BIOMECHANICS OF PROPULSION AND DRAG IN FRONT CRAWL SWIMMING

Huub M Toussaint
Institute of Fundamental and Clinical Human Movement Science,
Vrije Universiteit, Amsterdam, The Netherlands

Peak performances in sport require the full deployment of all powers an athlete possesses. How factors like force, technique, and endurance each on itself, but also in concert determine swimming performance is subject of inquiry. The accent in this overview of swimming biomechanics is with 2 performance factors: (i) drag encountered by the body *during swimming*, and (ii) the generation of propulsion in water.

KEY WORDS: swimming, drag, MAD-system, propulsion, axial flow.

INTRODUCTION: Swimming performance depends on the interaction of propulsive and resistive forces. A swimmer can improve by reducing resistive forces, or drag, that act on the swimming body at a given velocity or by increasing the propulsive forces. It is thus interesting to have knowledge of the backgrounds of both propulsion and drag. Especially when improvement of performance is at stake, one can only expect to evaluate a swimmer's ability to minimize resistance and maximize propulsion if one can measure the forces involved with some degree of accuracy (Hay, 1988). However, with respect to the generation of propulsion as with regard to drag, considerable controversy exist with respect to the fluid dynamic background of both forces. Consequently, measurement techniques regarding propulsion and drag are hotly debated. In this paper, the hydrodynamic backgrounds of drag is briefly sketched and the relationship between swimming technique and drag will be touched upon. (For a more extended discussion of the hydrodynamic backgrounds of drag, see two other papers in this proceeding: Toussaint, 2002; Toussaint, Stralen & Stevens, 2002). This is followed by an overview of the different theories proposed to relate the kinematics of the propelling surfaces to the produced propulsive forces. *Drag:* When swimming through the water, the body will undergo a retarding force due to resistance, or drag. This force is, given the magnitude of the competitive swimming speeds, predominantly due to turbulence behind the swimmer. Furthermore, when movement occurs at the water surface, additional resistance will arise due to wave formation by the swimmer. This total drag force is depending on swimming velocity to the power of (at least) two. Drag is therefore one of the factors that may limit swimming performance. Throughout the history of swimming research attempts have been made to measure this resistance. Amar (1920) was the first to assume that the resistance is related to the square of the swimming velocity according to:

$$F_d = K \cdot v^2 \tag{1}$$

in which F_d denotes drag force, K is a constant incorporating the density ρ, the coefficient of drag C_D, and the frontal area A_p, while v is the swimming velocity. The relation between resistance (N) and velocity ($m \cdot s^{-1}$) based on Amar's towing experiment was approximately $F_d = 29 \cdot v^2$. It was conjectured that the movements necessary to create propulsion could induce additional resistance. This led to attempts to determine the drag of an active swimming person. Techniques to determine this *active* drag were developed by several groups in the 70's (Clarys, Jiskoot, Rijken & Brouwer, 1974; Prampero, Pendergast, Wilson & Rennie, 1974; Clarys & Jiskoot, 1975; Holmér, 1975) all relying on extrapolation techniques; see for an overview Toussaint, Hollander, Berg & Vorontsov (2000). In the mid-80's, a technique was developed that relies on the *direct* measurement of push-off forces while swimming the front crawl: the system to measure active drag (M.A.D. system). Using this MAD-system, mean values for K of about 30 for male top-swimmers and about 24 for female top swimmers when swimming the front crawl were found (Toussaint, Groot, Savelberg, Vervoorn, Hollander & Ingen Schenau, 1988). It is remarkable that more recent determined K-values for top swimmers are about 10% lower than those determined for top-swimmers 18 years earlier: 22 for females and 27 for males (Toussaint, Truijens, Elzinga, Ven, Best, Snabel & Groot, 2002). Still, the total average drag force acting on the swimmer when swimming at a speed of 2 $m \cdot s^{-1}$ is with about 110 N considerable. This makes it interesting to investigate whether drag can be reduced using a proper technique by for example reducing the frontal area and/or the drag coefficient. However, the literature does not provide a straight forward answer: On the one hand drag seems determined by anthropometric dimensions (e.g. body cross-sectional area and height) in groups of elite swimmers that are more or less homogeneous with respect to swimming performance (Huijing, Toussaint, Clarys, Groot, Hollander, Vervoorn, Mackay & Savelberg, 1988). Probably a small reduction in drag can be achieved by stretching the arm in the glide phase of the stroke, as was suggested by Holmér (1979b). On the other hand, reduced velocity oscillations are observed in the more proficient swimmers (Kornecki & Bober, 1978; Holmér, 1979a; Colwin, 1992), suggesting that with a proper swimming technique drag might be reduced swimming the front crawl.

