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BALANCE OF BIOMECHANICAL AND PHYSIOLOGICAL CONTRIBUTIONS TO SWIMMING PERFORMANCE

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Swimming is a unique activity carried out in a unique environment. Performance depends on interplay between biomechanical and bioenergetic aspects, thus if we can understand their interaction, as a function of velocity, we can understand the biophysics of swimming. The relationship between stroke frequency and velocity and their impact on drag and efficiency are critical. The biomechanical aspects dictate the velocity-dependent metabolic demands of swimming, thus the maximal performance is determined by the balance of metabolic power among aerobic and anaerobic pathways. Training is a determinant of swimming performance, and applying bioenergetic principles could improve performance.

KEYWORDS: body drag, energy cost, oxygen consumption, anaerobic metabolism, efficiency, stroke frequency.

INTRODUCTION: Swimming is a unique activity carried out in a unique environment, and compared to terrestrial activities is more interesting from the physiological, and especially the biomechanical standpoint. The physics of swimming and the nature of swimming pools also make quantification of important parameters that determine swimming performance difficult to measure. Swimming performance depends on the interplay between biomechanical (stroke frequency, distance/stroke, maximal mechanical work per unit distance and efficiency) and bioenergetic aspects (energy derived from the anaerobic stores, maximal aerobic power, and the time constant with which $V'O_{2max}$ is attained at the onset of exercise). Thus if we can understand the biomechanical and physiology aspects of swimming, and their interaction, as a function of velocity we can better understand the biophysics of swimming. If these concepts are utilized in the training of swimmers, performance would be enhanced, even in elite swimmers where current improvements are small with traditional training (Costill, 1992) and greater when biomechanical and physiological considerations are used (Termin & Pendergast, 2001). Considerations of motor learning and psychological factors are important and will be discussed in the paper by Mason in this collection.

Biomechanics: Swimming technique result in intermittent application of a propulsive force (thrust) to overcome a velocity-dependent water resistance (drag, D). In seminal work, Craig and colleagues showed that to increase velocity, swimmers' increase their stroke frequency in characteristic manners and as the four competitive strokes use differing combinations of arm cycling and leg kicking their relationships (stroke curves) are different (Craig & Pendergast, 1979; Craig, Skehan, Pawelczyk & Boomer, 1985). In addition, they showed that there are stroke and individual dependent fluctuations of velocity, thus the relationship of thrust to drag. Individuals' stroke frequency relationship and fluctuations in thrust and velocity contribute to the highly variable performance in swimming. Craig's group showed that all swimming strokes (Figure 1) 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) (Craig & Pendergast, 1979, Craig et al., 1985):

$$v = SF \cdot d/S \qquad (1)$$

The characteristic SF-v curves have been shown for elite male and female swimmers (Craig & Pendergast, 1979). The front crawl had the greatest d/S and SF. The back crawl was similar to the front crawl except that at a given SF the d/S and v were less than for the front crawl. Increases of v of the butterfly were related almost entirely to increases in SF, except at the highest v. In the breaststroke increasing v was also associated with increasing in SF, but the d/S decreased more than in the other strokes. It was also showed that better swimmers had a greater maximal d/S and could maintain a higher d/S as the SF and v increased, and thus achieve a higher SF. 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 than 1976 (Craig et al., 1985) by increased d/S of the swimmers in many events, and this trend continues today (unpublished observations, U.S. Swimming). 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. However as the velocity increases, the freedom of choice becomes more limited. Training techniques that affect the SF-v remain open to question and need further investigation.

As suggested earlier, the intermittent application of thrust and the changes in drag, result in fluctuations in v. 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%) (Craig & Pendergast, 1979). In the breast stroke very large fluctuations in velocity as measured by the “Craig swim-meter” are observed, including a deceleration to zero velocity for a short period during the cycle (Termin & Pendergast, 1998). It has also been shown that swimmers with less variation in their inter-cycle v have faster velocities (Termin & Pendergast, 1998). As the energy cost increases exponentially with velocity, accelerations waste energy and should be minimized.

