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):
$$v = SF \cdot d/S \qquad (1)$$
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:
$$E'_{tot} = W'_{tot} / \eta \qquad (2)$$
Since the ratio of E'_{tot} to swimming velocity (v) is the energy cost of swimming per unit distance:
$$C_s = E'_{tot} / v = W'_{tot} / \eta \cdot v^{-1} = W_{tot} / \eta \qquad (3)$$
where W_{tot} is the mechanical work per unit distance. Equation 3 can also be expressed as:
$$v = E'_{tot} / C_s = E'_{tot} / (W_{tot} / \eta) \qquad (4)$$
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:
$$v_{max} = E'_{tot\ max} / Cs = E'_{tot\ max} / (W_{tot\ max} / \eta) \qquad (5)$$
where W_{tot} is the maximal mechanical work per unit distance.In turn, $E'_{tot\ max}$ is given by:
$$E'_{tot\ max} = AnS / t_p + MAP - MAP\tau (1 - e^{-tp/\tau}) / t_p \qquad (6)$$
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:
$$v_{max} = (SF \cdot d/S)_{max} = E'_{tot\ max} / Cs$$
$$v_{max} = (SF \cdot d/S)_{max} = (AnS / t_p + MAP - MAP\ \tau (1- e^{-tp/\tau}) / t_p) / (W_{tot\ max} / \eta) \qquad (7)$$
This shows that maximal swimming performance depends on the interplay between biomechanical (SF, d/S, $W_{tot\ max}$, η) and bioenergetic aspects (AnS, MAP, τ).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 (± 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'O$_2$ 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 post-swim 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 mlO$_2 \cdot$ kg$^{-1 \cdot}$ 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'O$_2$ 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.
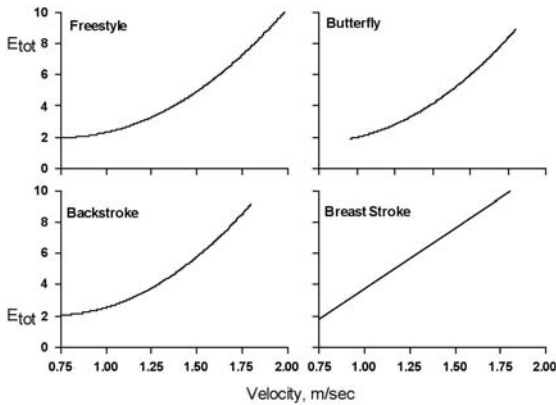

Figure 1. The total energy expenditure (E'$_{tot}$, aerobic + anaerobic) of swimming as a function of velocity for upper division swimmers in the four competitive strokes.

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 $\pm$ 4.3 N at a v of 2.2 m $\cdot$ 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 $\cdot$ 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 MAD-system (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 $\cdot$ s^{-1} in novice and 160 N at 1.8 m $\cdot$ 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.
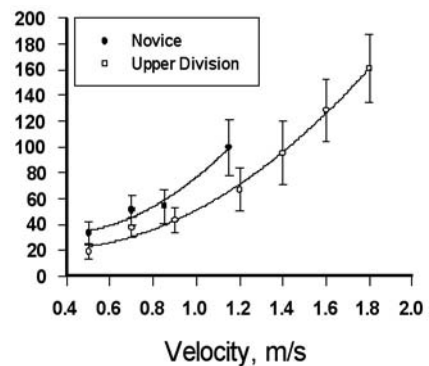

Figure 2. Active drag (D$_a$) is plotted as a function of swimming velocity for male novice (n = 18, ○) and Upper Division (n = 42, ●) swimmers, swimming the front crawl.

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 · 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".
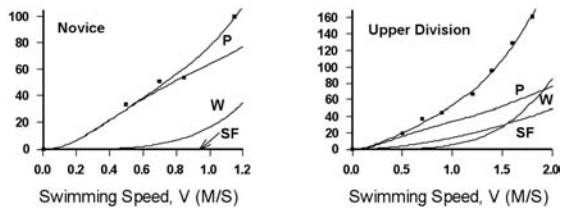

Figure 3. Active drag (D_a) is plotted as a function of swimming velocity for Upper Division (n = 43, left panel) and novice (n = 12, right panel) swimmers for total (●) and skin friction (SF), pressure (P), and wave (W) drag.

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 · s^{-1} were 2.62 and 2.52 m while at 1.8 m · 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_{int}, 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:

$$\eta_p = W'_{Da} / W'_{tot} = W'_{Da} / (W'_{ext} + W'_{int} + W'_k) \qquad (8)$$

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_p. 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 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 · s^{-1}, W'_k increased from 56.8 to112.3 W, W'_{Da} from 52.5 to 96.9 W and W'_{tot} from 122 to245 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'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 · 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).
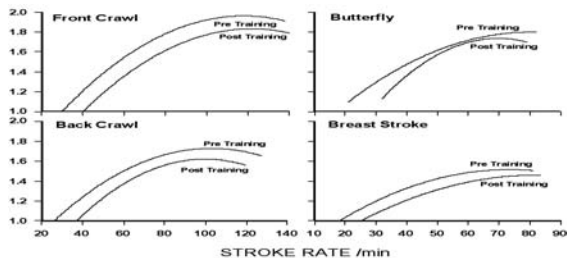
Figure 4. Velocity is plotted as a function of stroke frequency for Upper Division swimmers over their collegiate careers for their individual prime stroke. The "shift" in the relationship ("curve") to greater d/S and higher speeds progressed each year.