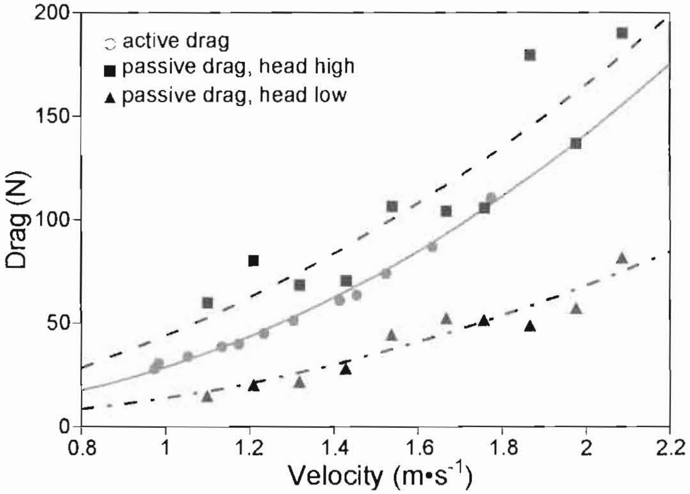

Figure 1. Active drag and passive drag (in two positions; head low = head in the water, high = head out of the water) presented dependent on velocity for one subject.

An interesting example of possible effects of technique on drag is given in Figure 1. For one subject a comparison was made between *active* drag as determined using the MAD-system (green filled dots) to *passive* drag determined in a flume. During testing it appeared that the position of the head had a great influence on passive drag determinations. While the legs were supported by the same small buoy used in the active drag measurements, determinations of passive drag were made when the subject kept the face down in the water and the head between the arms (head low, red triangles). Another series of passive drag determinations were made in which the head was lifted so that the tip of the chin was in level with the water surface (head high, blue squares). The results show that a change in head position can triple values for passive drag. This suggests that by changing body position during stroking some reduction in drag can be accomplished. From Figure 1 it is also clear that a change in body position can influence drag over a range beyond the difference between passive (head low, dashed dotted line) and active drag (solid line). Because body position can influence the drag values, it is thus of utmost importance to gather drag data on competitive swimmers in a relevant and stroke specific position.

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 (see for debate on the relative importance of the lift and drag component in swimming propulsion Rushall, Holt, Sprigings & Cappaert, 1994) is that the hand acts as a hydrofoil, generating both lift L and drag D (Counsilman, 1971).

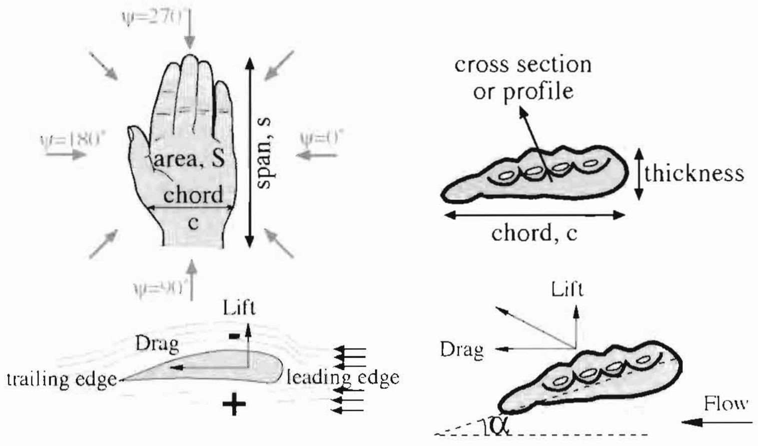

Figure 2. Relevant parameters describing the hand as hydrofoil (top). A hydrofoil subjected to flow (lower left) experiences a lift and drag force. The same is true for the human hand (lower right). The magnitude of the lift and drag forces depends on the angle of attack α and on the sweep back angle ψ.