Drag: Hydrodynamic resistance, termed drag, is the mechanical power required to overcome hydrodynamic resistance. Determination of drag in actual swimming (active drag, D_a), to date, has not been measured directly. Historically, drag has been measured by towing the swimmer against a strain gauge at increasing speeds (passive) (Karpovich & Millman, 1933) and more recently while swimming (active) (e. g. di Prampero, Pendergast, Wilson & Rennie, 1972; Holmér, 1972; Clarys, Jiskoot & Lewillie, 1973; Pendergast, di Prampero, Craig Jr., Wilson & Rennie, 1977; Kolmogorov & Duplisheva, 1992; Toussaint, Roos & Kolmogorov, 2004). There remains considerable debated in the literature (e. g. di Prampero et al., 1972; Clarys et al., 1973; Payton & Bartell, 1995; Toussaint et al., 2004; Zamparo, Gatta, Capelli & Pendergast, 2009; Zamparo, Capelli & Pendergast, 2011) regarding the validity of each of these different methods. The drag created by the movements of the swimmer is such that D_p significantly underestimates the D_a, a fact that has been confirmed by several studies (e. g. di Prampero et al., 1972; Pendergast et al., 1977; Toussaint & Beek, 1992); thus measuring D_a is an essential prerequisite to understand swimming performance. The two most reported techniques for determining D_a are the indirect extrapolation system of di Prampero et al. (1972) and Toussaint’s “MAD-system” (Toussaint et al., 1988). Each of these methods has limitations, di Prampero’s method is indirect and the Toussaint’s method does not include the drag created by the legs as they are floated and the maximal achievable velocity is below that of elite swimmers. Data for active drag (D_a) are shown in Figure 1 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 values reported by others using different techniques. This may be due to the added drag caused by movements of the arms/legs when swimming as well as to the density of the legs in setting the body’s angle compared to horizontal. The data using Toussaint’s method are reported elsewhere in this book. In addition these concepts will also be discussed by the Sander’s paper.

Total body drag is comprised of three velocity-dependent elements, friction, pressure (form) and wave. Friction drag is proportional to v ($D_{Friction} = k \cdot v$), and results from the direct contact between the swimmers skin and water. Pressure drag ($D_{pressure} = k \cdot v^2$) is caused by the resultant pressure force from the pressure distribution over the body. Usually, there is a higher resultant pressure force on the front of the body than on the back (adverse pressure gradient) causing separation of the flow. This causes a reduced velocity zone called the boundary layer (viscosity and friction). The velocity in the outer flow around a body reaches its maximum near the thickest part of the body, creating an adverse pressure gradient if the curvature is pronounced enough. The bigger the frontal surface area, the greater the pressure D_a. A region of recirculation and vortex formation called the wake then appears behind the body. Consequently, the energy taken by the wake causes an increase in drag on the body ($D_{wave} = k \cdot v^4$). Another phenomenon that affects the pressure distribution on a body is ventilation. Ventilation is the process of air being sucked into a cavity behind the body from the free surface.

The data for partitioned D_a, are shown in Figure 1 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”.

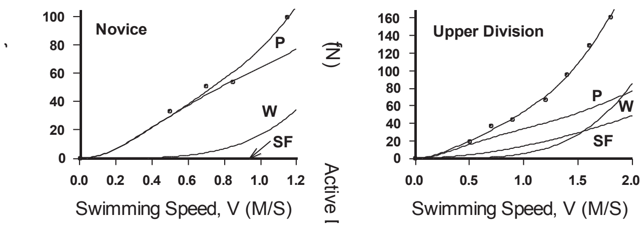

Figure 1: Active drag (D_a) is plotted as a function of swimming velocity for Upper Division (n = 43, left panel) and novice (n = 12, right panel) swimmers for total (●) and skin friction (SF), pressure (P), and wave (W) drag.