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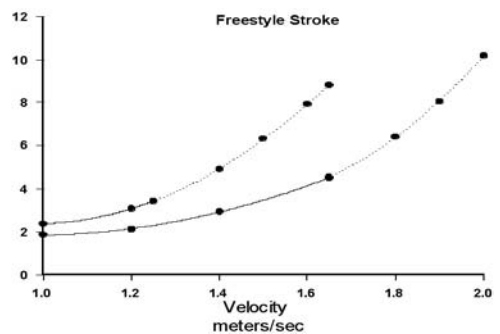
Figure 5. The total energy output is plotted for front crawl swimming at the beginning of training and after four years of training in Upper Division swimmers (data from 25).

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 $\dot{V}O_{2MAX}$ AND INTRA-CYCLIC 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

swam their own best technique until exhaustion at their previously determined $v\dot{V}O_{2max}$ to assess TLim-$v\dot{V}O_{2max}$. The test was videotaped in the sagittal plan and the APAS software was used to evaluate the horizontal velocity of the centre of mass (Vcm) and its intra-cyclic variation (dv) per swimming technique. Results pointed out that the strokes that presented higher intra-cyclic variations also presented larger values of TLim. Intra-cyclic speed fluctuations (dv) decreased during the TLim test in the four strokes studied, probably due to fatigue. Key words: VO₂, intra-cyclic velocity variations, time limit, centre of mass.

INTRODUCTION

Time to exhaustion at minimum intensities corresponding to maximal oxygen uptake ($v\dot{V}O_{2}máx$) is a relatively new topic of interest in swimming training and performance diagnosis (2). It is commonly new as Time Limit at $v\dot{V}O_{2}máx$ (Tlim-$v\dot{V}O_{2}máx$).

Previous studies of Time Limit in swimming were mainly conducted in swimming flume (3, 5, 6). However, the swimming flume can impose mechanical constrains that may compromise generalisation of results to free swimming conditions. So, a new protocol to assess Time Limit to the minimum speed corresponding to $\dot{V}O_{2}máx$ (Tlim-$v\dot{V}O_{2}máx$) in normal swimming-pools was recently proposed (7).

Despite Tlim-$v\dot{V}O_{2}máx$ in swimming remains a recent research topic, different influencing factors were already checked (3, 5, 6, 7) in literature. Among these, energy cost (8, 9) and stroke parameters (12) were the first biomechanical related parameters already exploited. Meanwhile, intra-cyclic fluctuations of the swimmer's velocity are among the most relevant performance determining biomechanical factors (1,11,15). Nevertheless, this parameter was never related to Tlim-$v\dot{V}O_{2}máx$ in the literature at our disposal. The aim of the present study was to explore the relationship between TLim-vVO₂máx and intra-cyclic variations of the centre of mass velocity (dv) in the four competitive swimming techniques.

METHODS
Subjects
Twelve elite male swimmers (19.8 ± 3.5 y, 70.1 ± 8.0 kg and 178.3 ± 6.5 cm) were volunteered to serve as subjects. All the swimmers were informed about the characteristics and the purposes of the study.

Test protocol
Tests were conducted in a 25m indoor swimming pool. First, all subjects performed an intermittent incremental protocol for freestyle $v\dot{V}O_{2max}$ assessment. The test used increments of 0.05 m/s each 200m stage, with 30s intervals until exhaustion. $\dot{V}O_{2}$ was directly measured by a portable gas analyser (K4 b² Breath by breath Pulmonary Gas Exchange System – COSMED, Italy) connected to the swimmers by a specific respiratory snorkel for swimming (10, 14). Expired air was continuously measured during the entire test and averaged every 5s. $v\dot{V}O_{2max}$ was considered to be the swimming velocity corresponding to the first stage that elicits $\dot{V}O_{2max}$.

Forty-eight hours late, the subjects swam their own best technique until exhaustion, at their previously determined $v\dot{V}O_{2max}$ to assess TLim-$v\dot{V}O_{2max}$. This protocol considered

in three different phases, all paced through a visual light pacer (TAR.1.1, GBK – electronics, Aveiro, Portugal) used to control swimming velocity: (i) a 10 minutes warm-up at an intensity corresponding to 60% $v\dot{V}O_{2max}$, followed by a short rest period (20s) for blood collection; (ii) a 50 m distance performed at progressive velocity, allowing the swimmers to reach their individual $v\dot{V}O_{2max}$, and (iii) the maintenance of that swimming $v\dot{V}O_{2max}$ until exhaustion. TLim was considered to be the total swimming duration at $v\dot{v}O_{2max}$ (7).