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

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

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

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 2). *Quasi-steady analysis of swimming propulsion:* Robert Schleihauf (1979) investigated the hydrofoil behaviour of an exact plastic resin replica of the hand in a flow channel through which fluid flowed at a constant speed. For different flow velocities and hand orientations (combinations of α and ψ) he determined the force acting upon the hand model (both lift (L, in N) and drag (D, in N)). The C_l and C_d values (with maximum values of about 1 and 1.2, respectively) reported by Schleihauf 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 equation 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; Schleihauf, Higgins, Hinrichs, Luedtke, Maglischo, Maglischo & Thayer, 1988). 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 3). Most scientists, coaches and swimmers quickly adopted this view. It forms the basis for most recent instructional books on competitive swimming with regard to skill mechanics (e.g. Colwin, 1992; Maglischo, 1993). 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.

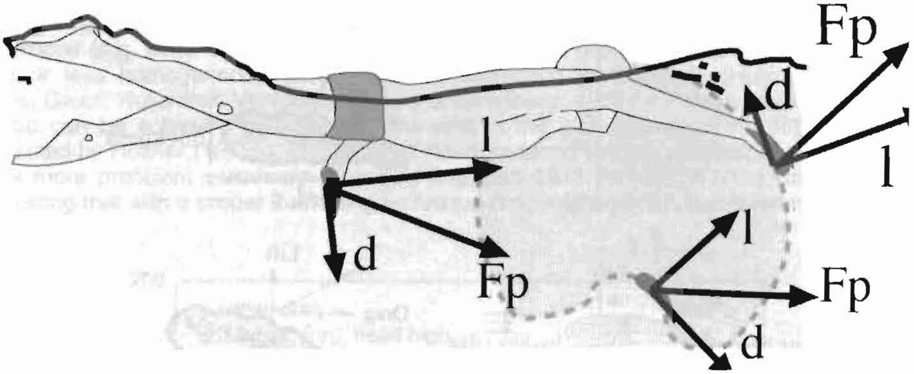

Figure 3. The direction of the hand velocity changes during the pull. The angle of attack is continuously adapted to direct the propulsive force F_p forward.

The quasi-steady analysis is appealing for its relative simplicity. Furthermore, it is a big step forward from the original 'rowing' theory of propulsion, as it can account for sculling movements of the hand. However, recently some doubt was cast whether the quasi-steady analysis can account quantitatively for high propulsive forces required for high-speed swimming. In a replication of Schleihauf's work Berger et al. (1996) found similar values of C_l and C_d of a model hand. However, the calculated quasi-steady forces were considerably lower (17%) than the measured propulsive forces (M.A.D.-system), when the hand velocity was set approximately equal to the velocity of the middle of the palm of the hand, i.e. the hand's aerodynamic centre according to Schleihauf (1983). Therefore, the, in essence 2-D, quasi-static approach to determine lift and drag coefficients has been questioned (Pai & Hay, 1988; Lauder & Dabnichki, 1996). Could it be that 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, which was faced with a similar crisis some time ago (for overview and background see Vogel, 1994; Ellington, 1995). Insect flight was analysed using the quasi-steady approach, equivalent to Schleihauf's work, which provided a satisfactory account of fast forward flight (e.g. Weis-Fogh, 1973). However, a number of observations led to gradual erosion of the confidence in the applicability of the quasi-steady assumption. Simultaneous direct measurement and quasi-steady calculation of instantaneous lift forces on tethered locusts flying in a wind tunnel revealed discrepancies of up to 50% (Ellington, 1984; Ellington, 1995). The application of the quasi-steady assumption even lead to the conclusion that bumble bees cannot fly (McMasters, 1989; Dudley & Ellington, 1990a; Dudley & Ellington, 1990b). Apparently, 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, Berg, Willmott & Thomas, 1996). 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 (Ellington, Berg, Willmott & Thomas, 1996; Berg & Ellington, 1997b; Berg & Ellington, 1997a). 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. Could a similar mechanism be operative in swimming?.

Flow visualisation: Following the hawkmoth model studies, flow around arm and hand was visualised using tufts (see Figure 4 Toussaint, Berg & Beek, 2002). 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.

