INVITED CONTRIBUTION

BIOPHYSICS IN SWIMMING

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Performance is the time (t) to cover a given distance (d), i. e. speed of swimming (v = d / t). In turn, v is the product of stroke rate (SR), and distance per stroke (d/S). Maximal v is set by maximal metabolic power (E'max) and energy cost of swimming (C_s). Drag (D), efficiency (η) and v set the metabolic requirements. D can be partitioned in friction (22%), pressure (55%) and wave (23%) drag. D reduction can be achieved by training and swim suit design. _ and C_s are influenced by D, by the energy wasted to water and by the internal work. E'_{tot} is a combination of aerobic and anaerobic power: it increases monotonically with the speed, is highly variable and, it decreases with training. Aerobic, anaerobic lactic and alactic energy supply 38, 43, and 19% in 200 yd and 19, 54, and 26% in 50 yds. At competitive v, C_s is lowest in front crawl and higher in backstroke, butterfly and breaststroke (in that order). The above mentioned factors are highly variable, but even among elite swimmers each is highly trainable.

Key Words: biomechanics, swimming, aerobic, anaerobic, drag, efficiency, training.

INTRODUCTION

Swimming is characterized by the intermittent application of a propulsive force (thrust) to overcome a velocity- dependent water resistance (drag, D). The thrust is generated by a combination of arm cycling and leg kicking which result in fluctuations of thrust and velocity. As the four competitive strokes use differing combinations of arm cycling and leg kicking their inherent fluctuations in velocity are different (3). Fluctuations in thrust, drag and velocity contribute to the highly variable performance in swimming. In all swimming strokes the average velocity (v) is the product of the stroke rate (SF) and the distance the body moves through the water with each stroke cycle (d/S) (3):

 $v = SF \cdot d/S$

(1)The generation of a given velocity requires a given metabolic power output (E'tot) that is velocity-dependent. It is determined by the mechanical power output (W'tot, of which D is a major component) and by the overall efficiency (η) of the

swimmer:

$$E'_{res} = W'_{res} / n$$
 (2)

Since the ratio of E'_{tot} to swimming velocity (v) is the energy cost of swimming per unit distance:

 $Cs = E'_{tot} / v = W'_{tot} / \eta \cdot v^{-1} = W_{tot} / \eta$ (3)where W_{tot} is the mechanical work per unit distance. Equation 3 can also be expressed as:

 $v = E'_{tot} / Cs = E'_{tot} / (W_{tot} / \eta)$ (4)

Equation 4 shows that the maximal velocity is set by the maximal metabolic power of the subject (E'_{tot max}), divided by Cs at

that speed:

v $_{max}$ = E' $_{tot\,max}$ / Cs = E' $_{tot\,max}$ / (W $_{tot\,max}$ / $\eta)$ (5) where W_{tot} is the maximal mechanical work per unit distance.In turn, E'tot max is given by:

 $E'_{tot max} = AnS / t_p + MAP - MAP\tau (1 - e^{-tp/\tau}) / t_p$ (6)where AnS is the energy derived from the anaerobic stores; t_p is the performance time, MAP is the maximal aerobic power and τ is time constant with which V'O_{2max} is attained at the onset of exercise (1). Combining equations 5 and 6, one obtains:

 $v_{max} = (SF \cdot d/S)_{max} = E'_{tot max} / Cs$ $v_{max} = (SF \cdot d/S)_{max} = (AnS / t_p + MAP - MAP \tau (1 - e^{-tp/\tau}) / t_p)$ $t_p) \; / \; (W_{tot \; max} \; / \; \eta)$ (7)

This shows that maximal swimming performance depends on the interplay between biomechanical (SF, d/S, $W_{tot max}$, η) and bioenergetic aspects (AnS, MAP, t). Thus if we can understand the biomechanical and physiology aspects of swimming as a function of velocity we can better understand the biophysics of swimming.

VELOCITY, STROKE RATE AND DISTANCE PER STROKE

The pioneering work of Craig (3) described the relationship between SF, d/S and velocity for all four competitive strokes in elite swimmers. A subsequent study (4) demonstrated the application of the SF-v relationship in competitive events. The basic observation of Craig (3) was that for low velocities, the increase in v was due mostly to the increase in SF. However, with increasing v, the increase of v was due to the combination of an additional increase of SF and a decrease of d/S. These stroke rate-velocity (SF-v) curves are unique to each competitive stroke but similar among swimmers within each stroke. These observations were confirmed by Termin (2001) (Figure 4). The front crawl (FC) had the greatest d/S and SF. The back crawl (BC) was similar to the FC except that at a given SF the d/S and v were less than for the FC.

