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How to predict peak front crawl swimming performance?

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〔abstract〕

Peak performances in sport require the full deployment of all powers an athlete possesses. How factors like mechanical power output, technique, and drag each on itself, but also in concert determine swimming performance is subject of inquiry. This overview of swimming biomechanics focuses on three performance factors: (i) generation of propulsion in water, (ii) drag encountered by the body during swimming and (iii) propulsive efficiency. The theoretical considerations will be put to use by predicting individual power requirements for swimming a world record in the 50 m free style based on experimental data.

Keywords: Drag, mechanical power output, propulsive efficiency, human, competitive swimming

INTRODUCTION: Human swimming performance is poor when compared to species whose habitat is aquatic. A maximum swimming speed of approximately 2 $m \cdot s^{-1}$ represents only about 16% of the maximum unaided speed obtained by humans on land. Although humans are obviously not suited for high-speed swimming, it is from a biomechanical point of view interesting to address the question what factors contribute to peak performance in competitive front crawl swimming.

It is tempting to think that human swimming performance depends solely on the interaction of propulsive and resistive forces. Given this 'force-balance-approach', a swimmer can only improve performance by reducing resistive forces, or drag, that act on the swimming body at a given velocity or by increasing the propulsive forces. However, this approach neglects the fact that some of the mechanical power generated by a swimmer is necessarily expended in giving water a kinetic energy change, since the propelling thrust is made against masses of water that acquire a backward momentum (Alexander, 1977; Toussaint et al., 1988a; Toussaint et al., 1991). This implies that part of the mechanical work the swimmer delivers during the push-off is spent on moving water. Hence, only a proportion of the total mechanical energy the swimmer delivers is used beneficially to overcome body drag. Since in competition swimming velocity is to be optimized, it is more relevant to look at the time derivative of the work produced by the swimmer, i.e. the mechanical power production. Thus in competitive swimming two important mechanical power terms of the total power (P_o) can be discerned: power used beneficially to overcome drag (P_d) and power lost in giving water a kinetic energy change (P_k). The ratio between the useful mechanical power spent to overcome drag (P_d) and the total mechanical power output (P_o) is defined

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as the propulsive efficiency ep (Alexander, 1977):

$$e_p = \frac{P_d}{P_o} = \frac{P_d}{P_d + P_k} \quad (1)$$

Swimming fast will therefore depend on 1. the ability to produce a high mechanical power output enabling the generation of high propulsive forces, 2. the ability to reduce drag, while 3. keeping power losses to pushed away water (P_k) low, i.e. swimming with a high propulsive efficiency. Therefore, knowledge of the backgrounds of propulsion, drag and propulsive efficiency is relevant if human swim performance is to be optimized. In this paper, an overview of the different theories proposed to relate the rather complex kinematics of the propelling hand to the produced propulsive forces is given. This is followed by a sketch of the background of drag in humans and the relationship between swimming technique and drag will be touched upon with a special focus on wave drag. Then, the measurement of propulsive efficiency will be sketched, enabling the evaluation of the effectiveness of technique. Finally, power requirements for swimming a 50 m front crawl record will be calculated given the speed-drag relationship and propulsive efficiency values determined for a Dutch top-swimmer.

PROPULSION

Propulsion is one of the key factors determining performance in human competitive front crawl swimming. It is therefore no surprise that the fluid dynamic mechanism of propulsion has been the subject of scientific inquiry. At present the dominant view is that the hand acts as a hydrofoil, generating both lift *L* and drag *D*. The fluid dynamic forces acting on an object are usually described as a function of its velocity relative to the fluid (u, $m \cdot s^{-1}$), its surface area (plan area *S*, m^2) and the density of the fluid (ρ, $kg \cdot m^{-3}$) according to

$$L = \frac{1}{2} \rho u^2 C_l S \quad (2)$$

$$D = \frac{1}{2} \rho u^2 C_d S \quad (3)$$

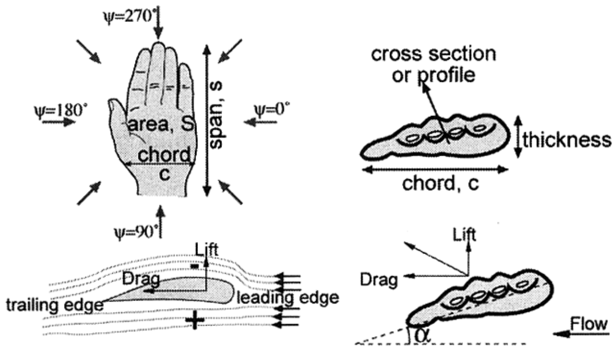

Figure 1: Relevant parameters describing the hand as hydrofoil (top). A hydrofoil subjected to flow (lower left) experiences a lift and drag force. The same is true for the human hand (lower right). The magnitude of the lift and drag forces depend on the angle of attack α, (lower right) and on the sweep back angle ψ, upper left).

where C_l and C_d are the lift and drag coefficients, respectively. The values of these coefficients are characteristic for the object tested and are a function of the *angle of attack*, α, and the *sweep back angle*, ψ (Figure 1).

Quasi-steady analysis of swimming propulsion: Robert Schleihauf (1979) determined C_d and C_l values for the hand using a flow channel through which fluid flowed at a constant speed. For different hand orientations (combinations of α and ψ), the force acting upon the hand model was determined. The C_l and C_d values showed that lift forces might indeed play a significant role in propulsion. The next step, therefore, was to combine the flow channel data with hand velocity data collected from film analysis of leading swimmers. Using equations 2 and 3 the magnitude and direction of the resultant of the lift and drag force acting on the hand throughout the stroke cycle was calculated (Schleihauf, 1986; Berger et al., 1997). These calculations corroborated Counsilman' s hypothesis that both lift and drag forces are generated during the stroke and that the resultant force is predominantly directed forward (see Figure 2). However, it is important to note that Schleihauf' s analysis of the swimming stroke is quasi-steady, i.e. it crucially depends on the assumption that the flow under steady conditions (constant velocity, constant angle of attack and sweep back angle) in the flow channel is comparable to the flow during the actual swimming stroke.

In a replication of the work of Schleihauf and of Berger, van der Meer & de Niet (2003) found that the calculated quasi-steady forces were considerably lower (up to 60%) than the measured propulsive forces using the M.A.D.-system (system to Measure Active Drag, see Figure 8). Therefore, the question was raised whether the quasi-steady assumption fails.

Insect Flight: Given this question it is interesting to make a side step to the fluid dynamics of insect flight. In this field of research it was concluded the conventional, steady-state laws of aerodynamics do not apply to the flapping wings of insects, particularly at low flight speeds. Given this situation, it was recognised that unsteady lift-enhancing mechanisms must play a crucial role in insect flight (Ellington et al., 1996). The high angles of attack of insect wings during hovering provided a clue. When the angle of attack of a wing exceeds the so-called *stall angle*, the flow separates and lift force drops dramatically. However, another unsteady effect occurs: flow separation takes time and lift force is in fact briefly increased due to the formation of a leading-edge vortex. This vortex has its centre of rotation above (and a little bit behind) the leading edge, increasing the underpressure on the top surface of the wing. A flow visualisation study with a robotic hawkmoth model, which accurately mimicked the intricate 3-D flapping, rotational and cambering movements of the real insect wings, revealed the presence of a strong 3-D leading-edge vortex, which could account for 1/3 of the required lift force (Berg & Ellington, 1997). This leading-edge vortex was highly unstable for the translating wing in the flowtank. However, the rotational movement of the robotic wing resulted in a strong axial flow component from the base to the tip of the wing, which stabilised the leading-edge vortex. Thus, the wing rotation itself was crucial for stabilising this powerful unsteady lift-enhancing effect.

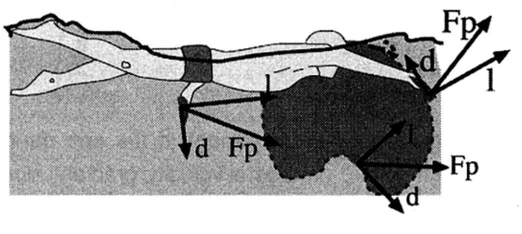

Figure 2: Side view of the hand trajectory during the pull. The angle of attack is continuously adapted to direct the propulsive force F_p forward.

Flow visualisation: Following the hawkmoth model studies, flow around arm and hand was visualised using tufts (Toussaint et al., 2002a). Rapid changes of velocity and direction of the hand throughout the insweep and outsweep was observed and the orientation of the tufts changed virtually from frame to frame, indicating that the flow directions changed rapidly throughout these phases (Figure 3). Another important observation was that the arm segments were mainly rotating rather than translating. Furthermore, free ends of the tufts showed a strong

