WAVE DRAG IN FRONT CRAWL SWIMMING

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When swimming at the surface, swimmers will experience wave drag. It is observed that above a certain speed, wave height grows rapidly with further speed increase, suggesting that wave drag cannot be neglected at high speed. Therefore, the magnitude of this component of total drag was estimated. Total drag was decomposed in 2 parts; wave- and pressure drag. Assuming wave drag to be negligible below 1.6 $m \cdot s^{-1}$, the velocity dependence of pressure drag was assessed by drag determinations at speeds below 1.6 $m \cdot s^{-1}$. By subtracting the estimated pressure drag from total drag values measured at higher speeds, wave drag was estimated. At a mean speed of 1.89 $m \cdot s^{-1}$, mean wave drag was 11.5 N, amounting to 12.1 % of total drag. These results underline the importance of reducing wave drag by diving under the surface after start and turns.

KEY WORDS: swimming, wave drag, MAD-system, hull speed, pressure drag.

INTRODUCTION: When swimming through the water the body will undergo a drag force. For swimming near the water surface three drag components can be distinguished; friction drag (F_f), pressure drag (F_p) and the so- called 'wave-making resistance' (F_w). Hence total resistance F_d equals (Toussaint & Beek, 1992):

$$F_d = F_f + F_p + F_w \qquad (1)$$

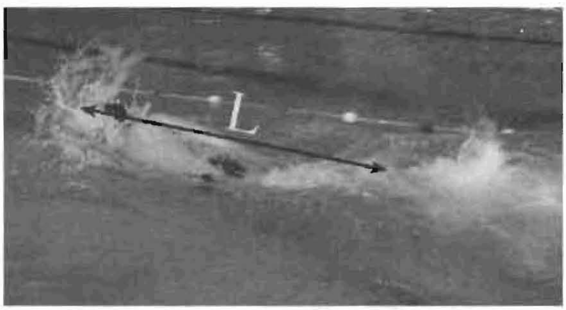

Figure 1. Wave length (L) of wave system created by the swimmer.

Wave drag only occurs when swimming near the surface, where the pressure surrounding the moving swimmer sets up a wave system. Both the wave-length (L, the crest to crest distance, see Figure 1) and the wave amplitude increase with increasing swimming speed. 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. Further increase in speed traps the swimmer in a trough, ultimately limiting further increase in speed (Vogel, 1994; Aigeldinger & Fish, 1995; Fish & Baudinette, 1999). To move faster, the swimmer would literally have to swim uphill, which is energetically very costly. For ships the hull speed (v_h) is a function of the square root of the waterline length of the hull or body (Prange & Schmidt-Nielsen, 1970):

$$v_h = \sqrt{\frac{g l_w}{2\pi}} \qquad (2)$$

where **g** is the gravitational acceleration, 9.8 $m \cdot s^{-2}$, and l_w is the waterline length along the longitudinal axis of the body (in m). With an arbitrary height of 2 m, a hull speed of 1.77 $m \cdot s^{-1}$ is found (Eq. 2). Since real maximum swim speed is about 2 $m \cdot s^{-1}$ 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. Can we make an estimate of wave making resistance and assess its relative importance?

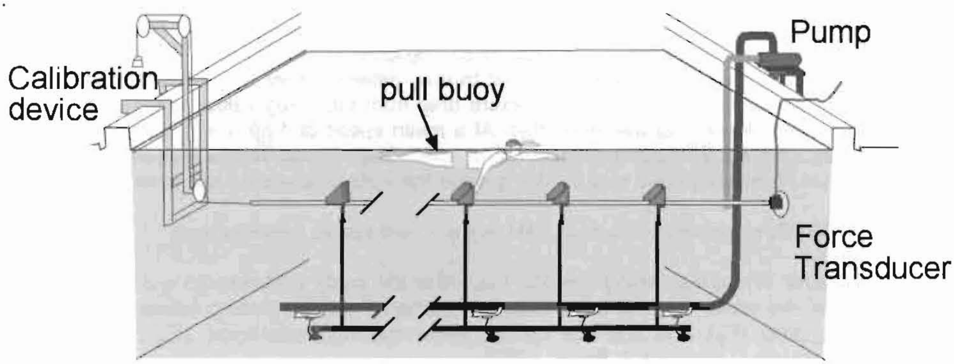

Figure 2. Schematic drawing of the MAD-system mounted in a 25 meter pool. (note: the cord leading to the calibration device is detached during drag-measurement)

METHODS: To measure total drag of a swimmer during active swimming we used the MAD System (System to Measure Active Drag, see Figure 2) (Toussaint, Groot, Savelberg, Vervoorn, Hollander & Ingen Schenau, 1988). 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. