

# Energetics of swimming: a historical perspective

P. Zamparo · C. Capelli · D. Pendergast

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**Abstract** The energy cost to swim a unit distance ( $C_{sw}$ ) is given by the ratio  $\dot{E}/v$  where  $\dot{E}$  is the net metabolic power and  $v$  is the swimming speed. The contribution of the aerobic and anaerobic energy sources to  $\dot{E}$  in swimming competitions is independent of swimming style, gender or skill and depends essentially upon the duration of the exercise.  $C_{sw}$  is essentially determined by the hydrodynamic resistance ( $W_d$ ): the higher  $W_d$  the higher  $C_{sw}$ ; and by the propelling efficiency ( $\eta_p$ ): the higher  $\eta_p$  the lower  $C_{sw}$ . Hence, all factors influencing  $W_d$  and/or  $\eta_p$  result in proportional changes in  $C_{sw}$ . Maximal metabolic power ( $\dot{E}_{max}$ ) and  $C_{sw}$  are the main determinants of swimming performance; an improvement in a subject's best performance time can more easily be obtained by a reduction of  $C_{sw}$  rather than by an (equal) increase in  $\dot{E}_{max}$  (in either of its components, aerobic or anaerobic). These sentences, which constitute a significant contribution to today's knowledge about swimming energetics, are based on the studies that Professor Pietro Enrico di Prampero and his co-workers carried out since the 1970s. This paper is devoted

to examine how this body of work helped to improve our understanding of this fascinating mode of locomotion.

**Keywords** Energy expenditure · Swimming economy · Swimming efficiency · Hydrodynamic resistance

## Introduction

The energetics of human locomotion has been studied for more than a century. In recent times, Professor Pietro Enrico di Prampero and his co-workers have significantly contributed to increase knowledge in this field of human exercise physiology. In particular, two of his papers, a review of the energetics of muscle exercise (di Prampero 1981) and a review of the energy cost of locomotion on land and water (di Prampero 1986) are seminal papers for those who want to approach this topic.

The studies that he and his co-workers have conducted on water locomotion at the surface including rowing (di Prampero et al. 1971; Celentano et al. 1974), kayaking (Pendergast et al. 1989; Zamparo et al. 1999; Zamparo et al. 2006a) and even Venetian gondolas (Capelli et al. 1990), traditional boats (Capelli et al. 2009) and pedal driven watercrafts (Zamparo et al. 2008a) are examples of both his theoretical and practical approach to the energetics of locomotion in this particular environment.

It is perhaps in swimming where he and his co-workers have made their greatest contribution by: (i) describing the energy cost of swimming as a function of velocity at sub-maximal (di Prampero et al. 1974; Pendergast et al. 1977; Capelli et al. 1995; Zamparo et al. 1996a) and maximal speeds (Capelli et al. 1998a; Termin and Pendergast 2000; Zamparo et al. 2000); (ii) developing and testing a method for determining hydrodynamic resistance during swimming

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(di Prampero et al. 1974; Pendergast et al. 1977; Zamparò et al. 2002; Zamparò et al. 2005a); and (iii) demonstrating the effect of body incline (torque) on the energy cost of swimming (Pendergast et al. 1977; Capelli et al. 1995; Zamparò et al. 1996a; Zamparò et al. 1996b; Zamparò et al. 2000; Zamparò et al. 2008b).

Until the 1970s, research in swimming was limited by the availability of the technology necessary to overcome the challenges of measuring energy expenditure in the aquatic environment. Although experiments in standard swimming pools were conducted, it was the development of the swimming flume in Stockholm (Sweden) and the annular swimming pool in Buffalo (USA) that created the opportunity to conduct more extensive studies on the energetics of swimming. Although these facilities allowed the determination of the energy cost of swimming at speeds that could be sustained with oxidative metabolism, no method was then available to determine the energy cost of high velocity swimming, where anaerobic metabolism dominates. To solve this problem, di Prampero developed and published three methods to estimate the energy cost of swimming at maximal speeds: (i) he demonstrated that blood lactate concentration could be utilized to estimate the energy derived from anaerobic lactic energy sources (di Prampero et al. 1978; di Prampero 1981); (ii) he adapted Wilkie's relationship (Wilkie 1980) to estimate energy expenditure during short bouts of exhaustive exercise (di Prampero 1986); and (iii) he showed that energy expenditure during maximal exercise can be estimated by determining the relationship between sub-maximal energy expenditure and "negative drag", the latter assessed by partially towing the swimmer at the surface (di Prampero et al. 1974).

For a complete understanding of the energetics of swimming, it is necessary not only to measure/estimate metabolic power expenditure but also to measure/estimate the work and the efficiency of swimming. Early investigations determined drag by towing the swimmer at the surface (for a review on these early passive drag studies, see Faulkner 1968) and many current studies use the same technique. To our knowledge, the method of determining active drag proposed by di Prampero et al. (1974) was the first to attempt to assess drag during actual swimming conditions. Even if values of efficiency based on passive drag measurements had already been published in the 1930s (e.g. Karpovich and Pestrecov 1939), the method proposed by di Prampero et al. (1974) was the first to allow an estimate of swimming efficiency based on the values of active drag.

In spite of the uniqueness of the methods and theories published by di Prampero et al., several issues remain unresolved (e.g. the methods to determine active drag and the energy equivalent of lactate were openly debated in the

literature). Still, his pioneering studies proved to be among the most innovative ways to address the very challenging topic of locomotion in water.

In the following paragraphs, today's knowledge about the energy cost and the efficiency of swimming will be reviewed and the contribution of Professor Pietro Enrico di Prampero to this knowledge will be emphasized.

### The energy cost of swimming

The energy cost per unit distance ( $C_{sw}$ ) can be defined as:

$$C_{sw} = \dot{E} \cdot v^{-1} \quad (1)$$

where  $\dot{E}$  is the net metabolic power expenditure and  $v$  is the speed of progression (e.g. di Prampero 1986). If the speed is expressed in  $m s^{-1}$  and  $\dot{E}$  in  $kJ s^{-1}$ ,  $C_{sw}$  results in  $kJ m^{-1}$ : it represents the energy expended to cover one unit of distance while swimming at a given speed and with a given stroke.

#### Energy cost of swimming at sub-maximal speeds

Net metabolic power expenditure ( $\dot{E}$ ) is quite easy to measure provided that the exercise is sub-maximal:

$$\dot{E} = \dot{V}O_2 \quad (2)$$

where  $\dot{V}O_2$  is steady state oxygen consumption (e.g. assessed by standard open circuit techniques). In these conditions, energy expenditure is based on "aerobic energy sources" (the rate of ATP utilization is equal to the rate of ATP resynthesized by lipid and glucid oxidation in the Krebs' cycle) as reviewed by di Prampero (1981).