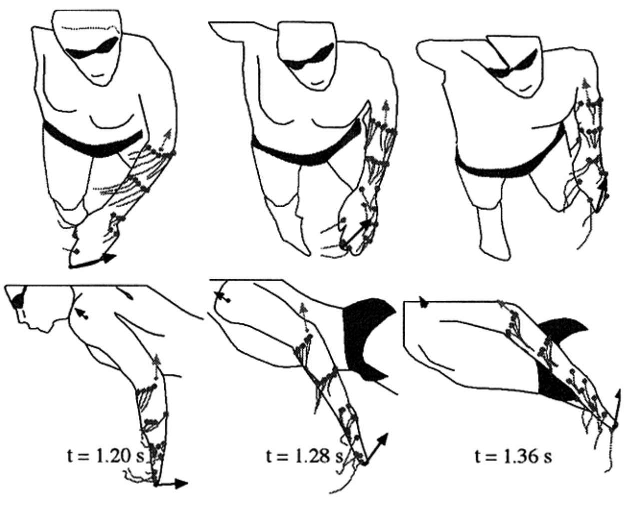

Figure 3: During the outsweep flow direction was not in the direction of the hand movement, but had a distinct axial component (towards the finger tips). The free ends of the tufts that belong to the same tuft cluster show v-shaped arrangement indicative for an accelerating axial flow along the trailing-side of the arm towards the hand after: (Toussaint et al., 2002a).

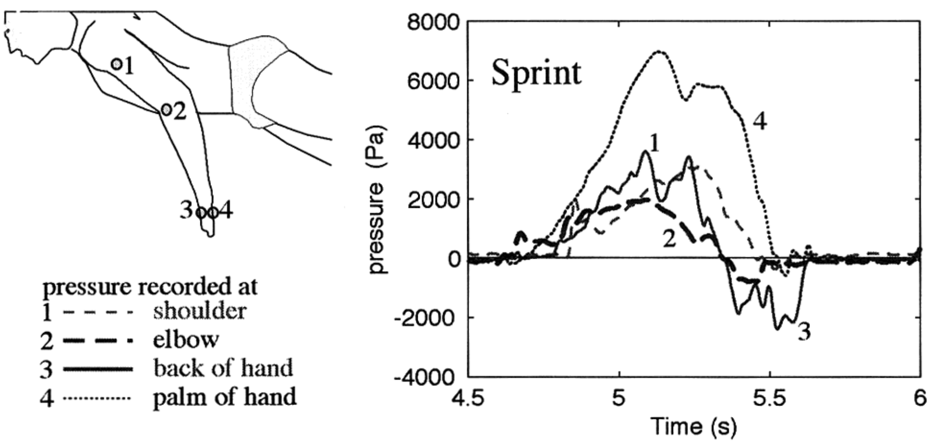

Figure 4: Pressure (relative to atmospheric pressure) recorded at the shoulder, elbow, dorsal side of the hand and palm of the hand swimming at sprint speed. Note that pressure was *not* corrected for differences in hydrostatic pressure due to differences in depth of the sensors.

tendency to cluster in a distal direction, which suggested that a strong pressure gradient along the arm occurred that induced axial flow directed from elbow to the hand. This axial flow is probably associated with the predominantly rotational movement of the arm segments. To further explore this possible explanation for the observed orientation of the tufts, pressure at shoulder elbow, and hand was recorded (Figure 4).

Pressure along a rotating arm: The pressure recordings (uncorrected for hydrostatic pressure) are supportive for the suggested pressure gradient along the arm. Especially at sprint speed, the pressure at the dorsal side of the hand is lower than the pressure at the shoulder and elbow (thus completely opposite the pressure gradient given the difference in depth of hand, shoulder, and elbow). Is it possible to relate the observed pressure difference to the rotation of the arm analogous to the mechanism observed in the hawkmoth?

Pumping fluid: Let us consider the simple model of a rotating stiff arm (Figure 5). This rotation will lead to a velocity gradient along the arm, so that the (tangential) velocity near the hand will be higher than near the elbow. It seems likely that the (tangential) velocity gradient along the limb will induce a (tangential) velocity gradient of the affected fluid close to the limb, which in turn will induce a pressure gradient, where local pressure close to the limb decreases in the direction of the fingertips. This pressure gradient will induce an axial fluid flow along the arm and hand towards the fingertips[1]. Thus the limb rotation leads to a pressure gradient *pumping* fluid along the arm towards the hand not unlike the axial flow observed above the rotating wing of a hovering insect. Of course, in reality the picture will be complicated due to rotations within the arm (elbow extension) and of the body (roll), forward movement of the shoulder and angular accelerations.