Increases of v of the butterfly (BF) were related almost entirely to increases in SF, except at the highest v. In the breaststroke (BS) increasing v was also associated with increasing in SF, but the d/S decreased more than in the other strokes. Craig (3) also showed that better swimmers had a greater maximal d/S and could maintain a higher d/S as the SF and v increased. The distance of swimming races was also shown to have a major effect on the SF-v relationship. In U.S. Olympic swimming trials faster velocities were achieved in 1984 (4) than 1976 (3) by increased d/S of the swimmers in many events. However, in selected events, faster v was achieved by using a higher SF, while in many events the higher d/S resulted in lower stroke frequencies. These data suggest that swimmers can choose their SF and d/S based on their technique and physiology, to obtain and sustain a specific velocity. Whether a swimmer can change his/her SF-v relationship and if so, what are the best training techniques.

The intermittent application of thrust and the changes in drag, result in fluctuations in v. As shown by Craig (3) the fluctuation of v in the front and back crawl were (\pm 15-20%) while in the breast and butterfly strokes this variability was much greater (± 45-50%). In the breast stroke Termin (23) demonstrated very large fluctuations in velocity, including a deceleration to zero velocity for a short period during the cycle. It has also been shown that swimmers with less variation in their inter-cycle v have faster v (23).

ENERGY COST OF SWIMMING

The velocity of swimming is determined by the energy cost of swimming and the swimmer's metabolic power (aerobic + anaerobic, eq. 4). In the aerobic range, the energy cost of swimming can be determined by measuring the rate of oxygen consumption V'O2 using standard open circuit techniques. At competitive swimming speeds the anaerobic contribution from anaerobic glycolysis can be estimated from venous blood lactate (La), as validated (8, 7) and used (1, 25). In practice (25) swimmers swam 50, 100, 200, and 400 yards. Each swim was on different days, under meet conditions in a competitive pool, and serial venous blood lactates were taken 6-10 min postswim on the pool deck under a pool heater. The peak value of net La was determined. Assuming net blood lactate accumulation starts at 10 s of exercise, the rate of La accumulation as a function of the speed. This was converted to oxygen equivalents assuming a La equivalent of 3 mlO₂ \cdot kg⁻¹ mM⁻¹ (6, 7, 8). The total metabolic power (E'tot) was estimated from adding the O_2 equivalent for lactate to the maximal aerobic power (8, 1, 25). These data are shown in Figure 1.

The E'_{tot} (indicated as V'O₂ in the figure) was similar for the FS and BC below 1.5 m \cdot s⁻¹. At greater speeds the energy expenditure of the BC increased at a faster rate than in the FC but the maximal E'_{tot}'s were similar. The maximal speed was less in BC than in FC (1.75 vs. 2.0 m \cdot s⁻¹). The energy expenditure of BS and BF were greater than FC and BC at all speeds with BS having the greatest cost and the lower maximal velocity.



Figure 1. The total energy expenditure $(E'_{tot}, aerobic + anaerobic)$ of swimming as a function of velocity for upper division swimmers in the four competitive strokes.

The energy cost per unit distance (Cs) within a stroke was constant for the FC, BC, BS and BF up to speeds of 1.7, 1.4, 1.35 and 1.3 m \cdot s⁻¹, respectively. At velocities greater than these values the Cs increased exponentially in all strokes.