The test was videotaped in a sagittal plan, with two cameras (JVC SVHS), that provided, after mixing and editing, a dual-media image of the swimmer (17). The APAS software (Ariel Dynamics Inc, USA) was used to evaluate the horizontal velocity of the centre of mass (Vcm) and its intra-cyclic variation (dv) per swimming technique. A complete cycle of all techniques was analyzed, in the first and last laps of the TLim test, as well as in all the intermediate 100m laps.

Statistical analysis
Means and standard deviations of all variables were calculated. The variation coefficient (VC) of the intra-cyclic time distribution of instantaneous horizontal swimming velocity of the centre of mass was also calculated within a stroke cycle. Linear regressions were computed between variables, as well, its coefficients of determination and correlation. The level of statistical significance was set at p ≤ 0.05.

RESULTS AND DISCUSSION
Figure 1 presents the regression line computed between the intra-cyclic fluctuations of the velocity of the centre of mass and the time duration of the TLim test, irrespectively of the swimming technique used.

Through the observation of the regression line of the Figure 1 it is recognizable that the swimmers with higher dv values perform longer at $v\dot{V}O_{2max}$. However, previous results available in literature support the hypothesis that dv should be taken as an indicator of energy cost of locomotion, inversely related to swimming economy and to the maximal velocity attainable by a given swimming technique (4, 13, 16).
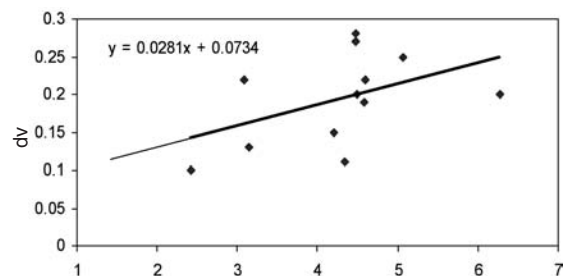

Figure 1. Relationship between TLim and dv for pooled data (r = 0.528, p = 0.078).

The apparent incongruence of the late finding with literature lead us to admit the hypothesis of a swimming technique specific effect on the relationship searched, suggesting the need of a stroke by stroke analysis. The results of such approach are presented in Figure 2. The Table 1 summarises the values of the correlation coefficients computed between TLim and dv.
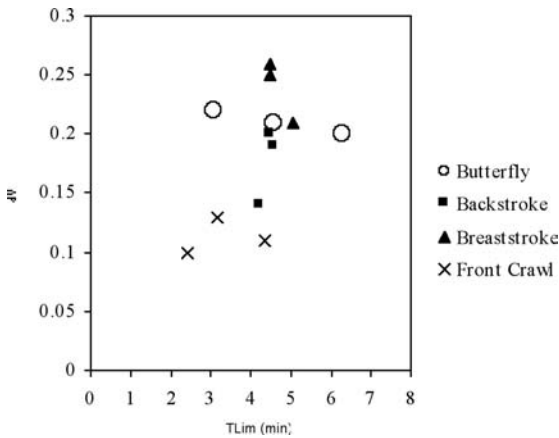
Figure 2. Relationship between TLim and dv for each swimming technique.

Table 1. Coeficients of correlation between TLim and dv.

Stroke	r	p
Buterfly	-0.296	0.809
Backstroke	0.911	0.271
Breastroke	- 0.945	0.212
ront Crawl	0.195	0.875

No statistical significant correlations were obtained between TLim-v$\dot{V}$O$_{2max}$ and dv values for the different techniques, probably due to the reduced number of subjects of the particular samples. Nevertheless, the r values obtained for backstroke and breaststroke were quite high (0.911 and -0.945, respectively).

It is possible to observe that the technique that presented smaller values of dv - the front crawl - is also characterised by low TLim results. The technique that showed larger intra-cyclic fluctuations of the CM velocity was the breaststroke, also the one that delivers the higher values of TLim. Very interesting to note was that the simultaneous swimming techniques were characterized by inverse relationships between both variables, while the alternated ones showed a direct one. So, both backstroke and butterfly assume intermediate dv / TLim relationships in the interval between the boundaries defined by front crawl and breaststroke.

In our opinion, the reason for such controversial results should be searched in relevant co-variants not controlled in this study, namely the relative anaerobic energy contribution at v$\dot{V}$O$_{2max}$ for each technique. It maybe the case that different muscular activity and particular biomechanics of different swimming techniques imposed different energy partitions, for instance a more anaerobic v$\dot{V}$O$_{2max}$ for the front crawl and the backstroke, imposing less TLim durations despite a more economic mechanics (lower dv) in comparison with butterfly and breaststroke. Further investigation is needed to clarify this particular issue.