Translation of the arm through a fluid results in a high

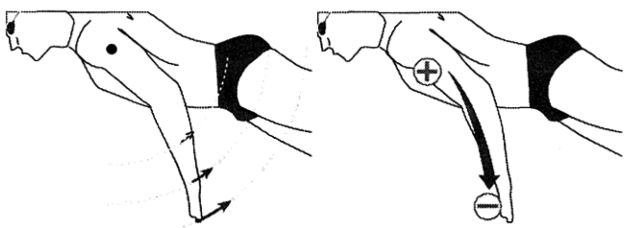

Figure 5: The rotational movement of the arm during the outsweep (left frame) creates a velocity gradient along the arm, that, according to Bernoulli's Principle (pressure inversely proportional to velocity), induces a pressure gradient, leading to an axial flow component towards the hand (red arrow, right frame).

pressure at the leading-side and a low pressure at the trailing-side; this pressure difference is the basis of propulsion by paddling. *Rotation* of the limb will induce an axial pressure gradient on both leading- and trailing-side. The interaction between the circumferential pressure gradient (due to translation) and axial pressure gradient (due to rotation) is not immediately clear. However, at the instantaneous centre of rotation, the velocity of the limb relative to the water is zero and thus the pressure difference between trailing- and leading-sides is zero. Therefore, it seems probable that the axial pressure gradient at the trailing-side is steeper than at the leading-side.

Pumped-up propulsion: The combination of translation and rotation of the arm and hand thus results in an enhanced pressure differential across the propelling surface (the hand). Consequently the propulsive force will increase. This hypothetical propulsion-enhancing mechanism, which was dubbed 'pumped-up propulsion' (Toussaint et al., 2002a), may be summarized as follows: the rapidly rotating arm during the outsweep acts as a rotational displacement pump, transporting water along the trailing side of the arm towards the hand, thus boosting the suction (low pressure) of the wake of the arm, which aids propulsion. Recent experiments revealed a proximo-distal pressure gradient together with the occurrence of a high angle of attack of the hand through the outsweep. The effective propulsive forces calculated using the pressure difference times the hand surface and accounting for the correct forward direction was 89% of the required propulsion as measured with the M.A.D.-system (whereas the quasi-steady calculations could explain only 41%) (Meer & Niet, 2003).

Now some light is shed on the background of the propulsion mechanism, the next part will detail the second performance determining factor that was described in the introduction: 'drag'.

Drag:

Drag is the force resisting movement through water. The total drag (F_d) swimming at a constant speed consists of frictional (F_f), pressure (F_p), and wave drag (F_w) components, namely (Fish, 1993):

$$F_d = F_f + F_p + F_w \qquad (4)$$

Frictional or viscous drag originates from fluid viscosity, and produces shear stresses in the boundary layer (a layer of water extending out from the body to the point at which it is moving at 99% of free stream speed; (Prandtl & Tietjens, 1957)). The magnitude of frictional drag will depend on the wetted surface area of the body and flow conditions within the boundary layer. Boundary flow can be laminar, turbulent or transitional. A boundary layer with turbulent flow produces the highest frictional drag. At what speed and where on the body turbulence first becomes apparent depends on the size and speed of the swimmer and by the density and viscosity of water. The onset of turbulence is often abrupt and occurs at a critical value of the so-called Reynolds number, Re (a dimensionless scaling number) that represents the interaction of the mentioned parameters:

$$Re = \frac{vL\rho}{\mu} \qquad (5)$$

where ρ and μ are the density and viscosity of water, v is the swimming velocity, and L is a characteristic length of the swimmer. Depending on the shape of the object, the critical value of Re will be in the order of 500,000. For a competitive swimmer, with v = 2 $m \cdot s^{-1}$, L = 2 m, ρ = 1000 $kg \cdot m^{-3}$, and μ = $0.897 \cdot 10^{-3}$ $N \cdot s \cdot m^{-2}$, Re will be about $4.5x10^6$ for the swimmer body. This implies that in competitive swimming turbulence will probably always play a role.

Pressure or form drag arises as a result of distortion of flow outside of the boundary layer. The orderly flow over the swimmers' body may separate at a certain point, depending on the shape, size and velocity of the swimmer. Behind the separation point, the flow reverses and may roll up into distinct eddies (vortices). As a result, a pressure differential arises between the front and the rear of the swimmer, resulting in 'pressure drag', which is proportional to the pressure differential times the cross sectional area of the swimmer. In general, pressure drag F_p will be dependent on the square of the swimming speed v, a dimensionless drag coefficient C_{Db} accounting for form effects of the body (e.g. bluff versus torpedo-shaped), the cross-sectional area A_p, and ρ, the density of water:

$$F_p = \frac{1}{2} \rho A_p v^2 C_{Db} \qquad (6)$$

For swimming near the water surface, a third component of the total resistance is due to the so-called 'wave-making resistance'. Kinetic energy from the swimmer is lost as it is changed into potential energy in the formations of waves. With increasing velocity both the wave-length (the crest to crest distance) and the wave amplitude increase. At a certain speed the wave-length will equal the "water-line length" of the swimmer, which is presumably proportional to the height of the swimmer. This swimming speed is called the "hull speed", a term from shipbuilding introduced into competitive swimming by Miller (1975). Further increase in speed traps the swimmer in a trough, ultimately limiting further increase in speed (Toussaint et al., 2002b). The relative speed that, together with the 'form of the swimmer' determines the magnitude of the wave-drag is defined as the Froude-number (F_r, another dimensionless number):