In previous studies (Mollendorf, Termin, Oppenheim & Pendergast, 2004, Pendergast, Mollendorf, Cuviello & Termin, 2006) it was found that total D_p increased monotonically up to 86.2 ± 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. In the same study it was also calculated that the transition-from-laminar-to-turbulence, for a swimmer 170 cm tall, was 25 cm from the top of the head with a turbulent region from the knee to the foot (Mollendorf et al., 2004). Further evaluations of the components of active drag are needed.

Effect of frontal surface area on drag: A major determinant of pressure drag is the area projected in the frontal plane. One determinant of the frontal surface area is the body composition of the swimmer, which specifically influences his/her underwater torque (T), that is tendency of the legs to rotate around the center of mass. Indeed, Cs has been shown to be directly proportional to T (Zamparo, Capelli, Termin, Pendergast & di Prampero, 1996). Male swimmers have greater torque than females with ratios of 1.69 at 13 years and 2.04 for adults (Zamparo et al., 1996). The T, and the resulting increase in frontal surface area, is offset by the hydrodynamic lift due to swimming speed, thus the body angle (in respect to the water’s surface) during passive towing decreased similarly in men and women as speed increased (Zamparo et al. 2009). The hydrostatic lift of the legs during actually swimming is most likely a result of the velocity generated by the arms, as the legs contribute relatively little to thrust and have a high internal work (Zamparo, Pendergast, Mollendorf, Termin Minetti, 2005). Further work is needed in this area to minimize the leg kick or changing its vector and improving the movement of the hand through the water to minimize Cs by drag reduction, secondary to improved swimming technique.

Thrust: When swimming at a constant speed, the average thrust must be equal to the average D_a, thus the maximal velocity, other things being equal, is set by the maximal thrust. This, in turn, is not determined by the maximal muscular force of the swimmer, but to the force he can effectively apply to the water (Payton & Bartett, 1995). Studies of Upper Division swimmers have failed to show an effect of upper body strength on the distance per stroke (d/S, an index of force application) or that adding resistance training to swim training improved swimming performance (Rielly, Kame, Termin, Tedesco & Pendergast, 1990; Roberts, Termin, Reilly & Pendergast, 1991). In addition, the maximal force of arm pulling is over 1000 N while the thrust generated against a strain gauge in tethered swimming is less than 200 N (only 20% of maximal). This leads to the conclusion that muscular strength is not the key issue in swimming fast or with minimal Cs, which rather depends on the propulsive efficiency (η_p).

Efficiency: The overall mechanical efficiency can be expressed by the ratio of total mechanical work per unit distance to the energy cost of swimming (equation 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). While D_a can be measured as described above, the other terms are difficult to determine. Propelling efficiency (η_p) is defined as the proportion of total mechanical power which is transformed in useful thrust:

$$\eta_p = W'_{Da} / W'_{tot} = W'_{Da} / (W'_{ext} + W'_{int} + W'_k) \qquad (2)$$