Measurements of energy expenditure in aquatic locomotion based on the open circuit technique stem back to the 1930s (e.g. Karpovich 1933; Karpovich and Pestrecov 1939; Adrian et al. 1966; Faulkner 1968). These early studies pointed out the higher energy expenditure that one has to face, at a given speed, when moving in water with respect to land.

The majority of the studies about swimming energetics reported in the literature to date have been conducted at sub-maximal speeds where aerobic energy sources are primarily used. However, measuring the energy cost at sub-maximal speeds has a limited appeal to those interested in competitive swimming performance since races are typically swum at much faster paces.

#### Energy cost of swimming at maximal speeds

Since  $\dot{V}O_2$  attains a steady state value with a time constant ( $\tau$ ) of about 30 s (e.g. Rossiter et al. 2002), the standard open circuit method could also be applied to measure the

aerobic contribution in maximal swimming trials lasting at least 2–3 min (e.g. more than 4–5 $\tau$ ) which is the typical case of swimming races over the 400 m distance (it lasts indeed about 4 min in the front crawl). Competitions over longer distances (800 and 1,500 m) also rely on aerobic energy sources and are swum at a fraction of  $\dot{V}O_{2\max}$  which is smaller the longer the race duration (e.g. Saltin 1973). In those cases, the contribution of anaerobic lactic energy sources plays an important role, the more so the shorter the distance, and a fraction of the ATP utilized by the muscles is resynthesized by anaerobic glycolysis (di Prampero 1981). To correctly compute the energy required to swim at these speeds is therefore necessary to determine, directly or indirectly, the lactic contribution to total energy expenditure. In other words, it is necessary to take into account the net rate of lactate production by the working muscles. This quantity is rather difficult to quantify in swimming humans but it has been estimated on the basis of the accumulation of lactate in venous blood as shown by di Prampero and co-workers (di Prampero et al. 1978; di Prampero 1981).

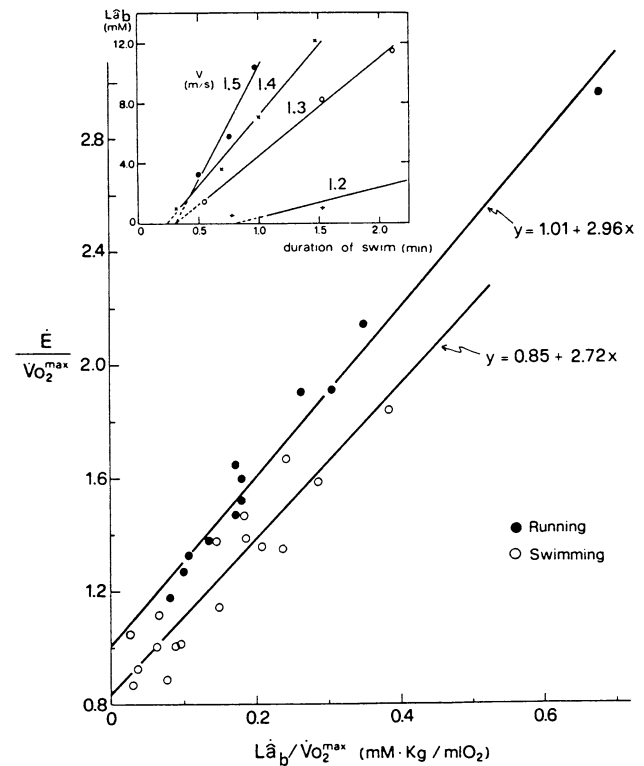
As indicated in the insert of Fig. 1 (taken from di Prampero 1981), peak blood lactate concentration ( $L_{a_b}$ , mM) depends both on the exercise intensity (the swimming speed) and on the duration of the exercise ( $t$ , min). At a given exercise intensity (for a given swimming speed),  $L_{a_b}$  increases linearly with the duration of exercise, the slope of the relationship between  $L_{a_b}$  (mM) and exercise duration ( $t$ , min) representing the rate of lactate accumulation in the peripheral venous blood ( $\dot{L}_{a_b}$ , mM min<sup>-1</sup>); this rate (slope) is higher the higher the exercise intensity (insert of Fig. 1). This holds true as long as blood is sampled from veins not directly draining the working muscles and if standardized conditions of sampling during recovery are applied (di Prampero 1981).

As shown by Fig. 1 (where both axes are normalized for  $\dot{V}O_{2\max}$  to compare different subjects),  $\dot{L}_{a_b}$  (the rate of lactate accumulation in the peripheral venous blood) increases linearly with the energy requirements of exercise (e.g. with  $\dot{E}$ , ml min<sup>-1</sup> kg<sup>-1</sup>):

$$\dot{E} = \dot{V}O_{2\max} + \beta \dot{L}_{a_b} \quad (3)$$

The intercept of this relationship corresponds to  $\dot{V}O_{2\max}$  and the slope ( $\beta$ ) represents the energy equivalent of lactate. Data obtained during running (Margaria et al. 1971) or swimming the front crawl (di Prampero et al. 1978) at supra-maximal speeds indicate similar values of this slope: it amounts to about 3 mlO<sub>2</sub> per mM and per kg of body mass.

In line with this reasoning, the energy balance of supra-maximal exercise can be estimated by adding to the measured steady state  $\dot{V}O_2$  (e.g. in ml min<sup>-1</sup> kg<sup>-1</sup>), the metabolic power output derived from anaerobic lactic metabolism. This can be calculated as the net lactate concentration (mM) multiplied by the energy equivalent of



**Fig. 1** Energy requirement of exercise ( $\dot{E}$ ) as a function of the rate of lactate accumulation in blood ( $\dot{L}_{a_b}$ ) in running and swimming. To compare different subjects both parameters are expressed as a ratio of the subject's  $\dot{V}O_{2\max}$ . The energy equivalent of lactate ( $\beta$ ) corresponds to the slope of these regressions: it amounts to about 3 ml mM<sup>-1</sup> kg<sup>-1</sup>. *Insert* shows peak blood lactate concentration as a function of the duration of preceding exercise in front crawl swimming at the indicated speeds. See text for details. Taken from di Prampero (1981) (with kind permission of Springer Science and Business Media)

lactate (mlO<sub>2</sub> mM<sup>-1</sup> kg<sup>-1</sup>) and divided by the exercise duration (min); the metabolic power output derived from anaerobic lactic metabolism is, thus, also expressed in ml min<sup>-1</sup> kg<sup>-1</sup>. This method to calculate the lactic component of energy expenditure demonstrates why the contribution of the anaerobic lactic energy sources decreases along with the duration of exercise, independently of the absolute peak lactate concentration in blood.

Whereas the method proposed by di Prampero could be, and has been, debated, he has shown that when the limitations of this approach are taken into account, these calculations can be utilized to estimate the energy requirement of supra-maximal exercise (di Prampero 1981; di Prampero and Ferretti 1999). Indeed, this method has been validated and utilized to estimate the energy requirements of supra-maximal exercises in several forms of locomotion and, of course, also in swimming (e.g. Capelli et al. 1998a; Termin and Pendergast 2000; Zamparo et al. 2000).