$$F_r = \frac{v}{\sqrt{gL}} \qquad (7)$$

where v and L have the same meaning as before, and g is the acceleration of free fall (9.81 $m \cdot s^{-2}$). Swimmers with equal body form, but differing in height, will create an identical wave system (relative to body dimensions) when their Froude number is equal. For the shorter swimmer this corresponds to a lower velocity.

The contribution of each of the three drag components to total drag depends on swimming speed. At (very) very low speed friction drag will be important since the speed of the water particles allows for an orderly flow around the body. Therefore, no pressure drop occurs at the rear of the swimmer and pressure drag will be negligible. When swimming speed increases pressure will decrease at the rear and increase at the front of the swimmer. Soon, pressure drag dominates. At again higher speeds (>1.5 $m \cdot s^{-1}$) wave drag becomes more and more important.

Measurement of drag: As became obvious in the introduction, the challenge associated with measuring forces in swimming is that swimmers do not have a fixed point to push off from (like they do in for example running). So where to put the force measuring device? To solve this problem push off pads

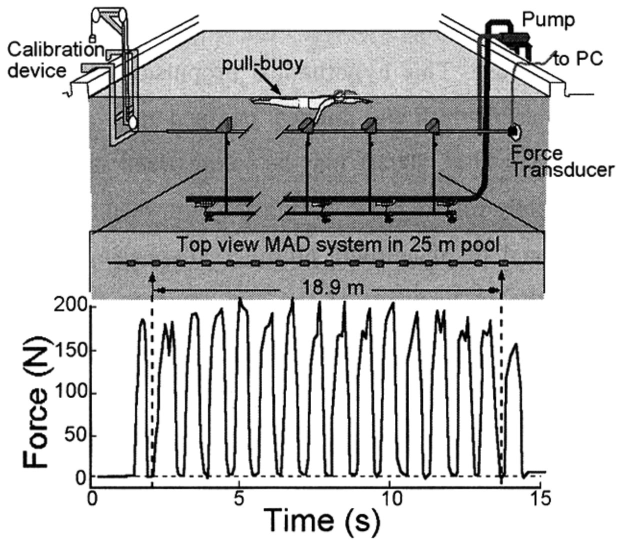

Figure 6: Schematic drawing of the MAD-system mounted in a 25 meter pool. The MAD-system allows the swimmer to push off from fixed pads with each stroke. These push-off pads are attached to a 22 meter long rod. The distance between the push-off pads can be adjusted (normally 1.35 m). The rod is mounted ± 0.8 m below the water surface. The rod is connected to a force transducer enabling direct measurement of push-off forces for each stroke (see lower panel). Subjects use their arms only for propulsion; their legs are floated with a small buoy. If a constant swimming speed is maintained, the mean propelling force equals the mean drag force. Hence, swimming one lap on the system yields one data-point for the speed-drag-curve. (note: the cord leading to the calibration device is detached during drag-measurement)

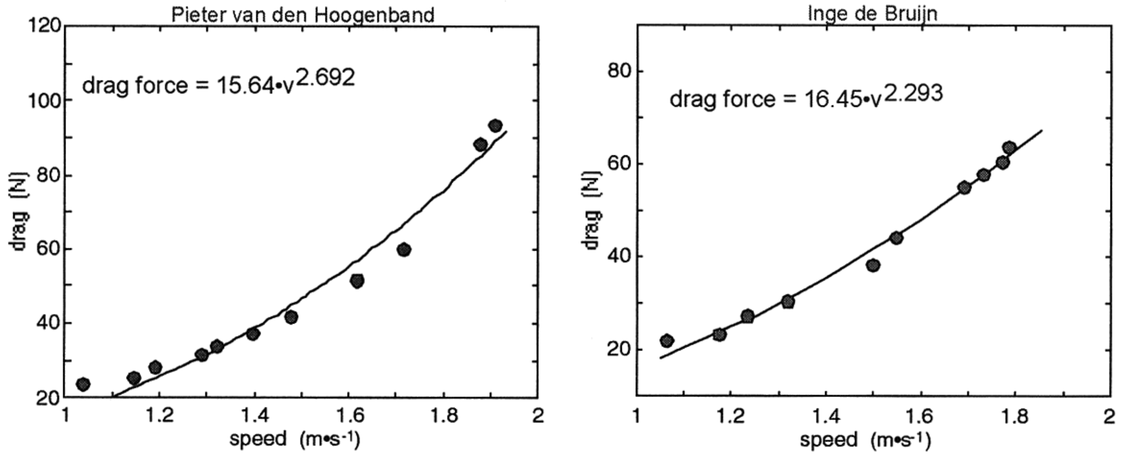

Figure 7: Drag dependent on speed for a male (left) and female (right) elite swimmer