Figure 3 show the behaviour of dv and Vcm values in different moments of TLim test for each technique.
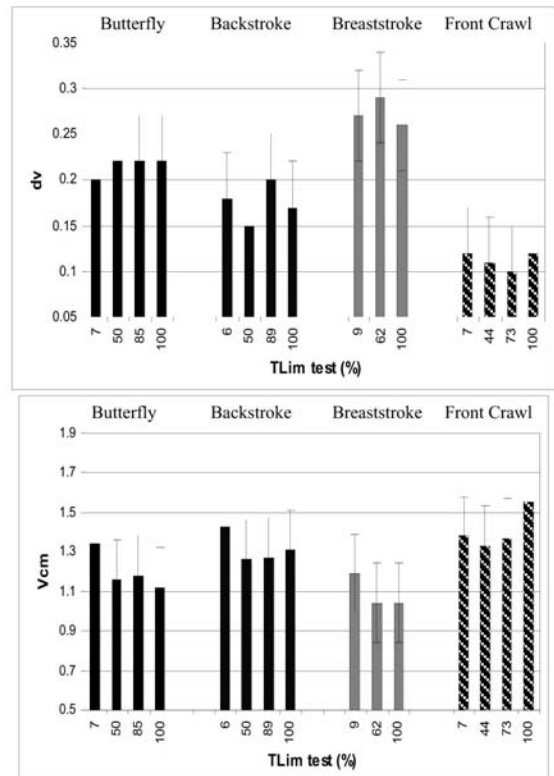

Figure 3. dv and Vcm values during TLim test in the four competitive techniques.

The techniques that present smaller dv values, Backstroke and Front Crawl, have larger values of Vcm, probably because dv allows for higher swimming economy and this one favours higher Vcm.

CONCLUSION
The results of the present research pointed out that the relationship between intra-cyclic speed fluctuations and TLim-v$\dot{V}$O$_{2max}$ may be strongly influenced by other co-variables, and that it should be searched, preferably, considering each swimming stroke independently. Butterfly, and breaststroke, the swimming techniques with higher speed fluctuations per stroke cycle are characterized by a tendency to an inverse relationship between speed fluctuations and TLim-v$\dot{V}$O$_{2max}$. The inverse tendency was perceived to the alternated techniques, and for the pooled data.

ACKNOWLEDGEMENTS

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RELATIONSHIPS BETWEEN ENERGY COST, SWIMMING VELOCITY AND SPEED FLUCTUATION IN COMPETITIVE SWIMMING STROKES

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The purpose of the study was to analyse relationships between total energy expenditure ($\dot{E}_{tot}$), energy cost (EC), intra-cycle variation of the horizontal velocity of displacement of centre of mass (dv) and mean swimming velocity (v). 17 Portuguese elite swimmers (4 at Freestyle, 5 at Backstroke, 4 at Breaststroke and 4 at Butterfly) were submitted to an incremental set of nx200-m swims. Bioenergetical and biomechanical parameters presented significant interrelationships. For pooled data, the relationship between $\dot{E}_{tot}$ and v was r=0.59 (p<0.01), between EC and dv was r=0.38 (p<0.01) and the polynomial relationship, between dv and v was r=0.17 (p=0.28). Individual evaluation and identification of biomechanical critical points may help the swimmers to become more efficient at a certain swimming velocity.

Key Words: competitive strokes, energy expenditure, energy cost, speed fluctuation, velocity.

INTRODUCTION
In swimming science, economy of movement is an interesting field of research. Several investigations have been conducted to understand the role of bioenergetics and its repercussions in performance. Most of those studies focused exclusively on the contribution of aerobic system to produce energy for movement even though all competitive swimming events also require significant contribution from anaerobic energetic system to cover total energy expenditure. Particularly in swimming, environmental factors have hindered the measurement of cardiorespiratory variables within the actual field setting. However, machinery to explore human aerobic energetics during field conditions has become available with the improvement of miniaturized metabolic measurement systems.
Intra-cycle variation of horizontal velocity of centre of body mass (dv) is a widely accepted criterion for biomechanical description of swimming techniques. There is a positive relationship between high dv and increased energy cost, especially in Breaststroke (12) and Butterfly stroke (2). In Backstroke and Freestyle the relationship was not so evident (1). In this perspective, it is important to obtain a better understanding of the relationship between the energy cost and dv in the competitive strokes.
Some investigators suggested the possibility of high dv being related with lower swimming velocities (e.g., 2, 12). It was

observed a significant and negative relationship between the mean horizontal velocity and the speed fluctuation in Butterfly stroke (10) and Breaststroke (9). Nevertheless, there is no study in the literature about the relationship between swimming velocity and dv, in Freestyle and Backstroke.

The purpose of this study was to analyse the relationships between total energy expenditure, energy cost, intra-cycle variation of horizontal velocity of displacement of centre of body mass and mean velocity of swimming.

METHODS

Subjects
17 elite swimmers (5 females and 12 males) of the Portuguese national team, volunteered to serve as subjects. 4 swimmers were evaluated performing Breaststroke (including 2 female swimmers), 4 swimmers performing Butterfly (including 1 female swimmer), 5 swimmers performing Backstroke and 4 swimmers performing Freestyle (including 2 female swimmers).