Hence W'_{tot} can be calculated if D_a, v ($W'_{Da} = Da \cdot v$) and propelling efficiency (η_p) are known. η_p for the arm stroke can be calculated by modeling the arm movements as those of a paddle wheel; for the leg kick by modeling the legs movements as those of slender fish (Zamparo et al., 2005).
It is safe to conclude that less than 10% of metabolic power input can be transformed into overcoming drag (e. g. Holmér, 1972, Pendergast et al., 1977, Kolmogorov & Duplisheva, 1992; Toussaint et al., 2004; Zamparo et al., 2005). Previous data for η_p were measured when swimming with only arms (Toussaint, Knops, de Groot & Hollander, 1990; Toussaint & Beek, 1992; Toussaint, Truijens, Elzinga, van de Ven, de Best, Snabel, & de Groot, 2002) and ranged from 0.45- 0.75 in the front crawl. Propelling efficiency in the front crawl when swimming with arm and legs was 0.40 (Zamparo et al., 2005), the lower values reflecting the effect of the addition of the legs. In addition the values of η_p reported in this study were associated with the d/S of the swimmers thus confirming notions previously suggested (Craig & Pendergast, 1979; Craig et al., 1985; Toussaint & Beek, 1992). 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 ($W_{int} = 38.2 \cdot SF^3$ and $W_{int} = 6.9 \cdot KF^3$) (Zamparo et al. 2005); while W'_{int} of the arms is minimal, that of the legs cannot be ignored. These data suggest that leg kicking should be minimized in swimming front crawl. For speeds from 1.0 to 1.4 $m \cdot s^{-1}$, W'_k increased from 56.8 to112.3 W, W'_{Da} from 52.5 to 96.9 W and W'_{tot} from 122 to 245 W. Overall efficiency (η, see equation 1) was 21%. Calculating overall (gross) and propelling efficiency also remains controversial. Values of h_O (= W'_T / E', where W'_T is total mechanical power output) (Toussaint et al., 1990; Zamparo et al., 2005) and of h_P (W'_D / W'_T) (Toussaint, Beleen, Rodenburg, Sargeant, de Groot, Hollander & van Ingen Schenau, 1988, Zamparo et al., 2005; Figueiredo, Zamparo, Sousa, Vilas-Boas & Fernandes, 2011) are uncertain and are a major determinant of performance and hence of great interest for sport scientist and coaches. Further discussion of these issues are in the Zamparo paper.

Physiological: Swimming at a specific velocity requires a given metabolic power output (E'_{tot}) that is velocity-dependent. It is determined by the mechanical power output (W'_{tot}) and by the overall efficiency (η) of the swimmer:

$$E'_{tot} = W'_{tot} / \eta \qquad (3)$$

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

$$Cs = E'_{tot} / v = W'_{tot} / \eta \cdot v^{-1} = W_{tot} / \eta \qquad (4)$$

where W_{tot} is the mechanical work per unit distance. Equation 4 can also be expressed as:

$$v = E'_{tot} / Cs = E'_{tot} / (W_{tot} / \eta) \qquad (5)$$

Equation 6 shows that the maximal velocity is set by the maximal metabolic power of the subject ($E'_{tot\,max}$), divided by Cs at that speed:

$$v_{max} = E'_{tot\,max} / Cs = E'_{tot\,max} / (W_{tot\,max} / \eta) \qquad (6)$$

where W_{tot} is the maximal mechanical work per unit distance. In turn, $E'_{tot\,max}$ is given by:

$$E'_{tot\,max} = AnS / t_p + MAP - MAP\ \tau\ (1- e^{-tp/\tau}) / t_p \qquad (7)$$

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 6 and 7, one obtains:

$$v_{max} = (SF \cdot d/S)_{max} = E'_{tot\,max} / Cs$$

$$v_{max} = (SF \cdot d/S)_{max} = (AnS / t_p + MAP - MAP\ \tau\ (1- e^{-tp/\tau}) / t_p) (W_{tot\,max} / \eta) \qquad (8)$$

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). As described in equation 5 the velocity of swimming is determined by the energy cost of swimming and the metabolic power the swimmer can generate (aerobic + anaerobic). 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 and having subjects swim with progressively increasing velocities up to maximal. This can easily be done in a flume (Holmér, 1972) or an annular swimming pool (di Prampero et al., 1972; Pendergast et al., 1977; Capelli, Pendergast, Termin & di Prampero, 1998; Zamparo et al. 2011). More recently portable breath-by-breath systems have been used in competitive pools which has made measurements more practical (Barbosa, Keskinen, Fernandes, Colaco, Lima & Vilas-Boas, 2005; Figueiredo et al., 2011).