Drag

Water resistance or drag is a major determinant of the energy cost of swimming. Determination of drag in actual swimming (active drag, D_a), to date, has not been measured directly. Drag determined by towing a non-swimming subject through the water, called passive drag (D_p), has been reported for more than a century. Drag measured in this latter manner ignores

the drag that the swimmer creates when he/she develops thrust to overcome the drag. However, measures of D_p can be utilized to investigate the components of total water resistance, namely friction ($D_p = kv$), pressure ($D_p = kv^2$) and wave drag ($D_p = kv^4$). In the study of Mollendorf (10) it was found that total D_p increased monotonically up to 86.2 ± 4.3 N at a v of 2.2 m · s⁻¹ when swimmers wore the traditional brief swim suit. Partitioning D_p revealed that pressure drag dominated D_p at all speeds accounting for 76 %, 63 %, 58 % and 54 % at 1.0, 1.5, 2.0 and 2.2 m · s⁻¹, respectively; whereas friction (5%, 10%, 15%, 18%) and wave (0%, 12%, 21%, 24%) drag shared similar percentages of D_p at the corresponding speeds. The conclusion from these data is that water pressure causes the greatest D_p and thus this form of drag is critical and reducing it could improve performance.

The drag created by the swimmer is such that D_p significantly underestimates the D_a, a fact that has been confirmed by several studies (e.g. 5, 13, 14, 27); thus measuring D_a is an essential prerequisite to understand swimming performance. Several methods have been proposed to measure D_a including di Prampero et al. (5): Clarys, Clarys and Jiskoot, Hollander et al. and Toussaint (26, 27, 28, 29): Zamparo et al. (33) and Payton (12). The two most reported techniques are the indirect extrapolation system of di Prampero et al (5) and Toussaint's MADsystem (26, 27, 28, 29). We are presenting here D_a data as obtained using the di Prampero (5) and Pendergast (14) approach. Data for active D_a are shown in Figure 2 for novice and Upper Division swimmers swimming the front crawl. D_a increased monotonically in both groups up to 100 N at 1.15 m · s⁻¹ in novice and 160 N at 1.8 m · s⁻¹ in Upper Division swimmers. The values of drag measured by this method are higher than D_p and of the values reported by others using different techniques (9, 26, 27). This may be due to the added drag caused by movements of the arms and the legs when swimming, which are not considered in other methods. It is only fair to say that this method is indirect, and may have its own limitations.



Figure 2. Active drag (D_a) is plotted as a function of swimming velocity for male novice $(n = 18, \circ)$ and Upper Division $(n = 42, \bullet)$ swimmers, swimming the front crawl.

The data for partitioned D_a , as described above for D_p , are shown in Figure 3 for novice and Upper Division swimmers. For the novice swimmers pressure D_a is the major contributor to total D_a over their entire range of speeds, which is consistent with the greater frontal surface area that they present

when swimming due to their poor technique. For the Upper Division swimmers pressure D_a also plays an important role, however at speeds greater than 1.5 m \cdot s⁻¹, where competitive events are swum, wave drag becomes as important as pressure drag and is consistent with their higher speeds and their position "on the water".



Figure 3. Active drag (D_a) is plotted as a function of swimming velocity for Upper Division (n = 43, left panel) and novice (n = 12, right panel) swimmers for total (\bullet) and skin friction (SF), pressure (P), and wave (W) drag.

Effect of frontal surface area on drag

A major determinant of pressure drag is the area projected in the frontal plane. One determinant of which is the body composition of the swimmer, specifically the underwater torque (T), that is tendency of the legs to rotate around the center of mass. Cs has been shown to be directly proportional to T (13). Increasing or decreasing torque by adding weights resulted in proportional changes in Cs (32). Male swimmers have greater torque than females with ratios of 1.69 at 13 years and 2.04 for adults (32). The T is offset by the hydrodynamic lift on the legs. This lift during swimming is due to the velocity generated by the arms, as the legs contribute relatively little to thrust (33); thus, the leg kick should be minimized.

Thrust

At constant speed, the thrust must equal the D_a. The maximal v is set by the maximal thrust, which is determined by the muscular force of the swimmer (11, 12). Hence, maximal swimming v should be related to muscular force and power. However, studies of elite swimmers have failed to support this relationship: the distance per stroke (d/S, an index of force application) at 1.25 m \cdot s⁻¹ were 2.62 and 2.52 m while at 1.8 m \cdot s⁻¹ were 1.82 and 1.7 m for the strongest vs. weakest swimmers on the team (17). Further evidence of the minor importance of strength was the absence of differences in swimming and physiological variables between elite swimmers that added resistance training to swim training (18). The maximal force of arm pulling is over 1000 N while the thrust in tethered swimming is less than 200 N (only 20% of maximal). Furthermore an increase of muscle mass, particularly in the legs, would increase torque and density and in turn Cs (33). This leads to the conclusion that muscular strength is not the key issue in swimming fast or with minimal Cs, which depends on efficiency (η) .