The energy expenditure over the shorter competitive swimming distances (50, 100 and 200 m) necessarily

implies the contribution of the anaerobic alactic energy sources, the more so the shorter the race duration. To compute the energy cost in such races requires therefore a measure of all three components of  $\dot{E}$ .

In 1980, Wilkie proposed an equation to describe maximal mechanical power ( $\dot{W}_{\max}$ , kW) as a function of the exhaustion time ( $t$ , s) in cycling for bouts lasting from few seconds to about 10 min:

$$\dot{W}_{\max} = A \cdot t^{-1} + B - B \cdot \tau(1 - e^{-(t/\tau)}) \cdot t^{-1} \quad (4)$$

where  $A$  is the amount of mechanical work (kJ) that can be derived from anaerobic energy sources (lactic and alactic),  $B$  is the maximal mechanical power sustainable on the basis of aerobic energy sources ( $\dot{V}O_{2\max}$ , kW) and  $\tau$  (s) is the time constant of the kinetics of  $\dot{V}O_2$  at the onset of exercise. The third term of Eq. 4 is a measure of the  $O_2$  debt incurred at exercise onset.

This equation was utilized by di Prampero (1986) to describe the relationship between maximal metabolic power ( $\dot{E}_{\max}$ , kW) and  $t$  in similar terms:

$$\dot{E}_{\max} = AnS \cdot t^{-1} + \alpha \dot{V}O_{2\max} - \alpha \dot{V}O_{2\max} \cdot \tau(1 - e^{-(t/\tau)}) \cdot t^{-1} \quad (5)$$

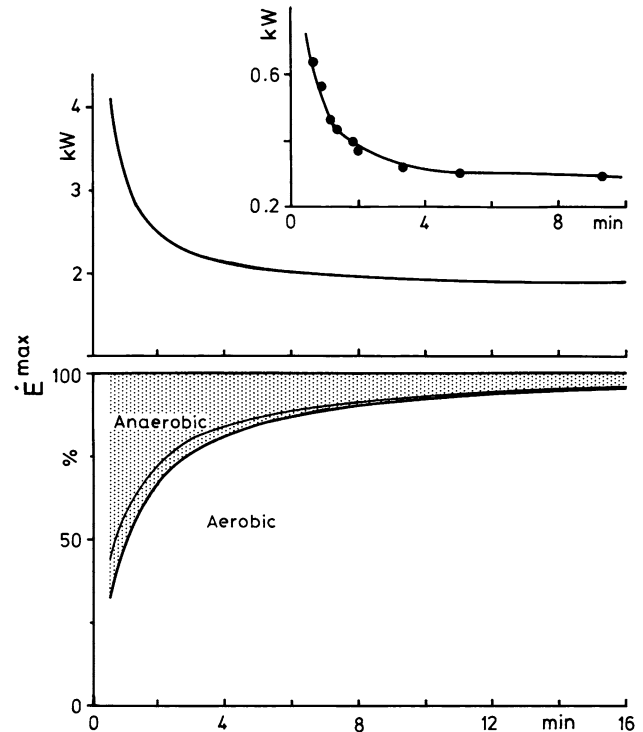
where  $\alpha$  is the energy equivalent of  $O_2$ ,  $\tau$  is time constant of the kinetics of  $\dot{V}O_2$  at the onset of exercise,  $AnS$  is the amount of energy (kJ) derived from anaerobic energy utilization and  $\dot{V}O_{2\max}$  (kW) is the net maximal oxygen uptake; see Fig. 2, taken from di Prampero (1986).

It is therefore possible to calculate the aerobic contribution (Aer, kW) to maximal metabolic power ( $\dot{E}_{\max}$ , kW) as the sum of the second and third term of Eq. 5, whereas the anaerobic contribution is represented by the term  $AnS \cdot t^{-1}$ . In turn,  $AnS$  is given by the sum of the energy derived from lactic acid production ( $AnL$ , kJ) plus that derived from maximal phosphocreatine (PCr) splitting in the contracting muscles ( $AnAl$ , kJ):

$$AnS = AnL + AnAl = (\beta La_b + PCr(1 - e^{-t/\tau}))M \quad (6)$$

where  $La_b$  is the peak accumulation of lactate after exercise (above resting values),  $\beta$  is the energy equivalent for lactate accumulation in blood,  $\tau$  is the time constant of PCr splitting at work onset and  $M$  (kg) is the mass of the subject. The implicit assumption is also made that the time constant of PCr breakdown at work onset is the mirror increment of the  $\dot{V}O_2$ —on response at the muscle level (e.g. Rossiter et al. 2002).

The energy derived from complete utilization of PCr stores ( $AnAl$ ) can be estimated assuming that, in the transition from rest to exhaustion, the PCr concentration decreases by 18.5 mM  $kg^{-1}$  muscle (wet weight) in a maximally active muscle mass (e.g. assuming it corresponds to 30% of body mass). Assuming further a  $P/O_2$  ratio of 6.25



**Fig. 2** Upper panel shows the maximal external power (kW) that can be maintained at a constant level during cycloergometric exercise as a function of the effort duration to exhaustion. Middle panel shows the relationship between maximal metabolic power (kW) and effort duration to exhaustion. In the lower panel, maximal metabolic power is partitioned into aerobic and anaerobic components. See text for details. Taken from di Prampero (1986) (with kind permission of Georg Thieme Verlag KG)

and an energy equivalent of 20.9 kJ  $IO_2^{-1}$ ,  $AnAl$  can be calculated as:  $(18.5/6.25) \times 0.3 \times 468.2 = 416$  J  $kg^{-1}$  body mass (e.g. Capelli et al. 1998a).

Even if the approach described above has been debated due to the many assumptions in the calculation of some of the parameters of interest (e.g. the PCr stores, the energy equivalent of lactate) it has proven to be useful to estimate the energy demands during supra-maximal exercise in several forms of locomotion. This method has been applied to running (di Prampero et al. 1993), cycling (Capelli et al. 1998a, b), kayaking (Zamparo et al. 1999, 2006a) and, of course, swimming (Capelli et al. 1998a; Zamparo et al. 2000).

As discussed in detail by Capelli et al. (1998a) these calculations apply only to “square wave” exercises of intensity close to, or above, maximal aerobic power. At these intensities, a true steady state of oxygen uptake cannot be attained and the energy contributions other than the aerobic play a major role. In swimming, this applies to all competitive races below 400 m (i.e. the majority of competitive races).

By means of the method described above, Capelli et al. (1998a) were able to calculate the energy cost of swimming ( $C_{sw} = \dot{E}_{tot}/v$ ) in each of the four strokes at speeds close to those attained during competitions (up to 1.5–2.0 m s<sup>-1</sup>, depending on the stroke). Their results confirm and extend those of previous studies performed at slower speeds (e.g. Holmér 1974, up to 1.2–1.4 m s<sup>-1</sup>) which show that front crawl is the most economical stroke followed by the backstroke and the breaststroke, with the butterfly being the more demanding stroke (in terms of  $C_{sw}$ ).