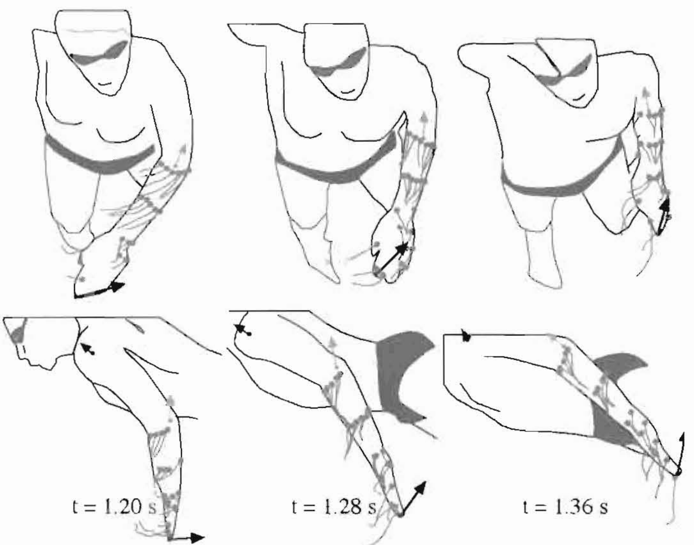

Figure 4. During the outsweep flow direction was not in the direction of the hand movement, but had a distinct axial component (towards the finger tips). The free ends of the tufts that belong to the same tuft cluster show v-shaped arrangement indicative for an accelerating axial flow along the trailing-side of the arm towards the hand.

Another important factor is that the arm segments were mainly rotating rather than translating. Furthermore, free ends of the tufts showed a strong tendency to cluster, which suggested that a strong pressure gradient along the arm occurred that induced axial flow. 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 5).

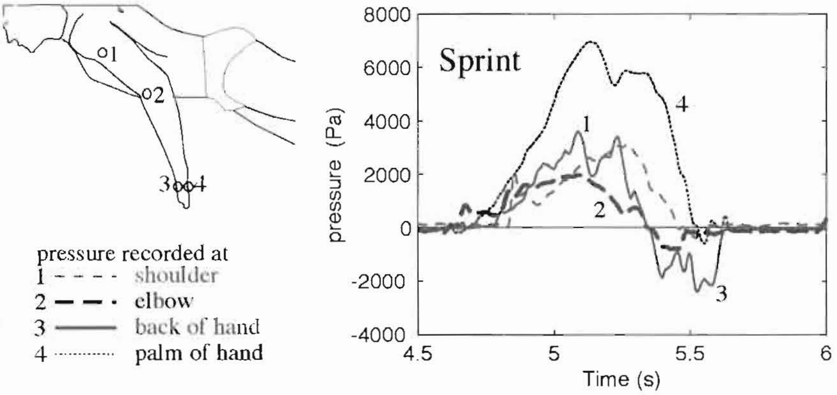

Figure 5. Pressure (relative to atmospheric pressure) recorded at the shoulder, elbow, dorsal side of the hand and palm of the hand swimming at sprint speed. Note that pressure was *not* corrected for differences in hydrostatic pressure due to differences in depth of the sensors.

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?

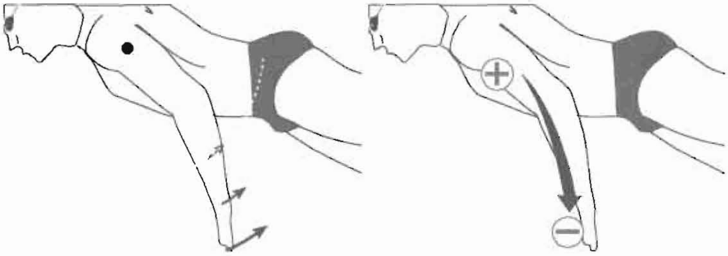

Figure 6. The rotational movement of the arm during the outsweep (left frame) creates a velocity gradient along the arm, that, according to Bernoulli's Principle (pressure inversely proportional to velocity), induces a pressure gradient, leading to an axial flow component towards the hand (red arrow, right frame).