Competitive swimming speeds are above the maximal $V'O_2$, and thus require a significant anaerobic contribution from anaerobic glycolysis. Although this component cannot be directly measured, it can be estimated from venous blood lactate (La), as originally proposed by Margaria and validated by others, including swimming (see di Prampero, Pendergast, Wilson & Rennie, 1978; Capelli et al., 1998; Barbosa et al., 2005, Zamparo et al., 2011), by measurements of La at different time points at a specific velocities. Importantly, venous blood lactate takes 6-10 min post-swim on the pool deck under a pool heater to achieve its peak. This allows the calculation of the rate of La accumulation as a function of the speed. This was converted to oxygen equivalents assuming a La equivalent of 3 $mlO_2 \cdot kg^{-1} \cdot mM^{-1}$ (di Prampero et al., 1978). Alactic (high energy phosphate) metabolism after the initial phase was assumed to be minimal in these swims; hence, the total metabolic power (E'_{tot}) was estimated from adding the O_2 equivalent for lactate to the maximal aerobic power. E'_{tot} is similar for the FS and back crawl below 1.5 $m \cdot s^{-1}$. At greater speeds the energy expenditure of the back crawl increased at a faster rate than in the front crawl but the maximal E'_{tot} were similar. The maximal speed was less in back crawl than in front crawl (1.75 vs. 2.0 $m \cdot s^{-1}$). The energy expenditure of breaststroke and butterfly were greater than front crawl and back crawl at all speeds with breaststroke having the greatest cost and the lower maximal velocity

($1.92\ m{\cdot}s^{-1}$). Further discussion of energy cost is included in the paper by Meucci, Guidetti and Baldari.

The energy cost per unit distance (Cs) within a stroke was constant for the front crawl, back crawl, breaststroke and butterfly 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. Cs can be calculated for total metabolic power of swimming (E'_{tot}), and the aerobic (E'_{aer}) and lactic (E'_{AnL}) and alactic (E'_{AnAL}) components can be determined. The relative contribution of the energy systems as a function of stroke are different (Capelli et al., 1998), but in general go from 12.3 ± 1.4% to 27.6 ± 2.0% for E'AnAl , 62.4 ± 3.8% to 21.6 ± 6.4% for E'Aer and 25.3 ± 2.8% to 50.9 ± 8.4% for E'An going from a moderate to maximal speed. Thus, the higher the speed, the lower the aerobic contribution, and the higher the contributions from the anaerobic energy stores.

More recent work has shown differences in Cs and in the relative contribution of energy systems during 100-m sections of a 400-m freestyle swim (Laffite, Vilas-Boas, Demarle, Silva, Fernandes & Billat, 2004). Velocity decreased in the first 100-m, due to reduced d/S, and then was constant, in spite of further decreases in d/S. However the E'_{aer} and E'_{AnL} components were similar during the first 300-m, but were significantly higher in the last 100-m. The E'_{AnL} decreased from 40% to 20% of total energy from the first to last 100-m.

Application of Biophysical Principals to Performing: The application of biophysical principals to swimming training has the greatest potential impact on swimming performance. Historically swimming training has involved over-distance swimming (60-80,000 yards/m per week) which has to be at moderate paces. This type of training may not lead to adaptation, and in fact has been suggested to lead to a fatigued state and requires swimmers to taper. One of the most important questions to the swimming community is what is the optimal training program? This process should include the integration of biomechanical and physiological principals to be effective.