Design
The subjects were submitted to an incremental set of nx200-m swims. The starting velocity was set at a speed, which represented a low training pace, approximately 0.3 m.s^{-1} less than a swimmer's best performance. The last trial should represent the swimmers all out pace. After each successive 200-m swim, the velocity was increased by 0.05 m.s^{-1} until exhaustion and/or until the swimmer could not swim at the predetermined pace. The resting period between swims was 30s to collect blood samples. Under-water pace-maker lights (GBK-Pacer, GBK Electronics, Aveiro, Portugal), on the bottom of the 25-m pool, were used to control the swimming velocity and to help the swimmers keep an even pace along each step. In addition, elapsed time for each swim was measured with a chronometer to control the swimmer's velocity.

Data Collection
The swimmers breathed through a respiratory snorkel and valve system (7, 11), connected to a telemetric portable gas analyzer (K4 b^2, Cosmed, Rome, Italy). The oxygen consumption (VO$_2$) was measured for each swim breath-by-breath. Blood samples (25 μl) from the hyperemisized ear lobe were collected to analyze blood lactate concentration (YSI 1500 L, Yellow Springs, Ohio, USA) before and after each swim, as well as, 1, 3, 5 and 7 minutes after the last swim. Total energy expenditure (E$_{tot}$) was calculated using the VO$_2$ net and the blood lactate net (difference between the highest value measured in the end of the stage and the rest value), transformed into VO$_2$ equivalents using a 2.7 mlO$_2$.kg^{-1}.l^{-1} constant (5). The energy cost (EC) was calculated dividing the E$_{tot}$ by the swimming velocity (v).

The swims were videotaped (50 Hz) in sagital plane with a pair of cameras (JVC GR-SX1 SVHS and JVC GR-SXM 25 SVHS, Yokoama, Japan), providing a dual-media images from both underwater and above the water perspectives as described elsewhere (2). The images of the two cameras were real time synchronized and edited on a mixing table (Panasonic Digital Mixer WJ-AVE55 VHS, Japan) to create one single image. Ariel Performance Analysis System (Ariel Dynamics Inc, California, USA) and a VCR (Panasonic AG 7355, Japan) at a frequency of 50 Hz were used to perform a kinematical analysis of the stroke cycles, including the dv of the centre of mass.

Zatsiorsky's model with an adaptation by de Leva (3) was used with the division of the trunk in 3 articulated parts. A filter with a cut-off frequency of 5Hz was used for the analysis of the horizontal velocity curve of the centre of mass.

Statistical procedures
Means and standard deviations of all variables were calculated. Coefficients of variation for the horizontal velocity of the centre of mass along with the stroke cycle were calculated. Linear regressions between the E$_{tot}$ and v, between EC and dv and polynomial regressions of 2nd order between dv and v were computed. Partial correlations between EC and dv controlling v and between EC and v controlling dv were also calculated. The level of statistical significance was set at p$\leq$ 0.05.

RESULTS AND DISCUSSION
Figure 1 presents the relationships between the bioenergetical and biomechanical variables studied. The relationship between E$_{tot}$ and v was r=0.70 (p<0.01) at Butterfly stroke, r=0.88 (p<0.01) at Breaststroke, r=0.67 (p<0.01) at Backstroke and r=0.85 (p<0.01) at Freestyle. The relationship between EC and dv was r=0.55 (p=0.01) at Butterfly stroke, r=-0.20 (p=0.43) at Breaststroke, r=0.38 (p=0.05) at Backstroke and r=0.79 (p<0.01) at Freestyle. Polynomial model presented a better adjustment than the linear approach, for the relationship between dv and v. The polynomial relationship between dv and v was r=0.47 (p=0.05) at Butterfly stroke, r=0.65 (p=0.02) at Breaststroke, r=0.45 (p=0.06) at Backstroke and r=0.65 (p<0.01) at Freestyle. For pooled data the relationship between E$_{tot}$ and v was r=0.59 (p<0.01), between EC and dv was r=0.38 (p<0.01), and the polynomial relationship between dv and v was r=0.17 (p=0.28).
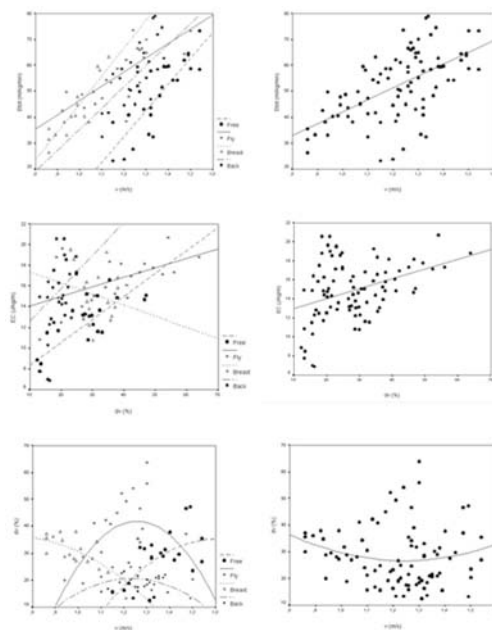

Figure 1. Relationships analysed between the bioenergetical and biomechanical variables, for each competitive stroke and for pooled sample.