Pumping fluid: Let us consider the simple model of a rotating stiff arm (Figure 6). 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 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 pr ssure 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. The resulting pressure differential across the propelling surface (the hand) would increase the propulsive force. This hypothetical propulsion-enhancing mechanism, which was dubbed 'pumped-up propulsion', 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. Here some calculations are made to assess how such a pumping action might assist propulsion. First an estimate of the velocity of the axial fluid flow is made followed by a consideration of how propulsion could be generated. *Magnitude of the pumping effect:* The magnitude of the suggested 'pumping' effect can be estimated using Bernoulli's equation. Consider for the sake of simplicity a rigid arm that rotates about the shoulder with a constant angular velocity ω Figure 6, left panel). The local tangential velocity along the length of the arm will equal $x \cdot \omega$ where x is the distance from the shoulder. Bernoulli's equation states that

---

[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.

the sum of the dynamic pressure ($0.5\rho \bullet x^2 \bullet \omega^2$) and static pressure (P) is constant. Rearranging yields:

$$\frac{P}{\rho} + \frac{1}{2}x^2 \bullet \omega^2 = \text{constant} \tag{4}$$

The pressure gradient along the length of the arm will then be

$$\frac{d}{dx}\frac{P}{\rho} = -x\,\omega^2 \tag{5}$$

It follows that the pressure gradient increases linearly with x, so that there will be an accelerating axial flow along the arm (as observed in the experiment).

If a slice of fluid with area S and infinitesimal thickness dx (and volume V equal to S•dx) is considered (Figure 7), there will be a difference in pressure across the slice, P_0 being larger than P_1, which leads to a difference in forces acting upon the volume V, $F_0 > F_1$. Consequently, a net force F_x (= $F_0 - F_1$) will act on the mass m of this volume, where m equals V•ρ. Furthermore, the acceleration a_x of the slice of water will be $F_x/V \bullet \rho$. Hence,

$$\frac{d}{dx}\frac{P}{\rho} = \frac{F_x}{dxS\rho} = \frac{F_x}{V\rho} = \frac{F_x}{m} = a_x \tag{6}$$

In other words, the acceleration in the x-direction is proportional to the pressure gradient in the x-direction.

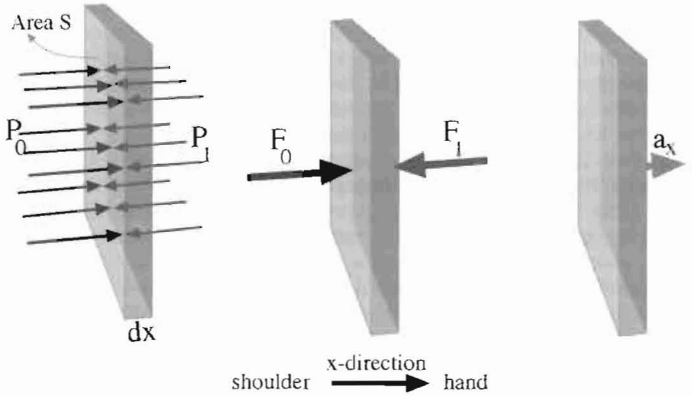

Figure 7. The pressure differential in the x direction acts upon a slice of fluid with area S and thickness dx (left panel). This leads to a difference in force on the volume (middle panel). Consequently, the pressure differential leads to a net force F_x that causes the acceleration a_x of the fluid (right panel).

Since a_x can be written as

$$\frac{dv_x}{dt} = \frac{dv_x}{dx}\frac{dx}{dt} = v_x\frac{dv_x}{dx}\,, \tag{7}$$

and finally the axial velocity gradient along the arm is calculated:

$$v_x\frac{dv_x}{dx} = x\omega^2 \tag{8}$$

By integration along x the axial velocity as a function of x equals:

$$\frac{1}{2}v_x^2 = \frac{1}{2}x^2\omega^2 + C \tag{9}$$

If is is assumed that the axial velocity v_x is zero at the centre of rotation (at x = 0), C is zero and the fluid velocity gradient ($v_x(x)$) along the arm induced by the pressure gradient is

$$v_x(x) = x\omega \tag{10}$$

Thus, this analysis shows that the axial fluid velocity at any point along the arm will be of the same magnitude but perpendicular to the local tangential velocity. This result is not too surprising: the pressure difference caused by the tangential velocity gradient, according to