Stroke mechanics: A previous study demonstrated that elite swimmers could not sustain d/S or v, in spite of increased SF, and the E'_{AnL} contribution to a 400m swim decreased during the swim (Laffite et al., 2004). This suggests that there may have been an increase in drag, decrease in η, or a failure of the metabolic system. It has been shown that 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 (Termin & Pendergast, 1998; 1999; 2001). To train swimmers three aids are proposed; first an individualized SF-v curve that can be "shifted" to the greater d/S and SF, 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) (Termin and Pendergast 1998, 1999, 2000; Fernandes, Cardoso, Soares, Ascensão, Colaço & Vilas-Boas, 2003; Laffite et al., 2004). 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, and this process is cycled. Data show that swimmers' could shift their SF-v relationship for all strokes (Figure 2) (Termin & Pendergast, 2002) and this implied that they also improved their $\eta_{p,}$ and reduced their W_{tot} (Zamparo et al., 2005).

Metabolism: Although it is a common belief that high v and SF cannot be sustained for longer distances, and swimmers tend to move down their SF-v curve (Craig et al. 1985), this may only be true if they are training traditionally. As described above, the relative contribution of aerobic and anaerobic power is velocity dependent, but similarly for the four strokes. It has been shown that training focused on the increase in d/S uses primarily aerobic metabolism, however, training at the upper end of the SF-v curve adds anaerobic lactic and alactic metabolism (Termin & Pendergast, 2000). To maximize the improvement in $V'O_{2max}$ and facilitate oxidative reduction of lactate, training at a v that required 110% of $V'O_{2max}$, which could be sustained for 8-10 min prior to reaching maximal tolerable lactate is successful (Termin & Pendergast, 2002), reducing Cs and improving $V'O_{2max}$ (48%) and maximal lactate of 33% over years of previous long-slow training. Training at the “up part of the SF-v curve” (faster v and higher SF, while maintaining d/S, up to the maximal v) using primarily 25 yard splits (30s to 15s rest intervals) for a one hour practice resulted in decreased energy requirements at higher speeds (48%) and increased total metabolic power (21%) and an increase in the maximal v (22%) (Termin & Pendergast, 2002). The combined effect of improved biomechanics and metabolism yielded an improved swimming performance in meets in this group of Upper Division swimmers by 5-10% over their college career, as compared to the 1-3% improvements seen in most collegiate swimmers who train traditionally (Costill, 1992).

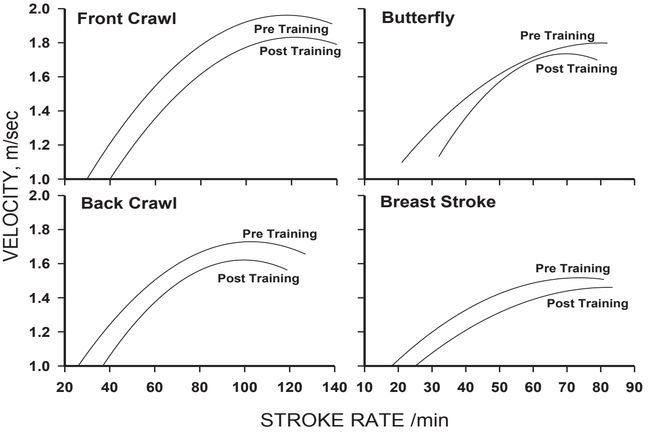

Figure 2: Velocity is plotted as a function of stroke frequency for Upper Division swimmers over their collegiate careers for their individual prime stroke. They “shift” in the relationship (“curve”) to greater d/S and higher speeds progressed each year.

Technology is important in training, including underwater training light systems (Termin & Pendergast, 1999; Fernandes et al., 2003; Laffite et al., 2004). In addition, to asses the changes in v within a stroke and in a swim a swim meter (Craig & Pendergast, 1979) can be used to determine instantaneous velocity during starts and during free swimming (Craig & Pendergast, 1979). Video analysis can also be used to evaluate instantaneous changes in v as well as biomechanics (Barbosa et al., 2005; Zamparo et al., 2005). For example, 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 D_a and decreases v. Whether or not the velocity goes to zero at the end of the deceleration depends on the angle of the thigh and the torso. If the angle is ninety degrees the velocity will go to zero. Greater angles are associated with velocities great than zero. These latter observations emphasize the relationships of D_a and v (Termin & Pendergast, 1998). The intra-cycle variation has also recently been shown for the butterfly using video technology (Barbosa et al., 2005), and during gliding (Marinho, Reis, Alves, Vilas-Boas, Machado, Silva & Rouboa, 2009).

