8 kJ (corresponding to 10.3–11.5 liters O_2), depending on the value assumed to hold for τ (10 or 23 s). The so obtained values, for both $\dot{V}O_{2max}$ and AnS are larger than those directly measured on this swimmer at 1.8 m·s^{-1}, which amounted to 5.10 l·min^{-1}for $\dot{V}O_{2max}$ and to 7.50 liters O_2 for AnS (see Results).

These overestimates are likely due to the fact that the subject did not reach $\dot{V}O_{2max}$ during the test at a speed of 1.8 m·s^{-1}, as well as the peak oxygen consumption, combined with the underestimation of maximum anaerobic capacity: alactic and lactic.

The overestimation could also be due to the fact that $\dot{E}_{req}$ was calculated from the C_{sw} values determined during constant speed

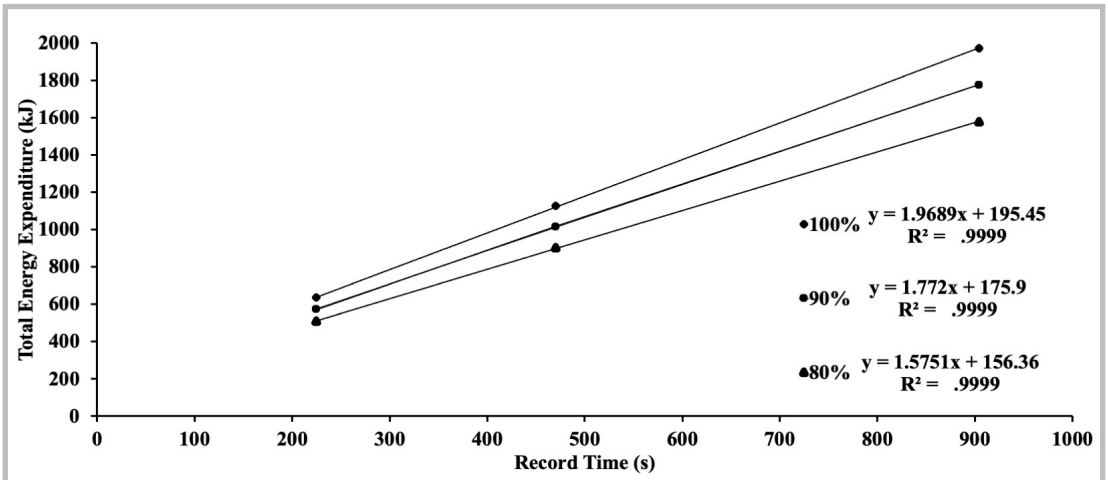

Figure 3. The total energy expenditure (Etot) during actual front crawl competitions is reported for one elite swimmer (D.L.) as a function of the corresponding best performance time over distances of 50, 100, 200, 400, 800, 1500m. Regressions were calculated over 400, 800 and 1500m only. They refer to Etot, as obtained during constant speed swimming (100%) or to 90% and to 80% thereof. Slopes of regressions yield $\dot{V}O2max$, intercepts on the y axis AnS – $\dot{V}O2max$ · τ. See text for details.

swimming, whereas actual competitions are performed with a dive start and regular leg pushes against the wall of the pool at each turn, a fact that inevitably leads to a reduction of the corresponding energy cost. Unfortunately, it is not possible to assess with certainty the amount of this reduction in C_{sw}. However, if it is assumed to be on the order of 10, or 20 % of the values applying for constant speed swimming, then the values of $\dot{V}O_{2max}$ and AnS, as calculated from the corresponding regressions amount to 5.08 and 4.52 $l \cdot min^{-1}$ for $\dot{V}O_{2max}$ and to 193.6-216.6 (kJ) (9.26-10.36 $l\ O_2 \cdot min^{-1}$) or to 172.2-192.7 (kJ) (8.24-9.22 $l\ O_2 \cdot min^{-1}$) for AnS.

In the future, it would be interesting to address the limitations of this study by involving a larger number of subjects and measuring both maximal oxygen consumption and maximal anaerobic capacity through maximal tests to exhaustion, in order to compare them with the estimated values.

Practical Applications

This study highlights a simple method to assess the individual energy cost of swimming as a function of the speed, thus making it possible to estimate the overall energy spent by the swimmer in question over any given time trial and any given distance (see Methods and Results, Figures 1 and 2). The overall energy expenditure can then be plotted as a function of the individual best time over a series of time trials, thus obtaining an estimate of the maximal aerobic power and of the maximal anaerobic capacity (see Discussion and Figure 3). This set of data is crucial for directing the specific training schedule towards the individual characteristics, technical and/or physiological, that needs to be improved. Indeed, the metabolic power requirement ($\dot{E}$) for swimming at any given speed (v) is the product of the energy cost at that speed (C_{sw}) and the velocity: $\dot{E} = C_{sw} \cdot v$. As described in the theory section, this equation shows that, for any given swimmer, the maximal speed is set by the ratio between his/her maximal metabolic power and the energy cost of swimming at that speed:

$$v_{max} = \frac{\dot{E}max}{Csw}$$

In turn, $\dot{E}_{max}$ is a function of the maximal aerobic power and of the anaerobic capacity, as described by equation 2. Hence the approach outlined above yields all the necessary information to predict best performances of any given swimmer over any given distance. Furthermore, the above approach yields information of maximal aerobic power, maximal anaerobic capacity and energy cost of swimming, separately from each other. This allows the coach to direct the training towards the subject's characteristics that need to be improved and that he deems more relevant in the competitions at stake.

The above considerations should be taken with a grain of salt, since they were obtained on one subject only and were limited to front crawl swimming. Even so, we think that they deserve serious consideration in practice.

Conclusions

These data suggest that the energy cost of front crawl swimming during actual competitions, because of the starting dive and of the leg pushes on the walls of the pool, is about 15% lower than observed at constant speed swimming. However, to pursue this analysis further it seems mandatory to perform this type of analysis on a larger number of swimmers.

We would like to point out also that the approach summarized above is similar to that proposed by Lloyd in 1966 [24] but, as suggested by di Prampero et al.[25], it takes into account the fact that the energy cost of swimming is not constant but increases with the speed. Finally, we would like to stress that, if the energy cost of swimming as the functional of speed is known, this approach yields reasonable estimates of the swimmers' maximal oxygen consumption and maximal anaerobic capacity.

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Informed Consent Statement

Informed consent was obtained from all subjects involved in the study.

Ethical Committee approval

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Topic

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Conflicts of interest

The authors have no conflicts of interest to declare.

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Author-s contribution

Conceptualization, A.B. and G.M.M.; methodology, A.B. and G.M.M; software, A.B.; validation, A.B. and P.E.dP.; formal analysis, A.B.; investigation, A.B. and G.M.M; resources F.DeS. and L.R.; data curation, A.B.; writing—original draft preparation, A.B. and P.E.dP.; writing—review and editing, A.B. and G.M.M.; visualization, A.L; supervision, J.P.;
project administration, A.B. and G.M.M. All authors have read and agreed to the published version of the manuscript.

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