Bernoulli, in turn results in an axial flow which also obeys Bernoulli, resulting in an axial velocity equal to the local tangential velocity. The side views of Figure 4 can be used to estimate the angular velocity ω of the arm (ignoring rotation in the transverse plane). Between frame 26 and 30 (a time interval of 0.16s) the arm rotated over approximately 34° or 0.59 rad, so that mean ω was 3.7 rad•s^{-1}. Assuming a distance between the centre of rotation and the hand of 0.65 m, the axial flow at the hand can be estimated (eq.10) as 2.4 m•s^{-1}. *Pumped up propulsion:* The next question is how this flow of water is used to generate propulsion. Three hydrodynamic effects that contribute to propulsion will be considered: (1) the paddling effect in which the hand acts like an oar, (2) an enhanced pressure differential due to the pumping effect, and (3) acceleration of the 'added' mass surrounding the hand and forearm. As an example data from a paper by Berger et al. (1999) will be taken. In their example the subject swam at 1.3 m•s^{-1} ; since drag related to velocity as 16.4•v$^{2.22}$, the average drag at this velocity was 29.5 N. The average hand velocity during the outsweep was 2.2 m•s^{-1}, the average hand acceleration 1.75 m•s^{-2}. It is important to note that, roughly speaking, the hand accelerates throughout the stroke up to the last few frames before the hand is pulled out. Here the magnitude of each of these effects for the outsweep is discussed. Note that probably no propulsion is generated during the glide phase (45% of the stroke cycle) and a limited amount during the insweep (10% of the cycle). Hence, the mean propulsive force during the outsweep (45% of the stroke cycle) can be expected to be roughly twice the mean required propulsion for the whole stroke, i.e. roughly 59N. *ad 1*: The magnitude of the paddling effect can be calculated with equation 3 (assuming C_D = 1, (see Berger, Groot & Hollander, 1995) and a hand plan area of 0.015 m^2) as 0.5•1•997•2.2^2•0.015 = 36 N. *ad 2:* The magnitude of the pumping effect may be approximated as follows: The axial flow, with velocity v_x = 2.2 see Eq 10, at the back of the hand enhances the pressure differential across the propelling surface. Assuming no axial flow occurs on the leading edge side of the arm, the effect can be calculated using Bernoulli's equation to be 0.5•997•2.2^2•0.015 = 36 N. *ad 3:* The magnitude of the added mass can be estimated according to chapter 16 of Vogel (1994). Assuming the forearm and hand to be one cylinder with slenderness ratio 1 yields an added mass coefficient of 1 (Vogel, 1994). The mass of underarm and hand is about (0.025 • body mass) = 1.6 kg; the added mass will thus be equal to that. Given the average hand acceleration of 1.75 m•s^{-2}, the effect of the acceleration of added mass plus hand and forearm will be 3.2•1.75 = 5.7 N. The latter calculation excludes the possibility that the axial volume flow of water due to the pumping effect is also involved. In that case the added mass effect would be much stronger. Simple addition of the paddling-, pumped up and added mass effects yields a propulsive force of 78 N, which is 2.6 times the average drag force swimming at 1.3 m•s^{-1}, which is in very good agreement. The above simple analysis suggests that in addition to the paddling mechanism (Counsilman, 1968), the pumping mechanism could enhance the pressure differential across the propelling surface as well as enlarge the added mass effect and thus account for the observed propulsive forces. Note that the effect of the pumped up propulsion is of the same magnitude as the simple paddling effect. (of course, the effects are probably not simply additive, particularly the paddling and pumping effects will interact, possibly reducing the total net propulsion). 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. Furthermore, it has been left without discussion how the hand guides the volume flow along the arm to the rear, so that efficient propulsion is generated. Presumably, the sculling movements of the hand play a crucial role in this issue. Finally, it is noteworthy that the described mechanism is most likely not confined to the arm action in front crawl swimming. The leg action is also a combination of rotations in hip, knee and ankle. Therefore it is expected that the kinematics of the leg action, dominated by rotations, will induce a pressure gradient enhancing propulsion. And, to take it one step further, the described mechanism seems also relevant in other forms of aquatic locomotion, wherever a propelling element is rotated (e.g. fins, paddles, wings, legs).

CONCLUSION: New developments have shed more light on the hydrodynamic background of both propulsion and drag. Especially studies on propulsion show that unsteady effects seem to play a significant role in the generation of force (Sanders, 1999). 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 (Clarys, Jiskoot, Rijken & Brouwer, 1974; Toussaint, Groot, Savelberg, Vervoorn, Hollander & Ingen Schenau, 1988; 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. 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.