were positioned under water at regular intervals (Toussaint et al., 1988a), see Figure 6. The swimmer is instructed to push off from each pad using a front crawl like action. The legs of the swimmers are floated with a buoy such that only the arms generate propulsion. The force generated during each push off is measured. When swimming at a constant speed, the average push off force will equal the average drag force. By swimming several laps, each at a constant but different speed, the relationship between swimming speed and drag can be determined. An example of this drag-speed relationship is given in Figure 7 for a male and a female elite swimmer.

The total average drag force acting on the (male) swimmer when swimming at a speed of 2 $m \cdot s^{-1}$ is about 110 N and will therefore require 220 W mechanical power to overcome drag. This makes it interesting to investigate what factors determine drag when swimming at near world record speeds (the 100 m front crawl World Record is 47.84 s). The relation between morphology and active drag was evaluated and it was established that drag is determined to a great extent by the maximal body cross-section area (r^2 = 0.76). Furthermore, the difference in mean body cross sectional area (0.091 m^2 males versus 0.075 m^2 females) could explain the difference in mean drag between male and female swimmers (Toussaint et al., 1988b).

When contemplating drag swimming at higher speeds near the water surface, wave drag is an important component (Vogel, 1994). In this context it is interesting to calculate the 'hull speed'. Similar to what occurs for ships, wave-length (λ) and wave amplitude increase with increasing swimming speed. The created wave system will travel on the surface with the same speed as that of the swimmer. The crest-to-crest distance of the wave system (λ) depends on this speed (v) according to:

$$\lambda = \frac{2\pi \cdot v^2}{g} \quad \text{(where } g \text{ is the gravitational acceleration } = 9.8\ m \cdot s^{-2}) \qquad (8)$$

Similar to ships, the hull speed *(vh)* will be reached when λ equals the water line length *lw*. This speed

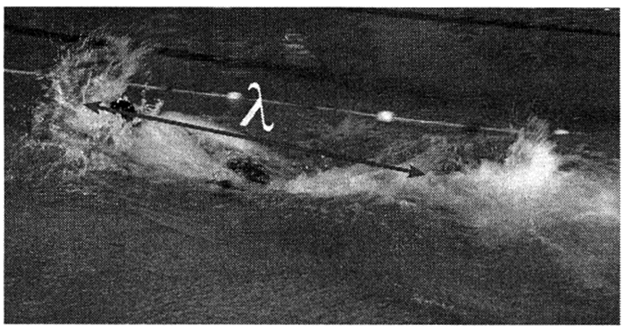

Figure 8: Wave length (λ) of wave system created by the swimmer.

can be calculated recasting equation 8 into:

$$V_h = \sqrt{\frac{gl_w}{2\pi}} \qquad (9)$$

With an arbitrary height of 2 m, a hull speed of 1.77 m·s^{-1} is found. Since real maximum swim speed is about 2 m·s^{-1} this suggests that 1) humans seem to be able to swim faster than the hull speed and 2) wave making resistance matters at competitive swimming speed (see Figure 8). Apparently, the "non-stationarity" of the hull of the swimmer (technique) has an effect on wave drag. In line with these suggestions it has been observed that proficient swimmers create waves of lower amplitude than less skilled swimmers (Takamoto et al., 1985, see Figure 9).

Is it possible to make an estimate of wave making resistance and assess its relative importance? A first approximation is to determine the wave drag using the longitudinal wave cut method (Eggers et al., 1967). Wave drag was estimated while drag was measured swimming arms only on the M.A.D.-system enabling a comparison of the magnitude of wave drag to that of total drag. Results indicate that wave drag amounts up to 50% of total drag swimming arms only at maximal speed (Figure 10). The results show that wave drag cannot be neglected when contemplating improvement of competitive swimming speed. It remains to be determined whether wave drag and thus total drag may be diminished by improving the swimming technique as was suggested previously (Counsilman, 1968). It could be theorized that the forward stretched arm increases the length of the 'hull', with consequent reduction of the wave-making resistance. Also, the gliding arm could reduce the pressure above it and in front of the head, thereby reducing the amplitude of the bow-wave, i.e. similar to function of the cone shaped nose (bulbous bow) below the water-line in large ships (Larsen et al., 1981). In effect, measurement of wave amplitudes of swimmers revealed that the amplitude of the bow wave was smaller than halve the amplitude of the stern wave (Toussaint et al., 2002b). For some swimmers leg activity actually seems to induce lower wave drag (Figure 10), probably by reducing the stern wave by disrupting the pressure field at the rear of the swimmer.