On the basis of this approach it is also possible to calculate the percentage contribution of the aerobic and anaerobic energy sources to total energy expenditure: for swimming this contribution was shown to be independent of swimming style, gender or skill and to depend essentially upon the duration of the exercise (Capelli et al. 1998a; Zamparo et al. 2000). The contribution of the three energy sources when swimming at sub-maximal and maximal speeds in the four strokes and over different distances is reported in Table 1 (adapted from Capelli et al. 1998a). The exercise duration is indeed the major determinant of the energy source to be exploited in all forms of locomotion as shown by all the studies cited above and recently pointed out by di Prampero (2003).

The determinants of the energy cost of swimming

Since the relationship between metabolic power ( $\dot{E}$ ), power to overcome drag ( $\dot{W}_d$ ) and the propelling ( $\eta_P$ ) and overall/gross ( $\eta_O$ ) efficiency of swimming (described later in more detail) is given by:

$$\dot{E} = \dot{W}_d / (\eta_P \cdot \eta_O) \tag{7}$$

and since, for any given speed,  $C_{sw} = \dot{E}/v$  and  $\dot{W}_d = W_d \cdot v$ , it follows that:

$$C_{sw} = W_d / (\eta_P \cdot \eta_O) \tag{8}$$

Equation 8 indicates that at any given speed and for a specific  $\eta_O$ , an increase in  $\eta_P$  and/or a decrease in  $W_d$  lead to a decrease in  $C_{sw}$  (e.g. allowing the swimmer to spend less energy to cover a given distance or to cover the same distance at a higher speed).

Underwater torque

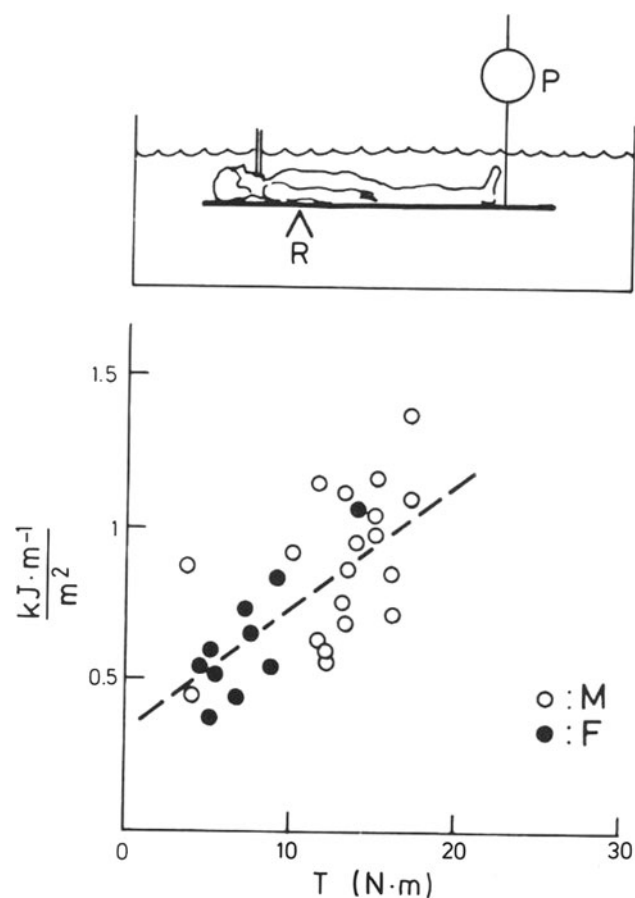
The underwater balance was developed by di Prampero and co-workers in the 1970s (di Prampero et al. 1974; Pendergast and Craig 1974; Pendergast et al. 1977) to understand the effects of  $W_d$  on  $C_{sw}$ . By means of this method, they were able to demonstrate the effect of the “static position in water” described quantitatively by measuring the underwater torque ( $T$ ) on the energy cost of swimming: the greater the  $T$  (a measure of the body incline) the higher the energy required to cover a given distance at a given speed. Figure 3, taken from di Prampero (1986) indicates that while the function relating  $C_{sw}$  and  $T$  is the same for both genders, men spend more energy per unit distance than women, as they have greater values of  $T$ . Further experiments have supported these findings and extended these results to different speeds and to swimmers of different age groups (Capelli et al. 1995; Zamparo et al. 1996a; Zamparo et al. 2000; Zamparo et al. 2008b). These studies have shown that, at low swimming speeds, about 70% of the variability of  $C_{sw}$  is explained by the variability of  $T$ , regardless of the sex, age and technical level of a swimmer.

As suggested by di Prampero (1986), body incline in water (and hence  $T$ ) depends on the anthropometric characteristics of the swimmer. This has been confirmed by recent studies by Zamparo et al. (1996b, 2008b) who have shown that  $T$  can be estimated on the basis of measures of body mass, stature and density. These papers further demonstrated what di Prampero had suggested in his review: “that with sexual maturity boys “deteriorate” their body asset in water more than girls” (see Fig. 4, taken from Zamparo et al. 2008b). The advantage of having a lower  $T$  for girls/females is apparent in long distance races (swum at relatively slow speeds) were the gap in performance between females and males is reduced, or eliminated, in comparison with sprint races (Zamparo et al. 1996b).

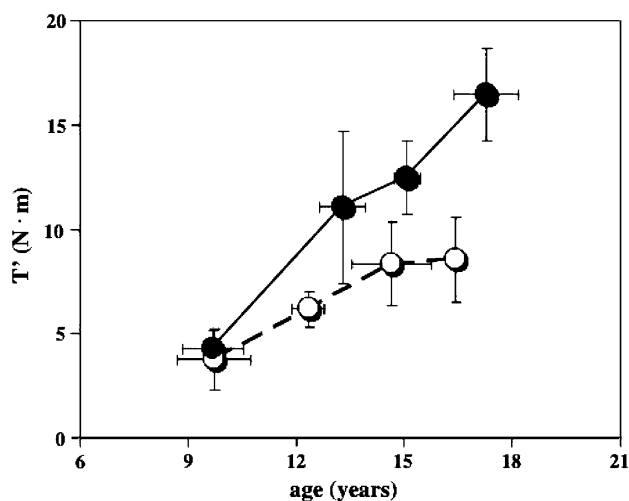
Both the definition of  $T$  and the usefulness of its measurement have been debated. As defined in early studies (di Prampero et al. 1974; Pendergast and Craig 1974; Pendergast et al. 1977), underwater torque is caused by “the

**Table 1** Percentage contribution of anaerobic alactic (AnAl), anaerobic lactic (Anl) and aerobic (Aer) energy sources to the overall energy expenditure during maximal swimming trials in the four strokes over three distances (adapted from Capelli et al. 1998a)