In all situations, increases of E_{tot} were significantly related to increases in swimming velocity. The increase of E_{tot} is due to the necessity to overcome drag force, which is related to v. The higher adjustment of the linear relationship compared to the cubic one is due to the decrease of internal mechanical work to compensate the hydrostatic torque at higher velocities (4). Increases of the dv promoted significant increases of the EC, except for Breaststroke. Speed fluctuation while swimming as compared to swimming with constant velocity leads to an increase in the amount of total energy expenditure done by the swimmer (2). This increase is related to the need of overcoming the inertia and the drag force. Polynomial relationship between dv and v presented a better adjustment than the linear one. This phenomenon is described on regular bases for terrestrial locomotion (8). The parabolic function is explained by the curve between force and velocity for neuromuscular activity (6, 8). So, the data suggests that the neuromuscular activation of several muscles in a multi-segment and multi-joint movement follows the force-velocity relationship pattern for a single joint system (6).

Table 1 presents the partial correlations between EC and dv controlling the effect of v and the partial correlation between EC and v controlling the effect of dv. It seems that the increases of EC are strongly related to dv. Moreover, increases of EC are also strongly related to v, when controlling the effect of dv in the four competitive strokes. However, when a large number of observations from several competitive strokes are pooled together, the dependence of EC from v it is not so evident.

Table 1. Partial correlations between energy cost (EC), speed fluctuation (dv) and swimming velocity (v).

	Correlation between EC and dv controlling v	Correlation between EC and v controlling dv
Freestyle	r= 0.62 (p<0.01)	r=0.43 (p=0.05)
Backstroke	r= 0.55 (p<0.01)	r=0.56 (p<0.01)
Breaststroke	r= 0.60 (p=0.01)	r=0.86 (p<0.01)
Butterfly stroke	r= 0.55 (p=0.01)	r=0.51 (p=0.02)
Pooled sample	r= 0.39 (p<0.01)	r=0.16 (p=0.14)

CONCLUSION

The bioenergetical and biomechanical parameters analyzed presented significant relationships in each of the competitive strokes, so that changes in dv enhanced EC and E_{tot} considerably. Biomechanical evaluation of swimming technique, and identification of execution critical points, may, consequently, be critical for performance enhancement in a biologically restricted supply of energy.

ACKNOWLEDGMENTS

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METABOLIC AND MECHANICAL CHARACTERISTICS OF OLYMPIC FEMALE GOLD MEDALIST

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To clarify metabolic and mechanical characteristics of a superior swimmer, an Olympic gold medalist was compared to 16 elite Japanese college swimmers who belonged to an inter-college champion team. Maximal oxygen uptake ($\dot{V}O_2max$), maximal blood lactate concentration (LA_{max}), a drag coefficient, a drag exponent, drag-swimming speed relationship and maximal propulsive power (MPP) were determined. In the comparison of $\dot{V}O_2max$, LA_{max}, and MPP, no marked differences were observed between the gold medalist and the other swimmers. On the other hand, the drag-swimming speed relationship revealed lower drag for the gold medalist, especially at higher swimming speed (near race pace). Taken all, it is suggested that mechanical (technical) factors, such as propelling efficiency and the stroke technique to reduce drag, should be considered as more significant determinants of superior swimming performance.

Key Words: metabolic capacity, active drag, stroke technique, performance, gold medallist.

INTRODUCTION

Swimming performance is determined by several factors like metabolic capacity, drag and stroke technique, and thus many investigations have examined the relative importance of these factors for swimming performance. However, since data related to top swimmers are very limited, it would be interesting to investigate metabolic and mechanical characteristics of an Olympic gold medalist. Therefore, to enhance the understanding of the relative importance of various swimming performance for superior swimming performance, we performed a physiological and biomechanical analysis of an Athens Olympic gold medalist, and compared her profile to those of Japanese college top swimmers.

METHODS

Subjects

The subjects were 16 elite Japanese college swimmers who belonged to an inter-college champion team in 2005, and the 800m free style an Olympic gold medalist. Their mean (±SD) age, height, and body mass were 20(±1) yrs, 1.65(±0.05) m, and 57.3(±3.1) kg, respectively. The physical characteristics and best records are indicated in Table 1. Each subject was fully informed of the purposes, protocol, and procedures of this experiment, and any risks, and voluntarily participated in this study.

Experimental procedures

Maximal oxygen uptake ($\dot{V}O_2$max), maximal blood lactate concentration (LA_{max}), and swimming speed at onset of blood lactate accumulation (V_{OBLA}) were measured as indices of metabolic capacity. Also a drag coefficient, a drag exponent, drag-swimming speed relationship and maximal propulsive power (MPP) were determined as indices of mechanical characteristics. Metabolic and mechanical measurements were done on a separate day following procedures described below, and it took almost one week to complete all measurements.