Another approach to reduce total drag is to evade wave drag by swimming substantially below the water surface after start-dive and turns. This approach is in line with the observation that some excellent swimmers showed outstanding results in competition by covering up to 50% of the competitive distance under water using the butterfly kick only. This suggests that there may be a performance advantage

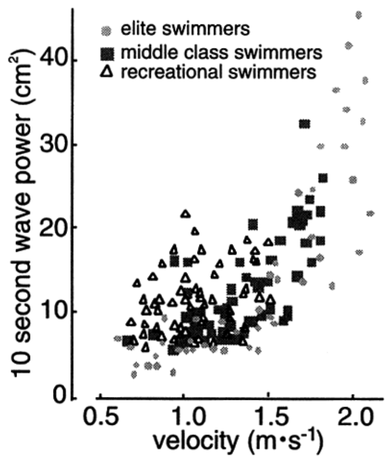

Figure 9: Wave height dependent on swimming speed and swimming technique (adapted from Takamoto, et al., 1985).

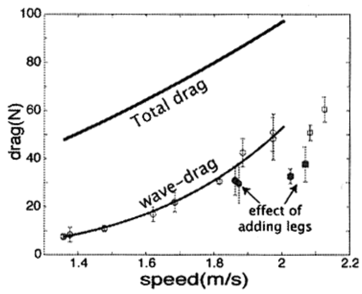

Figure 10: Individual estimates for wave drag dependent on speed. Error bars indicate the uncertainty interval of each estimate. The wave drag swimming free arms only is not different from that swimming on the M.A.D.system (filled dots). The addition of leg activity (swimming whole stroke; filled squares) seems to induce lower wave drag for this swimmer (Hout, 2003).

when the swimmer 'dives under' the wave-making-resistance at the short competitive distances where a high swimming speed can be developed.

PROPULSIVE EFFICIENCY:

The generation of propulsion in a fluid *always* leads to the loss of mechanical energy of the swimmer that will be transferred in the form of kinetic energy to the fluid. Two aspects of this analysis are important for human swimming: (i) the power losses are considerable (e_p << 100%), and (ii) the power losses to the water are highly dependent on technique.

The first aspect is underlined by the propulsive efficiency values observed in fish swimming. For trout values range from e_p = 15% (swimming at 20% of maximum speed) up to e_p = 80% at maximal speed (Webb, 1971). Even if it is assumed that humans could use a swimming technique as efficient as trout, still 20% of the available mechanical power would be 'lost' to moving water backward instead of moving the swimmer forward. Hence, a considerable amount of mechanical power is not transferred into forward speed of the swimmer.

The magnitude of the propulsive efficiency depends on the propulsion mechanism. The efficiency is higher if the swimmer accelerates a large mass of water per unit time to a low velocity, than if it obtains the same propulsion by accelerating a small mass to a high velocity (Alexander, 1977). Or, as already stated by Counsilman (1971), the technique should be such that the amount of water against which the push-off takes place is as large as possible. Thus swimming *at the same speed* requiring the *same propulsive force* can have different associated energy costs depending on the technique that is employed. Consequently, maximal swimming speed can be achieved by a swimming technique where optimal propelling force is obtained with an optimal propulsive efficiency and a minimal body drag.

Measurement of propulsive efficiency: The total mechanical power a swimmer produces is apportioned to power to overcome the total resistance and power to generate the propulsion. If for simplicity it is assumed that average drag relates to speed squared, the average mechanical power required to overcome drag will thus equal (Toussaint et al., 1990)

$$P_d = \boldsymbol{D} \cdot v = K \cdot v^2 \cdot v = K \cdot v^3 \qquad (10)$$

The calculation of the mechanical power lost in the generation of propulsion (P_k) and therewith the determination of ep, is less obvious. One approach is to compare the speed swimming of all out sprints 'free' to the speed swimming sprints on the M.A.D.-system. Again, the fixed push of pads below the water enabling propulsion generation without loss of energy to the water. Therefore, all-out sprints performed on the M.A.D.-system enable faster swimming than all-out sprints swimming 'free'. Considering that power to overcome drag relates to swimming speed cubed and assuming equal power output in two 25 m sprints (free and M.A.D.), the ratio of speed cubed sprinting all-out 'free' relative to the speed cubed sprinting all-out on the M.A.D.-system reflects e_p:

$$e_p = \frac{P_d}{P_o} = \frac{K \cdot v_{free}^3}{K \cdot v_{M.A.D.}^3} = \frac{v_{free}^3}{v_{M.A.D.}^3} \qquad (11)$$