Stroke	Distance (m)	Speed (m s <sup>-1</sup> )	AnAl (%)	Anl (%)	Aer (%)
Crawl	45.7	1.97	25.8	58.9	15.3
	91.4	1.75	19.6	47.2	33.3
	182.9	1.62	13.8	24.7	61.5
Backstroke	45.7	1.73	23.1	59.4	17.4
	91.4	1.64	20.0	43.6	36.4
	182.9	1.52	12.6	28.2	59.2
Breaststroke	45.7	1.50	29.3	43.7	27.1
	91.4	1.34	18.7	34.8	46.5
	182.9	1.23	10.4	21.7	67.9
Butterfly	45.7	1.85	25.9	57.3	16.9
	91.4	1.63	19.2	47.5	33.3
	182.9	1.41	12.3	26.6	61.1



**Fig. 3** Net energy cost of swimming the front crawl (normalized per body surface) as a function of the underwater torque ( $T$ , N m). *Upper panel* is a schematic representation of the underwater balance ( $R$  fulcrum,  $P$  strain gage). See text for details. Taken from di Prampero (1986) (with kind permission of Georg Thieme Verlag KG)



**Fig. 4** Underwater torque ( $T$ , N m) as a function of age (years) in male (full circles) and female (open circles) swimmers. See text for details. Taken from Zamparo et al. (2008b) (with kind permission of Springer Science and Business Media)

tendency of the feet to sink around the center of volume of air in the lungs”. This definition has no physical validity since the “true torque” to which an immersed body is subjected to is due to the tendency of the upper part of the body (more buoyant because of the air filling the lungs) to rotate around the center of mass. However, as demonstrated by Capelli et al. (1995) and by Zamparo et al. (1996b) underwater torque (as measured with the method proposed by di Prampero et al.) takes into account both the effect of underwater weight and of “true torque”. Moreover, its value is independent of the phases of the breathing cycle. As such,  $T$ , although not theoretically correct, is indeed a good index to estimate the forces that influence the position a body assumes while submerged in water and thus of the factors which influence hydrodynamic resistance.

At high swimming speeds, the hydrodynamic lift counteracts the tendency of the legs to sink and, at least in the front crawl, the body remains horizontal, whatever the static position would be. The relationship between  $C_{sw}$  and  $T$  in the first studies (di Prampero et al. 1974; Pendergast and Craig 1974; Pendergast et al. 1977) was investigated at low (below  $1 \text{ m s}^{-1}$ ) swimming speeds compared to competitive swimming. More recently, Zamparo et al. (2000) have shown that the relationship between  $C_{sw}$  and  $T$  is “significant” only up to  $1.2\text{--}1.4 \text{ m s}^{-1}$  as at higher speeds there seems to be no relationship between the static and dynamic positions in water. Even with this limitation, measuring this parameter can be very useful to: (i) characterize the swimming aptitude of a young swimmer; (ii) to monitor the changes in this attitude during the pre to post pubertal age; (iii) to understand the determinants of performance over long distance races (covered at speeds lower than  $1.2 \text{ m s}^{-1}$ ).

The importance of  $T$  in determining  $C_{sw}$  (and hence performance) is of course due to its relationship with the dynamic position in water (body incline) and on hydrodynamic resistance as recently pointed out by Zamparo et al. (2008b, 2009) and Kjendlie et al. (2004a). Indeed  $T$  is an indirect measure of the effective frontal area of the subject ( $A$ ), which is one of the determinants of pressure drag ( $D_p$ ):

$$D_p = \frac{1}{2} \rho A C_d v^2 \quad (9)$$

where  $C_d$  is the coefficient of hydrodynamic resistance,  $\rho$  is the water density and  $v$  the swimming speed.

To understand the relationship between  $C_{sw}$  and  $W_d$  is of course better to measure  $W_d$  directly.

## Hydrodynamic resistance

Before the 1970s hydrodynamic resistance was measured/estimated on subjects passively towed in water (e.g. Faulkner 1968; Karpovich 1933; Karpovich and Pestrecov

1939). In the 1970s, di Prampero and co-workers devised and utilized a method to assess drag during actual swimming conditions (di Prampero et al. 1974; Pendergast et al. 1977). With this method, the swimmer's body drag can be increased or decreased by known amounts by applying to the swimmer a constant force acting along the direction of movement (Fig. 5, taken from di Prampero 1986). The relationship between added drag ( $D_a$ ) and energy expenditure, for a given speed is linear and, when this relationship is extrapolated to resting  $\dot{V}O_2$ , it allows to estimate the force that, when applied to the swimmer, is equal (in value) and opposite (in sign) to the drag that the swimmer has to overcome at that speed.

This method also allows estimation of energy expenditure at speeds greater than that corresponding to the subject's  $\dot{V}O_{2\max}$ : the extrapolation of the function relating  $D_a$  to  $\dot{V}O_2$  to  $D_a = 0$  is a measure, in  $O_2$  equivalents, of the energy required to swim at the given speed (see left side of Fig. 5). Thus, this method can be used to estimate both drag and energy expenditure at the high swimming speeds used in competitive swimming. It is also a method that can be employed to evaluate any of the four competitive strokes, an advantage in respect to other methods that are limited to the front crawl.

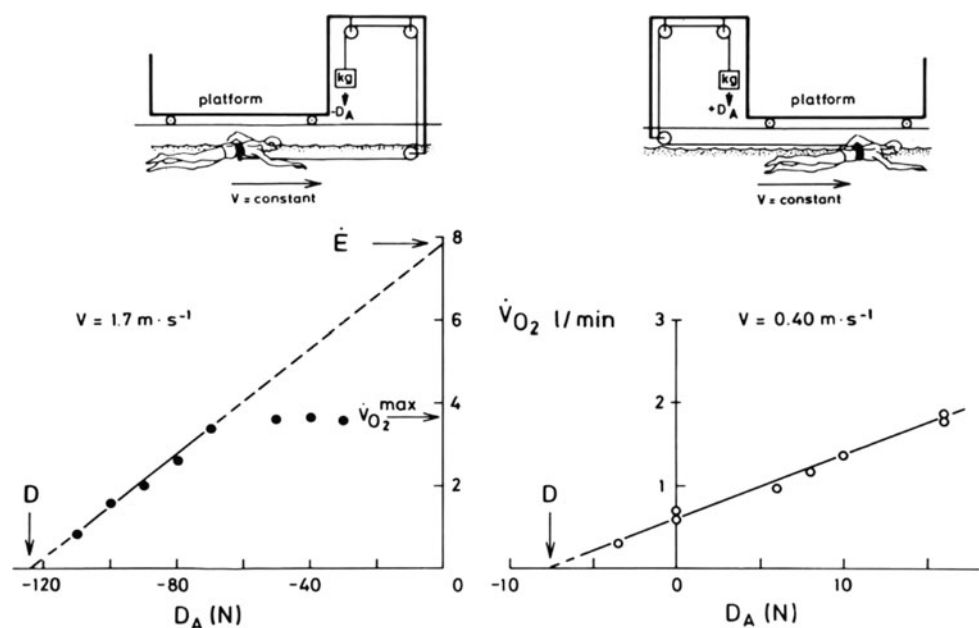
The method described above has recently been utilized to estimate active drag (Zamparo et al. 2002, 2005a) even if some of the assumptions of the method have been questioned in the literature. The major objection to this method is that the decrease of  $\dot{V}O_2$  observed as a consequence of adding masses to the pulley system could not be attributed to changes in hydrodynamic resistance only ( $W_d$ ) but to changes in total mechanical work ( $W_{\text{tot}}$ ). This remark