As shown by Mollendorf et al. (2004), during the dive or turn, the velocity rapidly decreases to levels below the average steady-state swimming speed. When this happens, the swimmer has to use one or two strokes 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.

SUMMARY Recent advances and incorporation of previous ideas have progressed in the understanding of the biophysics of swimming. These advances with further development should contribute to the improvement in swimming performance, if implemented by the swimming community.

REFERENCES:

Barbosa, T.M., Keskinen, K.L., Fernandes, R., Colaco, P, Lima, A.B. & Vilas-Boas, J.P. (2005). Energy cost and intracyclic variation of the velocity of the centre of mass in butterfly stroke. *European Journal of Applied Physiology,* 93, 519-523.

Capelli, C., Pendergast, D.R., Termin, B. & di Prampero, P.E. (1998). Energetics of swimming at maximal speed. *European Journal of Applied Physiology*, 78, 385-393.

Clayrs, J.P., Jiskoot, J. & Lewillie, L. (1973). A kinamatographic, electromyographic, and resistance study of waterpolo and competition from crawl. In Cerguiglini, Venerando & Wartenweiler (Eds.), *Biomechanis III* (pp 446-452). Karger, Basel.

Costill, D.L. (1992). Less may be best. *Swim Magazine*, Sept/Oct, 25-31.

Craig, Jr., A.B. & Pendergast, D.R. (1979). Relationships of stroke rate, distance per stroke, and velocity in competitive swimming. *Medicine Science and Sports Exercise,* 11(3), 278-283.

Craig, Jr., A.B., Skehan, P., Pawelczyk, J.A. & Boomer, W.L. (1985). Velocity, stroke rate, and distance per stroke during elite swimming competition. *Medicine Science and Sports Exercise,* 17, 625-634.

di Prampero, P.E., Pendergast, D.R., Wilson, D.R. & Rennie, D.W. (1972). Body drag and efficiency in swimming. *Archive Physiology,* 69, 502-515.

di Prampero, P.E., Pendergast, D.R., Wilson, D.R. & Rennie, D.W. (1978). Blood lactic acid concentrations in high velocity swimming. In B. Eriksson & B. Furburg (Eds.), *Swimming Medicine IV* (pp 249-261). USA: University Park Press.

Fernandes, R.J., Cardoso, C.S., Soares, S.M., Ascensão, A., Colaço, P.J. & Vilas-Boas, J.P. (2003). Time limit and VO2 slow component at intensities corresponding to VO2max in swimming. *International Journal of Sports Medicine,* 24, 576-581.

Figueiredo, P., Zamparo, P., Sousa, A., Vilas-Boas, J.P. & Fernandes, R.J. (2011). An energy balance of the 200 m front crawl race. *European Journal of Applied Physiology,* 111, 767-777.

Holmér, I. (1972). Oxygen uptake during swimming in man. *Journal of Applied Physiology,* 33: 502-509.

Karpovich, V. & Millman, N. (1933) Water resistance in swimming. *Research Quarterly*, 5, 215-220.

Kolmogorov, S.V. & Duplisheva, O.A. (1992). Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity. *Journal of Biomechanics,* 25, 311-318.

Laffite, L.P., Vilas-Boas, J.P., Demarle, A., Silva, J., Fernandes, R. & Billat, V.L. (2004). Changes in physiological and stroke parameters during a maximal 400-m free swimming test in elite swimmers. *Canadian Journal Applied Physiology,* 29, S17-31.