Table 1 Physical characteristics and personal best records for each particular stroke of subjects

subject	height m	body mass kg	Age yrs	Best record	min.s.		min.s.
A	1.76	62.3	23	400m FR	4.06.74	800m FR	8.24.54
B	1.62	54.8	22	200m BU	2.13.63	200m BR	2.34.64
C	1.59	54.5	22	200m FR	2.05.26	400m FR	4.21.75
D	1.67	59.2	22	100m BA	1.04.36	200m BA	2.16.68
E	1.60	52.7	21	100m BA	1.02.62	200m BA	2.12.04
F	1.63	52.1	21	100m FR	58.31	200m FR	2.04.01
G	1.63	54.9	21	50m FR	27.19	100m FR	58.45
H	1.66	60.6	21	200m BA	2.16.62	100m BA	1.04.51
I	1.60	53.6	20	200m IM	2.18.47	400m IM	4.51.32
J	1.66	57.2	20	200m FR	2.02.27	400m FR	4.17.10
K	1.71	56.4	20	400m FR	4.24.71	800m FR	9.01.27
L	1.60	59.0	19	200m IM	2.24.00	400m IM	4.57.10
M	1.70	58.7	19	400m FR	4.19.08	800m FR	8.57.00
N	1.60	60.2	19	400m FR	4.14.19	800m FR	8.41.80
O	1.62	60.4	19	100m BU	59.69	200m BU	2.11.67
P	1.67	58.4	19	50m FR	26.7	100m FR	58.2
Q	1.66	59.8	19	50m FR	26.6	100m FR	58.1

FR : free, BR : breast, BA : back, BU : butterfly, IM : individual medley

$\dot{V}O_2$max

The measurement of $\dot{V}O_2$max was carried out during front crawl swimming in a swimming flume (length 17.2 m, width 5.0 m, height 8.0 m). Water was circulated in a 2.1 m wide and 1.4 m deep channel (Ogita and Tabata 1993). An incremental swimming speed test was used to determine $\dot{V}O_2$max and the water flow rate was increased by 0.03-0.05 m•s^{-1} every minute. The protocol was set individually to cause exhaustion in 8-12 min. VO_2 was measured every 30 s during the last few minutes of exercise, and the highest value was taken as $\dot{V}O_2$max.

V_{OBLA} and LA_{max}

To determine the relationship between swimming speed and blood lactate concentration, each subject was asked to swim five times 200m at the swimming speed of 80%, 84%, 88%, 92% and 100% (maximal effort) of her best record. From 1st to 4th trial, each trial was separated by 5 minutes, and blood lactate concentration was measured at 1 minute after the end of 200m swimming. Before the 5th trial, the subject was allowed to rest for at least 20 min, and blood lactate concentration was measured at 3 and 5 min after the end of swimming. V_{OBLA} was estimated by intrapolating to a swimming speed at which 4 mmol•l^{-1} would occur using the relationship between swimming speed and blood lactate concentration. The highest [La$^+$] value was accepted as LA_{max}.

Active drag and MPP

All mechanical analyses were completed with a modified MAD system similar to that described by Toussaint et al. (1988) (Fig. 1). The essential aspects of the apparatus and the accuracy of the collected data have been previously described in detail (Ogita 2004, Toussaint 1988). The important points are summarized here.
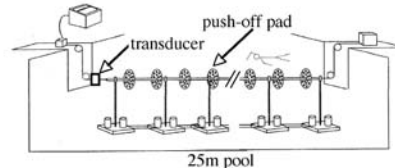

Fig.1 Schematic side view of system to measure active drag (MAD system) used in this study

The MAD system allowed the swimmer to push off from fixed pads at each stroke. The 15 push-off pads were fixed 1.30 m apart on a 23 m horizontal rod 0.75m below the water surface. At one end of the swimming pool, the rod was connected to a force transducer. Force signal was low-pass filtered (30-Hz cut-off frequency), on-line digitized at 100-Hz sampling rate, and stored on a computer hard disk. For the drag measurement, the subject performed only arm stroke (without leg kicking), while the legs were supported and fixed together by the same pull buoy (buoyant force 15.7N). Therefore, the average propulsive force applied by the arms equaled the average drag force (F_d). For the calculation of average F_d, the first and last push-off force were neglected to eliminate influence of the push-off from the wall (first-pad) and the deceleration of the swimmer at the end of the lane (last pad). The remaining force signal is time integrated, yielding the average F_d. The mean swimming speed was computed from the time needed to swim the distance between second and last pad (i.e. 16.9m).
To determine the drag-swimming speed relationship, the subject was asked to swim 25 m 8 to 12 times at different but constant swimming speed. On each trial, mean F_d and mean swimming speed (v) were measured. These v and F_d data were least-squares fitted to the function

$$F_d = A \cdot v^n$$

Where A and n are constants of proportionality, and were respectively adopted as drag coefficient and drag exponent in this study. Propulsive power was calculated by the product of F_d and v, and the highest value was accepted as MPP.