is quite correct and indeed the reciprocal of the slope of the  $\dot{V}O_2$  versus  $D_a$  relationship is not a measure of overall efficiency, as originally postulated by di Prampero et al.; rather, is a measure of drag efficiency (see Zamparo et al. 1996a and discussion below about the efficiencies in swimming). However, as discussed by Zamparo et al. (1996a, 2002) the  $\dot{V}O_2$  versus  $W_{\text{tot}}$  relationship, for a given speed, is also linear (albeit with a different slope) and the contribution of  $W_d$  to  $W_{\text{tot}}$  is larger the larger  $D_a$ . Thus, when extrapolated to resting  $\dot{V}O_2$ , this relationship crosses the same point on the  $D_a$  axis: this, therefore, does not affect the estimation of drag.

The other “active” methods reported in the literature present advantages and disadvantages with respect to the method proposed by di Prampero and coworkers.

The method proposed by Kolmogorov and Duplisheva (1992) has the advantage that it could be applied to the four strokes but the disadvantage that it could be applied only at maximal speeds. Moreover, with this method drag is estimated from the difference in swimming speed when the subject swims free or with a hydrodynamic body attached (that creates a known additional resistance); a further assumption is made that in the two cases, the swimmer is expressing the same power output. As recently pointed out by Toussaint et al. (2004), the equal power assumption is easily violated and this leads to errors in the determination of drag. When this assumption is valid (when the “free swimming speed” is close to the speed attained when swimming with the hydrodynamic body), this method yields values of drag similar to those that can be assessed with the measuring active drag (MAD) system at the corresponding speed (Toussaint et al. 2004).

**Fig. 5** Net oxygen consumption ( $\dot{V}O_2$ ,  $l \cdot \text{min}^{-1}$ ) when swimming the front crawl at constant speed (left panel  $1.7 \text{ m} \cdot \text{s}^{-1}$ , right panel  $0.4 \text{ m} \cdot \text{s}^{-1}$ ) as a function of the added drag ( $D_a$ , N). Upper panels show the method used to apply known forces to the swimmer's body. See text for details. Taken from di Prampero (1986) (with kind permission of Georg Thieme Verlag KG)



As far as the MAD system is regarded (e.g. Toussaint 1990), its advantage is that it allows to measure directly the push off forces exerted during “swimming” on fixed pads positioned underwater. This method could be applied only to the front crawl but it allows to investigate drag at different swimming speeds (sub-maximal and maximal). The major criticism to this method (as far as the determination of drag is regarded) is that the swimmer uses the arm stroke only since the legs are floated with a small buoy. It goes without saying that this condition affects the effective frontal area of the subjects (thus affecting the measure of  $\dot{W}_d$ ).

This state of affairs can be summarized by stating that the measure of active drag is still a controversial issue, a conclusion on which several authors seem to agree (e.g. Havriluk 2007; Toussaint et al. 2004; Wilson and Thorp 2003; Zamparo et al. 2009).

### Age and gender

As indicated by several studies in the literature, women have a lower energy cost than men (e.g. Chatard et al. 1990; Chatard et al. 1991; Montpetit et al. 1983; Montpetit et al. 1988; Pendergast et al. 1977; Zamparo et al. 2000) and their higher economy is traditionally attributed to a smaller hydrodynamic resistance due to their smaller size, larger percentage fat and more horizontal position in comparison to male swimmers. This is in accordance with theoretical considerations (e.g. Eq. 8). Changes in the anthropometric characteristics (and thus on  $T$  and  $\dot{W}_d$ ) are also observed during development and this should have an effect on  $C_{sw}$ . Indeed it was found that, at comparable speed, the energy cost is lower in children than in adults (Poujade et al. 2002; Kjendlie et al. 2004b), i.e. the younger the subjects the lower is  $C_{sw}$  (Zamparo et al. 2008b).

### Technical skill

At variance with other sport activities (e.g. cycling) where minimal differences in efficiency are observed among subjects with different technical abilities, skill greatly influences the energy cost of swimming (e.g. Holmér 1974): the lower the skill level, the higher the energy cost for a given swimming speed and stroke.

Training is expected to improve technical skills. As shown by Termin and Pendergast (2000) a 4-year training period resulted in both a decrease in the energy requirements of swimming at a given speed and a right and upward shift in the stroke frequency versus speed relationship; this shift reflected an increase in the distance

traveled per stroke which, in turn, is an index of propelling efficiency (e.g. Craig and Pendergast 1979; Toussaint et al. 2000; Zamparo et al. 2006 b). According to Eq. 8, these changes are expected to lead to a decrease in  $C_{sw}$ , as experimentally found by these authors. On the other hand, training can lead to a decrease in water resistance (active drag, as reported by Pendergast et al. 2005); according to Eq. 8 this reduction contributes to the decrease in the energy cost of swimming observed after a training period.

### Propelling efficiency

As indicated by Eq. 8, along with hydrodynamic resistance, propelling efficiency is one of the major determinants of  $C_{sw}$ . The relationship between these two parameters can be understood provided we give a clear definition of the efficiencies in aquatic locomotion.

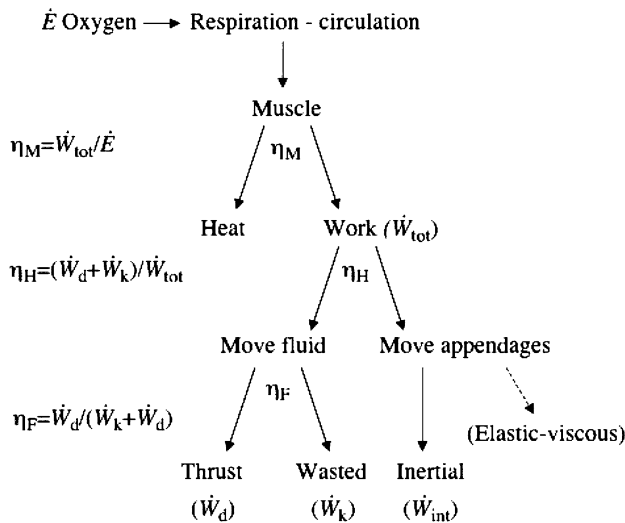
The concepts of efficiency and economy (energy cost) are not interchangeable: an efficient locomotion is one where most of the metabolic power is transformed into mechanical power; if the mechanical power output is close to the minimum necessary and most of it contributes to progression, locomotion is also economical (Minetti 2004).