Marinho, D.A., Reis, V.M., Alves, F.B., Vilas-Boas, J.P., Machado, L., Silva, A.J. & Rouboa, A.I. (2009). Hydrodynamic drag during gliding in swimming. *Journal of Applied Biomechanics,* 25, 253-257.

Mollendorf, J.C., Termin, A.C., Oppenheim, E. & Pendergast, D.R. (2004). Effect of swim suit design on passive drag. *Medicine Science Sports & Exercise,* 36(6), 1029-1035.

Payton, C.J. & Bartlett, R.M. (1995). Estimating propulsive forces in swimming from three-dimensional kinematic data. *Journal of Sports Science,* 13, 447-54.

Pendergast, D.R., di Prampero, P.E., Craig Jr., A.B., Wilson, D.R. & Rennie, D.W. (1977). Quantitative analysis of the front crawl in men and women. *Journal of Applied Physiology,* 43, 475-479.

Pendergast, D.R., Mollendorf, J.C., Cuviello, R. & Termin, A,C, II. (2006). Application of theoretical principles to swimsuit drag reduction. *Sports Engineering,* 9, 65-76.

Rielly, M.F., Kame, Jr., V.D., Termin, B., Tedesco, M.E. & Pendergast, D.R. (1990). Relationship between freestyle swimming speed and stroke mechanics to isokinetic muscle function. *Journal of Swimming Research,* 6, 16-21.

Roberts, A.J., Termin, B., Reilly, M.F. & Pendergast, D.R. (1991). Effectiveness of biokinetic training on swimming performance in collegiate swimmers. *Journal of Swimming Research,* 7, 5-11.

Termin, B. & Pendergast, D.R. (1998). How to optimize performance. *Swim Technique*, 34, 41-46.

Termin, B. & Pendergast, D.R. (1999). Pace lights and swim performance. *Swim Technique,* 36, 18-20.

Termin, B. & Pendergast, D.R. (2001). Training using the stroke frequency-velocity relationship to combine biomechanical and metabolic paradigms. *Journal of Swimming Research,* 14, 9-17.

Toussaint, H.M. & Beek, P.J. (1992). Biomechanics of competitive swimming. *Sports Medicine,* 13, 8-24.

Toussaint, H.M., Knops, W., de Groot, G. & Hollander, A.P. (1990). The mechanical efficiency of front crawl swimming. *Medicine Science Sports & Exercise,* 22, 408-402.

Toussaint, H.M., Truijens, M.J., Elzinga, M.J., van de Ven, A., de Best, H., Snabel, B. & de Groot, G. (2002). Effect of a Fast-skin “body” suit on drag during front crawl swimming. *Sport Biomechanics,* 1, 1–10.

Toussaint, H.M., Beleen, A., Rodenburg, A., Sargeant, A.J., De Groot, G., Hollander, A.P., & van Ingen Schenau, G.J. (1988). Propelling efficiency of front crawl swimming. *Journal of Applied Physiology,* 65, 2506-2512.

Toussaint, H.M., Roos, P.E. & Kolmogorov, S. (2004). The determination of drag in front crawl swimming. *Journal of Biomechanics,* 37, 1655-1663.

Zamparo, P., Capelli, C., Termin, B., Pendergast, D.R. & di Prampero, P.E. (1996). Effect of the underwater torque on the energy cost, drag and efficiency of front crawl swimming. *European Journal of Applied Physiology,* 73, 195-201.

Zamparo, P., Pendergast, D.R., Mollendorf, J., Termin, A. & Minetti, A.E. (2005). An energy balance of front crawl. *European Journal of Applied Physiology,* 94, 134-144.

Zamparo, P., Gatta, G., Capelli, C. & Pendergast, D.R. (2009). Active and passive drag, the role of trunk incline. *European Journal of Applied Physiology,* 106, 195-205.

Zamparo, P., Capelli, C. & Pendergast, D.R. (2011). Energetics of swimming: a historical perspective. *European Journal of Applied Physiology,* 111, 367-378.