Efficiency

The overall mechanical efficiency can be expressed by the ratio of total mechanical work per unit distance to the energy cost of swimming (eq.3). In swimming W_{tot} is the sum of the work to accelerate/decelerate the limbs around the center of mass (W_{intr} internal work) and the work to overcome the external

forces (W_{ext}), the latter including the work to overcome D_a (thrust, W_{Da}), and the work to accelerate water away from the body not useful for propulsion (W_k). Propelling efficiency (η_p) is defined as the proportion of total mechanical power which is transformed in useful thrust:

 $\eta_{p} = W'_{Da} / W'_{tot} = W'_{Da} / (W'_{ext} + W'_{int} + W'_{k})$ Hence W'_{tot} can be calculated if D_a , v ($W'_{Da} = Da \cdot v$) and propelling efficiency (η_p) are known. η_p can be modeled for arm movements (as a paddle wheel) and leg kick (slender fish) (33). η_p measured with only arms (26, 27, 28, 29) ranges from 0.45- 0.75 (FC). η_p in FC was 0.40 with arms plus legs (33), the lower values reflecting the negative effect of the legs on Σ_1 In addition the values of η_p reported (33) were associated with the d/S of the swimmers, confirming previous speculation (3, 4, 27). The internal power during front crawl swimming (W'_{int}) was shown to range from 13 to 36.2 W and to be proportional to the arm (SF) and leg kick (KF) frequencies ($W_{int} = 38.2$ SF 3 and $W_{int} = 6.9 \text{ KF} ^{3}$) (33); while W'_{int} of the arms is minimal, that of the legs can not be ignored. These data suggest that leg kicking should be minimized in swimming FC. For speeds from 1.0 to1.4 m \cdot s⁻¹, W'_k increased from 56.8 to112.3 W, W'_{Da} from 52.5 to 96.9 W and W' $_{\rm tot}$ from 122 to 245 W. Overall efficiency (η, see eq. 1) was 21%, a quite reasonable value compared to other types of locomotion (8).

Drag reducing swimming suits

It is commonly believed that drag-reducing suits (microscopic vortex generators and ribblets) reduce skin friction, as does shaving (21); however, this effect would be relatively small due to low skin friction. However testing these suits revealed that total D_p was reduced at competitive swimming speeds by 3% to 10%, due mostly to reduced pressure drag (10). These data suggest that the water flow was tripped by frictional drag, remained attached to the body, thus reducing pressure drag. This concept has been supported by data from suits that used ribblets (30) or a trip wire technology (10). Studies of the effects of a drag reducing suit on active drag at low to moderate speeds failed to show a benefit (20, 29), however at the fastest speed the suit reduced the D_a of some of the swimmers (29). One study based on physiological data demonstrated and advantage (22), while another study did not (19). It is our opinion that drag reducing suits do reduce drag, particularly if they cover both the torso and legs at velocities above 1.5 m/s.

METABOLIC POWER

The approach described above under **Energy Cost of Swimming** provides an estimate of Cs as well as of the total metabolic power of swimming (E'_{tot}) (1, 5, 6, 7, 13, 14, 15, 16, 25). According to Equation 6, E'_{tot} can be subdivided into the aerobic (E'_{aer}) and anaerobic (AnS) components, and the latter can be further partitioned into the lactic (E'_{AnL}) and alactic (E'_{AnAL}) components. The relative contribution of the energy systems are affected by v; the higher the speed the lower the aerobic (19%) and the higher from the anaerobic sources (54 and 26%). At a given speed these contributions nor E'_{tot} are similar among the four competitive strokes.