The total mechanical power of locomotion ( $\dot{W}_{tot}$ ) is the sum of two terms: the power needed to accelerate and decelerate the limbs with respect to the center of mass (the internal power,  $\dot{W}_{int}$ ) and the power needed to overcome external forces (the external power,  $\dot{W}_{ext}$ ) (Cavagna and Kaneko 1977).

In aquatic locomotion  $\dot{W}_{ext}$  can be further partitioned into: the power to overcome drag that contributes to useful thrust ( $\dot{W}_d$ ) and the power that does not contribute to thrust ( $\dot{W}_k$ ). Both  $\dot{W}_d$  and  $\dot{W}_k$  give water kinetic energy but only  $\dot{W}_d$  effectively contributes to propulsion (e.g. Alexander 1977; Daniel 1991; Zamparo et al. 2002). A schematic representation of the energy flow in aquatic locomotion is reported in Fig. 6 (taken from Zamparo et al. 2002).

The efficiency with which the overall mechanical power produced by the swimmer is transformed into useful mechanical power is termed propelling efficiency ( $\eta_P$ ) and is given by  $\dot{W}_d/\dot{W}_{tot}$ . The efficiency with which the overall mechanical power produced by the swimmer is transformed into external power is termed hydraulic efficiency ( $\eta_H$ ) and is given by  $\dot{W}_{ext}/\dot{W}_{tot}$ . The efficiency with which the external mechanical power produced is transformed into useful mechanical power is termed Froude (theoretical) efficiency ( $\eta_F$ ) and is given by  $\dot{W}_d/\dot{W}_{ext}$ . It follows that  $\eta_P = \eta_F \eta_H$ . Hence, if the internal power is nil or negligible (and if the hydraulic efficiency is close to 1)  $\eta_P = \eta_F$ . Thus, propelling efficiency will be lower than Froude efficiency the higher the internal power and the lower the hydraulic efficiency (e.g. Alexander 1977; Daniel 1991; Zamparo et al. 2002).





**Fig. 6** Flow diagram of the steps of energy conversion in aquatic locomotion. See text for details. Taken from Zamparò et al. (2002)

Whereas the Froude, propelling and hydraulic efficiencies refer to the mechanical partitioning only, performance and overall efficiency also take into account the metabolic expenditure. The efficiency with which the metabolic power input ( $\dot{E}$ ) is transformed into useful mechanical power output is termed performance (or drag) efficiency ( $\eta_D$ ) and is given by  $\dot{W}_d/\dot{E}$ . The efficiency with which the metabolic power input ( $\dot{E}$ ) is transformed into mechanical power output ( $\dot{W}_{tot}$ ) is termed overall (or gross or mechanical) efficiency ( $\eta_O$ ) and is given by  $\dot{W}_{tot}/\dot{E}$ . It follows that  $\eta_O = \eta_D/\eta_P$  (e.g. Alexander 1977; Daniel 1991; Zamparò et al. 2002).

A similar description of the power partitioning and the efficiencies in human swimming is reported in the papers of Toussaint et al. (e.g. Toussaint et al. 1988, 2000). These authors, however, do not take into account the contribution of internal power to total power production; therefore, in their calculations the implicit assumption is also made that hydraulic efficiency is 100% and hence  $\eta_F = \eta_P$ .

The first attempts to quantify efficiency in human swimming were made in the 1930s by computing the ratio  $\dot{W}_d/\dot{E}$  (e.g. by calculating  $\eta_D$ ). Indeed, at the time, it was assumed that the power to overcome drag was the majority of total power output in aquatic locomotion, it was hence assumed that  $\eta_D = \eta_O$ . This was also the assumption made in the papers published by di Prampero and co-workers (di Prampero et al. 1971; Pendergast et al. 1977). The values of  $\eta_D$  reported in the literature range from about 0.01–0.02 (e.g. Karpovich and Pestrecov 1939) to 0.03–0.09 (di Prampero et al. 1974; Holmér 1972; Pendergast et al. 1977; Toussaint et al. 1988) indicating that less than 10% of the metabolic power input can be transformed into useful mechanical power output (to overcome drag forces).

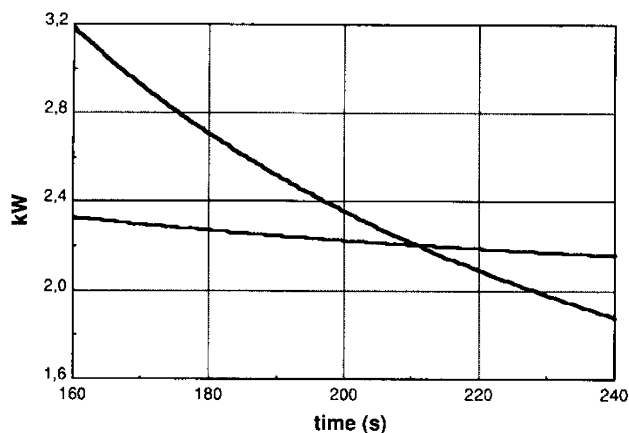
The source of the difference in the values of  $\eta_D$  reported in the literature depends on the method with which the power to overcome drag ( $\dot{W}_d$ ) is measured (active or passive drag) (see above).

The first estimates of  $\eta_P$  for human swimming were reported by Toussaint et al. in the 1980s, with a series of experiments in which the MAD system was utilized. As pointed out by these authors the power wasted to impart non-useful kinetic energy to the water is not negligible ( $\dot{W}_d \neq \dot{W}_{tot}$  and  $\eta_D \neq \eta_O$ ). Thus, they were the first to underline that, besides the conversion of metabolic power input to mechanical power output, it is important to investigate the partitioning of this power output into its useful ( $\dot{W}_d$ ) and non-useful components ( $\dot{W}_k$ ). The values of  $\eta_P$  reported by these authors range from 0.45 to 0.75, i.e. 25–50% of the available mechanical power generated by the muscles is bound to be wasted in aquatic locomotion. Further experiments by this group (e.g. Toussaint 1990; Toussaint et al. 1991) have shown that differences in propelling efficiency do exist according to gender, skill (e.g. triathletes or competitive swimmers) and propelling surface (e.g. when swimming with or without hand paddles). In accordance with Eq. 8 these differences are accompanied by differences in  $C_{sw}$ . It must be pointed out, however, that with the MAD system the legs are floated by a pull buoy, and no measurements of internal power are made so that the values of  $\eta_P$  reported in these studies are, strictly speaking, values of Froude efficiency of the arm stroke.