REFERENCES:

Amar J. (1920). *The human motor.* London: G. Routledge & Sons, Ltd.

Berg C. van der & Ellington C.P. (1997a). The three-dimensional leading-edge vortex wake of a 'hovering' model hawkmoth. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* **352**, 329-340.

Berg C. van der & Ellington C.P. (1997b). The vortex wake of a 'hovering' model hawkmoth. *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences* **352**, 317-328.

Berger M.A.M. (1996). *Force generation and efficiency in front crawl swimming.* Amsterdam: Ph.D.-thesis, Vrije Universiteit.

Berger M.A.M., Groot G. de & Hollander A.P. (1995). Hydrodynamic drag and lift forces on human hand/arm models. *Journal of Biomechanics* **28**, 125-133.

Berger M.A.M., Hollander A.P. & Groot G. de (1999). Determining propulsive force in front crawl swimming: A comparison of two methods. *Journal of Sports Sciences* **17**, 97-105.

Clarys J.P. & Jiskoot J., Clarys J.P. & Jiskoot J.s. 1975. Total resistance of selected body positions in the front crawl. Baltimore: University Park Press.

Clarys J.P., Jiskoot J., Rijken H. & Brouwer P.J. (1974). Total resistance in water and its relation to body form. In: Nelson R.C. & Morehouse C.A. (Eds.) *Biomechanics IV,* 187-196. Baltimore: University Park Press.

Colwin C.M. (1992). *Swimming into the 21st Century.* Champaign, Ill. Human Kinetics Publishers.

Counsilman J.E. (1968). *Science of Swimming.* Englewood Cliffs, N.J. Prentice-Hall.

Counsilman J.E. (1971). The application of Bernoulli's principle to human propulsion in water. In: Lewillie L. & Clarys J.P. (Eds.) *Swimming I,* 59-71. Brussels: Université Libre de Bruxelles.

Dudley R. & Ellington C.P. (1990a). Mechanics of forward flight in bumblebees. I. Kinematics and morphology. *Journal of Experimental Biology,* **148**, 19-52.

Dudley R. & Ellington C.P. (1990b). Mechanics of forward flight in bumblebees. II. Quasi-steady lift and power requirements. *Journal of Experimental Biology,* **148**, 53-88.

Ellington C.P. (1984). The aerodynamics of hovering insect flight I The quasi-steady analysis (1-15), II Morphological parameters (17-40), III Kinematics (41-78), IV Aerodynamic mechanisms (79-113), V A vortex theory (115-144), VI Lift and power requirements (145-181). *Philosophical Transactions of the Royal Society of London. Series B: Biological Sciences,* **305**, 1-181.

Ellington C.P. (1995). Unsteady aerodynamics of insect flight. In: Ellington C.P. & Pedley T.J. (Eds.) *Biological Fluid Dynamics,* 626-630.

Ellington C.P., Berg C. van der, Willmott A.P. & Thomas A.L.R. (1996). Leading-edge vortices in insect flight. *Nature,* **384**, 626-630.

Hay J.G. (1988). The status of research on the biomechanics of swimming. In: Ungerechts B.E., Wilke K. & Reischle K. (Eds.) *Swimming Science V,* 3-14. Champaign, Ill.: Human Kinetics Books.

Holmér I. (1975). Efficiency of breaststroke and freestyle swimming. In: Clarys J.P. & Lewillie L. (Eds.) *Swimming II,* 130-136. Baltimore: University Park Press.

Holmér I. (1979a). Analysis of acceleration as a measure of swimming proficiency. In: Terauds J. & Bedingfield E.W. (Eds.) *Swimming III,* 118-125. Baltimore: University Park Press.

Holmér I. (1979b). Physiology of swimming man. In: Hutton R.S. & Miller D.I. (Eds.) *Exercise and Sport Sciences Reviews,* 87-123. Philadelphia: The Franklin Institute Press.

Huijing P.A., Toussaint H.M., Clarys J.P., Groot G. de, Hollander A.P., Vervoorn K., Mackay R. & Savelberg H.H.C.M. (1988). Active drag related to body dimensions. In: Ungerechts B.E., Reischle K. & Wilke K. (Eds.) *Swimming Science V* (pp. 31-37). Champaign, Ill.: Human Kinetics Books.

Kolmogorov S.V. & Duplisheva 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.