Using the latter approach propulsive efficiency values of on average 73% (range 65.5 - 81.2%) for an average speed of 1.64 $m \cdot s^{-1}$ were found. Using the oxygen uptake approach (which necessitates slower swimming given the limited capacity of the aerobic system) an average value of 63.5% (range 50 - 77%) at 1.29 $m \cdot s^{-1}$ was found for competitive swimmers, while in well-trained, but not so skilled swimmers (triathletes) a value for e_p of 44% was observed underlining the importance of technique (i.e. optimizing the propulsive efficiency) as a performance determinant (Toussaint, 1990).

The observed values for e_p are with 73% nearly as high as the 80% found for fish swimming at high speed (Webb, 1971). This is rather unexpected considering the relative small propulsive area (e.g. hand and fore

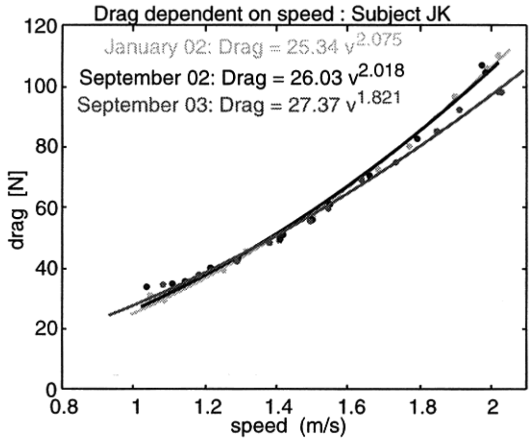

Figure 11: Drag dependent on speed for subject JK.

arm). An explanation for this could be that the arm rotation inducing a proximo-distal axial flow along the arm towards the hand, transports significant fluid masses to the propelling surfaces. This enables the involvement of larger masses of water in propulsion generation thereby increasing e_p.

Power requirements to swim a 50 m front crawl world record:

Swimming speed will depend on power output and propulsive efficiency given the drag-speed relationship. Measurements of those factors are combined to predict and plan individual performance in a training season. The data of JK will be used as an example. JK is a world-class sprinter ranking 4th at the 2003 World Championships Swimming in Barcelona (50 m best time 22.14 s). For the planning of his training in the Olympic season 2004 the question is raised what power output is required to break the 50 m front crawl record (21.64 s)

Drag dependent on speed for JK equals $27.37 \cdot v^{1.821}$ (Figure 11). The maximal power output measured in March 2003, swimming arms only, is 220 W while reaching a speed of 2.06 m/s. Sprinting arms only 'free', a speed of 1.88 m/s is reached yielding a calculated propulsive efficiency of 78%. Sprinting with arms and legs on the MAD-system, a speed of 2.22 m/s is reached requiring a total power output of 281 W. With these performance factors a 'free' swimming speed of 2.10 m/s was reached, the start not included, yielding a 50 m time of 22.14 s.

Beating the world record requires a speed improvement of at least 2.3% leading to a total power requirement of 320 W. Considering that during tests in January 2003 JK already reached power outputs of 297 W, setting a world record is within reach of this swimmer, at least when physical performance factors are taken into consideration.

CONCLUSION:

New developments have shed more light on the hydrodynamic background of both propulsion and drag. The discussion of both propulsion and drag show that unsteady effects seem to play a significant role in the generation of force (Toussaint et al., 2002a). It is remarkable that with respect to drag most, if not all, studies assume that the swimmer is swimming at constant speed, treating drag as a stationary process that does not exhibit relevant fluctuations during one stroke cycle (Toussaint et al., 1988b; Kolmogorov & Duplisheva, 1992). However, given the rather large changes in form of the swimmer during the stroke cycle, non-stationary effects are to be expected for drag as well (Hout, 2003). Hence, both propulsion and drag will fluctuate during each stroke cycle. The challenge is to study the fluctuations of both forces and their interaction during the stroke cycle. Knowledge of this interaction of propulsion and drag will enhance the ability to evaluate a swimmer' s skill to minimize resistance and maximize propulsion.

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1 The mechanism can be demonstrated quite easily in a swimming pool. Tie a woollen thread around the forearm and stand in the pool where the water level is just above the shoulder. Gently rotate the stretched arm in a horizontal plane through the water by making a whole body rotation about the longitudinal axis. At first the woollen tuft will be at 90_ to the long axis of your arm. Increasing the angular velocity will suddenly flip the tuft such that it clings to the skin and points towards the fingertip.