Other  $\eta_P$  data reported in the literature were obtained by modeling the arm stroke as it was a paddle wheel motion: the values of  $\eta_P$  calculated with this method range from about 0.25 (Martin et al. 1981) to 0.45 (Zamparò et al. 2005a; Zamparò 2006b) in competitive swimmers. According to these authors (Martin et al. 1981; Zamparò et al. 2005a; Zamparò 2006b), the mechanical power used for propulsion ( $\dot{W}_d$ ) is therefore smaller (and  $\dot{W}_k$  larger) than that reported by Toussaint et al.

According to Zamparò (Zamparò 2006b; Zamparò et al. 2008b)  $\eta_P$  of the arm stroke is almost the same in male and female swimmers of the same age and swimming skill: it amounts to about 0.30 before puberty, 0.38–0.40 at 20 years of age and declines to 0.25 in swimmers older than 40 years. The relationship between  $C_{sw}$  and  $\eta_P$  has been pointed out in these and other studies (Zamparò et al. 2002, 2005a, b, 2009): larger the  $\eta_P$  lower the  $C_{sw}$ , for a given subject and a given swimming speed.

Finally, the values of overall efficiency ( $\eta_O$ ) reported in the literature were found to range from about 0.1 (e.g. Toussaint et al. 1990a) to about 0.2 (Zamparò et al. 2005a). Also in this case the difference in the values of  $\eta_O$  is dependent on the different methods utilized to determine active drag and to the fact that the contribution of the legs and of the internal work to total work production were



**Fig. 7** Top curve indicates the metabolic power requirement in track running (kW) to cover 1,500 m as a function of time. Bottom curve indicates the maximal available metabolic power of a top athlete on the same time axis. See text for details. Taken from di Prampero et al. (1993) (with kind permission of the American Physiological Society)

taken into account in the latter study (Zamparo et al. 2005a) but not in the former (Toussaint et al. 1990).

### The interplay between $C_{sw}$ and $\dot{E}_{max}$ in determining swimming performance

Swimming performance (as determined by the shortest time needed to cover a given distance, i.e. by the maximal attainable speed) is given by the ratio:

$$v_{max} = \dot{E}_{max} / C_{sw} \quad (10)$$

where  $\dot{E}_{max}$  is the maximal metabolic power derived from both aerobic and anaerobic energy sources and  $C_{sw}$  is the energy cost of swimming at that speed. Equation 10 is obtained by rearranging Eq. 1 and applying it to maximal conditions.

It necessarily follows that, for a given  $\dot{E}_{max}$ , a subject with a good propelling efficiency and a low hydrodynamic resistance (and hence with a low  $C_{sw}$ ) will be able to swim faster than a subject with a poor  $\eta_p$  and a large  $W_d$  (and

hence with a high  $C_{sw}$ ), as indicated by Eq. 8. On the other hand, a subject with an elevated  $\dot{E}_{max}$  could swim faster than a swimmer with a better  $C_{sw}$  but characterized by a lower maximal aerobic and/or anaerobic power.

A method to investigate the role of  $C_{sw}$  and  $\dot{E}_{max}$  in determining human performance (based on an adaptation of Wilkie's equation described above) was proposed by di Prampero (1981) to perform an energetic analysis of world records. This method was later applied to the analysis of best performance times (BPT) in middle distance running (di Prampero et al. 1993), track cycling (Capelli et al. 1998a, b) and swimming (Capelli 1999).

In short, since the metabolic power required to cover a given distance ( $d$ ) in the time  $t$ , is set by:

$$\dot{E} = C_{sw} \cdot v = C_{sw} \cdot d/t \quad (11)$$

and since, for any given racing distance: (i)  $v$  is a decreasing function of  $t$  and (ii)  $C_{sw}$  is an increasing function of  $v$ , it necessarily follows that larger the  $\dot{E}$  lower the value of  $t$ . For any given distance, the shortest time will then be achieved when  $\dot{E}$  is equal to the individual maximal metabolic power ( $\dot{E}_{max}$ ) as indicated by Fig. 7 (from di Prampero et al. 1993). Since also  $\dot{E}_{max}$  is a decreasing function of  $t$  (e.g. di Prampero 1981), it is possible to estimate the best performance time (BPT) of a swimmer by solving the equality:

$$\dot{E}_{max}(t) = \dot{E}(t) \quad (12)$$

Since  $\dot{E}_{max}$  can be calculated/estimated by means of Eq. 5, with this approach it is also possible to quantify the role of the aerobic and anaerobic (lactic and alactic) energy sources (as well as of  $C_{sw}$ ) in determining best performance times, i.e. by calculating the changes in BPT obtained when each of these variables is changed by a given percentage. As shown by Capelli (1999), in swimming an improvement in a subject's BPT can more easily be obtained by a reduction of  $C_{sw}$  rather than by an (equal) increase in  $\dot{E}_{max}$  (in either of its components, aerobic or anaerobic) (see Table 2). A similar analysis of the BPTs was proposed by Toussaint et al. (2000). These authors also

**Table 2** Percent decrease of theoretical best performance times (BPTs) obtained by increasing by 1% maximal aerobic power ( $\dot{V}O_{2max}$ ), anaerobic alactic capacity (AnAl) and anaerobic lactic capacity (Anl) or by decreasing by 1% the energy cost of front crawl swimming ( $C_{sw}$ )

Distance (m)	Time (s)	AnAl 1% increase (%)	Anl 1% increase (%)	$\dot{V}O_{2max}$ 1% increase (%)	$C_{sw}$ 1% decrease (%)
50	25.2	-0.160	-0.044	-0.034	-0.251
100	55.3	-0.110	-0.042	-0.084	-0.241
200	117.1	-0.069	-0.303	-0.141	-0.237
400	238.2	-0.038	-0.017	-0.187	-0.233
800	485.8	-0.021	-0.008	-0.215	-0.233
1,500	926.7	-0.012	-0.005	-0.229	-0.233

Time values in s (second column) indicate the BPTs calculated utilizing values of  $\dot{V}O_{2max}$ , Anl, AnAl and  $C_{sw}$  of a hypothetical elite athlete (adapted from Capelli 1999)

showed that an improvement in propelling efficiency (e.g. a decrease in the energy cost of swimming) gives the highest performance gain, as compared to an (equal) improvement in the aerobic or anaerobic power.

Thus, these data further underline the importance of the energy cost of locomotion as a major determinant of the maximal speeds attainable during swimming competitions.

## Conclusions

A significant contribution to our current understanding of the bioenergetics and biomechanics of locomotion, including swimming, comes from studies that Professor Pietro Enrico di Prampero has carried out since the 1970s. In his theoretical and empirical papers, he has proposed original and innovative methods to solve, with particular ingenuity, problems related to the determination of drag, efficiency and energy cost of high velocity swimming. These seminal studies have led to further investigations by his co-workers into the physiological and mechanical determinants of swimming performance. His studies have left a mark on the development of the science of swimming and have endeared Professor di Prampero to his colleagues, co-workers and scholars.

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