Kornecki S. & Bober T. (1978). Extreme velocities of a swimming cycle as a technique criterion. In: Eriksson B.O. & Furberg B. (Eds.) *Swimming Medicine IV* (pp. 402-407). Baltimore: University Park Press.

Lauder M.A. & Dabnichki P. (1996). A proposed mechanical model for measuring propulsive forces in front crawl swimming. In: Haake S. (Ed.) *Engineering of Sport* (pp. 257-262). Rotterdam: Balkema.

Maglischo E.W. (1993). *Swimming even Faster*. Palo Alto: Mayfield Publishing Cy.

McMasters J.H. (1989). The flight of the bumblebee and related myths of entomological engineering. *American Scientist,* **77**,164-169.

Pai Y.C. & Hay J.G. (1988). A hydrodynamic study of the oscillation motion in swimming. *International Journal of Sports Biomechanics,* **4**, 21-37.

Prampero P.E.d., Pendergast D.R., Wilson D.W. & Rennie D.W. (1974). Energetics of swimming in man. *Journal of Applied Physiology,* **37**, 1-5.

Rushall B.S., Holt L.E., Sprigings E.J. & Cappaert J.M. (1994). A re-evaluation of the forces in swimming. *Journal of Swimming Research,* **10**, 6-30.

Sanders R. (1999). Hydrodynamic characteristics of a swimmer's hand. *Journal of Applied Biomechanics,* **15**, 3-26.

Schleihauf R.E. (1979). A hydrodynamic analysis of swimming propulsion. In: Terauds J. & Bedingfield E.W. (Eds.) *Swimming III*, 70-109. Baltimore: University Park Press.

Schleihauf R.E. (1986). Swimming skill: a review of basic theory. *Journal of Swimming Research,* **2**,11-20.

Schleihauf R.E., Gray L. & DeRose J. (1983). Three-dimensional analysis of swimming propulsion in the sprint front crawlstroke. In: Hollander A.P., Huijing P.A. & Groot G. de (Eds.) *Biomechanics and Medicine in Swimming* 173-184. Champaign, Ill.: Human Kinetics Publishers.

Schleihauf R.E., Higgins J.R., Hinrichs R., Luedtke D., Maglischo C., Maglischo E.W. & Thayer A. (1988). Propulsive techniques: front crawl stroke, butterfly, backstroke, and breaststroke. In: Ungerechts B.E., Wilke K. & Reischle K. (Eds.) *Swimming Science V*. 53-59. Champaign, Ill: Human Kinetics Books.

Toussaint H.M. (2002). The Fast-Skin™ 'body' suit: Hip, hype, but does it reduce drag during front crawl swimming? In: Gianikellis K. (Ed.) *XXth International Symposium on Biomechanics in Sports* Caceres. University of Extremadura.

Toussaint H.M., Berg C. van der & Beek W.J. (2002). Pumped-up propulsion during front crawl swimming. *Medicine and Science in Sports and Exercise,* **34**, 314-319.

Toussaint H.M., Groot G. de, Savelberg H.H.C.M., Vervoorn K., Hollander A.P. & Ingen Schenau G.J. van (1988). Active drag related to velocity in male and female swimmers. *Journal of Biomechanics,* **21**, 435-438.

Toussaint H.M., Hollander A.P., Berg C. van der & Vorontsov A. (2000). Biomechanics of swimming. In: Garrett W.E. & Kirkendall D.T. (Eds.) *Exercise and Sport Science,* 639-660. Philadelphia: Lippincott, Williams & Wilkins.

Toussaint H.M., Stralen M. van & Stevens E. (2002). Wave drag in front crawl swimming. In: Gianikellis K. (Ed.) *XXth International Symposium on Biomechanics in Sports*. Caceres. University of Extremadura.

Toussaint H.M., Truijens M., Elzinga M.J., Ven A. van de, Best H. de, Snabel B. & Groot G. de (2002). Effect of a Fast-Skin 'Body' Suit on drag during front crawl swimming. *Sport Biomechanics,* **1**,1-10.

Vogel S. (1994). *Life in Moving Fluids; The physical biology of flow*. Princeton, N.J.: Princeton University Press.

Weis-Fogh T. (1973). Quick estimates of flight fitness in hovering animals, including novel mechanisms for lift production. *Journal of Experimental Biology*, **59**, 169-230.