Measurements

VO_2 was determined by the Douglas bag method. The face mask used for collecting expired gas allowed unhindered movement of the arms during swimming. Expired gases passed through a low resistance valve and tubing (length; inspiration side: 1.0-m, expiration side 2.0-m, inner diameter 36 mm). The O_2 and CO_2 fraction in the expired gas were determined by an automatic gas analyzer (Vmax 29, Sensormedics Corporation, California, USA). Expired gas volume was measured by a dry gas meter. Blood lactate concentration was determined by an automatic analyzer (Lactate Pro, Arkray, Kyoto, Japan).

Statistics

The values were expressed as mean and SD or individual value. Standard correlation statistics were done to test the relationship between swimming speed and several variables, and the 0.05 level of significance was used.

RESULTS

Relationship between swimming performance and measured variables

When swimming speed calculated from the swim time of the 200m exhaustive trial was related to measured variables, significant correlations were only observed for V_{OBLA} (r=0.753, P<0.01) and for the drag coefficient (r=-0.583, P<0.05) (Table 2).

Table 2 Correlation between 200m swimming performance and measured valuables

	VO₂max		Lamax	V@OBLA	A	n	MPP
	l•min⁻¹	ml•kg⁻¹•min⁻¹	mmol•l⁻¹	m•s⁻¹			W
200m speed	0.227	0.296	0.053	0.753**	-0.583*	0.182	0.101

**P≤ 0.01   *P≤ 0.05

Gold medalist vs other elite swimmers

The gold medalist was the tallest of our subjects, and had a better physique compared to the others (Table 1). In the comparison of VO_2max, the absolute value of the gold medalist was relatively high, but this value expressed as per unit of body mass was close to the average (Fig. 2). LA_{max} of the gold medalist was considerably low. On the other hand, her V_{OBLA} was the highest of all swimmers.
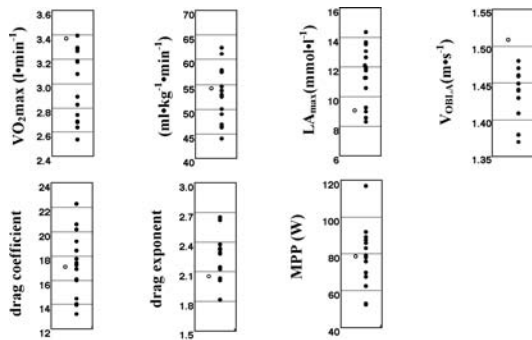

Fig.2 Comparison of metabolic and mechanical data between gold medalist and top swimmers
Open circle indicates the value of the gold medalist.

In the comparison of mechanical factors, drag coefficient, drag exponent, and MPP of the gold medalist were almost equal to, or smaller than the average of the others. However, the drag-swimming speed relationship for the gold medalist showed a tendency for below average drag values, especially at higher swimming speeds (near race pace) (Fig. 3).
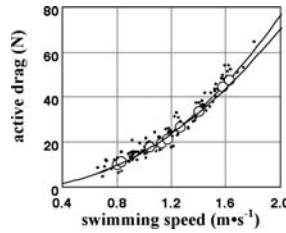

Fig.3 Comparison of drag-swimming speed relationship between gold medalist (open circles) and top swimmers (closed circles).

DISCUSSION

It has been considered that higher metabolic capacity is a very important factor determining swimming performance. Indeed, if swimming efficiency is the same, it should be true that a higher metabolic capacity will enable faster swimming. However, the metabolic capacity for this gold medalist as measured with the, i.e. VO_2max$\cdot$kg⁻¹ and LA_{max} for the gold medalist was not exceptional in this study. This suggests that her superior swimming performance would not be caused by higher metabolic capacity, but by swimming efficiency. Swimming efficiency is determined by the product of mechanical (gross) efficiency and propelling efficiency (Toussaint 1994). According to Toussaint (Toussaint 1990a, b, 1994), the mechanical efficiency in swimming does not differ between elite swimmer and less skilled swimmer. On the other hand, propelling efficiency reveals greater difference between competitive swimmer (61%) and triathletes (44%), which would largely depend on the swimming technique. Therefore, higher propelling efficiency could be one of important determinants of superior swimming performance.

Also, it is a common observation that proficient swimmers are much more economical in VO_2 than that in the less skilled swimmers (Holmér 1972, Toussaint 1990a). The lower VO_2 would be attained not only by higher propelling efficiency but also by lower power to overcome drag (i.e. lower drag). Actually, in the gold medalist, the drag at higher swimming speed became lower in comparison to the other swimmers even though her physique is the biggest of the subjects. Therefore, drag which can be reduced by a better swimming technique would be considered as a significant determinant of superior swimming performance.

CONCLUSION

Finally, it is concluded that metabolic capacity might not be necessarily a dominant determinant in top swimmers but that mechanical (technical) factors, such as propelling efficiency and the stroke technique to reduce drag should be considered more significant determinants of superior swimming performance.

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