Training based on biomechanical and metabolic principles *Stroke mechanics*

The studies described above formed the basis for the swimming training program at University at Buffalo (Termin 1998; 1999;

2000). The first step was improving d/S and SF. To improve d/S the swimmer has to take less SF at a given v which can only be done at slow speeds, however, as the biomechanics improved, the swimmer could swim faster, maintaining the same d/S at higher speeds. To train the swimmers three aids had to be provided; first an individualized SF-v curve that was "shifted" to the greater d/S and SF (3), second a velocity pacing system that set the v, splits and rest intervals (a computerized underwater light pacing system), and finally a stroke pacing system (goggles or beeper metronome) (24, 25). Over the weeks of training, the swimmer's workouts were moved to higher v, and SF, attempting to maintain the greatest d/S, until they reached the peak v. Once peak v was reached they returned to slow speeds and the d/S was increased, and the cycle repeated. Studies have shown that weight training was not an advantage to d/S and therefore this training was not done. Data showing the results of this training over a 4 year Upper Division collegiate career are show in Figure 5 for all four strokes. The conclusion of this study was that swimmers' could shift their SF-v relationship for all strokes (25) and this implied that they also improved their η_{p} and reduced their W_{tot} (33).

Metabolism

The relative contribution of aerobic and anaerobic power in the four strokes is similar and, even if this contribution is velocity dependent, at all speeds all factors play an important role and therefore should be trained. During the first phases of training, focused on the increase in d/S, the metabolism was primarily aerobic, however, at the upper end of this phase, anaerobic lactic and alactic metabolism becomes important. To maximize the improvement in $V^{\prime}O_{2max}$ and facilitate oxidative reduction of lactate, 8 weeks of training were performed at a v that required 110% of V'O $_{2max}$, which could be sustained for 8-10 minutes prior to reaching maximal tolerable lactate. This period was followed by 10 min of active recovery, and then was followed by two more of these cycles (one hour total time, paced by the light system). This phase of training reduced Cs at aerobic speeds (Figure 6). This training system also improved $V'O_{2max}$ 3.38 to 4.86 l \cdot m^-1 (48%) and maximal lactate from 8.71 to 11.59 mM (33%) in swimmers with over 10 ears of previous long-slow training, most of which occurred in the first two years of training (25).





The second phase of the training involved moving the swimmers "up their curve" progressively, to faster v and higher SF,

while maintaining d/S, up to the maximal v. To accomplish this goal swimmers' swam primarily 25 yard splits with rest intervals decreasing from 30s to 15s for a one hour practice (25 for more detail). These practices relied more and more on the lactic and alactic energy systems and the effects of it can be seen in Figure 6. There was a decrease in the energy requirements for a given speed (of 48% at higher speeds), an increased total metabolic power (21%) and an increase in the maximal v (22%).

Performance

Improved biomechanics and metabolism improved performance. The times of competitive events improved 5-10% over the swimmer's career, as compared to the 1-3% improvements seen in swimmers who train traditionally (2). In addition, the swim meter (3) was used to determine instantaneous velocity during starts (23, 10) and during free swimming (23). An example of this is during breaststroke swimming, the v accelerates during the arm stroke. After that the v decreases rapidly to zero or slightly greater than zero the legs are flexed in preparation for the leg kick. During this deceleration between time of the arm and the leg actions the frontal area of the swimmer increases, and this change of position increases Da and decreases v (23). During the dive or turn, the velocity rapidly decreases to levels below the average steady-state swimming speed (Mollendorf 2004). When this happens, the swimmer has to use one or two stroke to get back to the desired speed. The overall time for the lap is compromised by the period when the v is less than the swimmers surface speed. In addition, accelerations and decelerations are part of each stroke (more in breaststroke and butterfly), with greater fluctuations resulting in increased Cs. Thus the most uniform v throughout a stroke or race would result in the lowest Cs.



Figure 5. The total energy output is plotted for front crawl swimming at the beginning of training and after four years of training in Upper Division swimmers (data from 25).

SUMMARY

Swimming is a unique sport as both its energy cost and metabolic power requirement are more variable. Active drag is a crucial determinant of the energy cost of swimming; its reduction allows the swimmers to make the biggest gains in performance. The general principles of exercise metabolism should be applied to swimming, and training paradigms should be shifted to higher intensity training.

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TIME LIMIT AT THE MINIMUM VELOCITY OF $\dot{\nabla}O_{2MAX}$ AND INTRACYCLIC VARIATION OF THE VELOCITY OF THE CENTRE OF MASS

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The purpose of this study was to analyse the relationship between time limit at the minimum velocity that elicits maximal oxygen consumption (TLim-v $\dot{v}O_{2max}$) and intra-cyclic variations of the velocity of the centre of mass (dv) in the four competitive swimming techniques. Twelve elite male swimmers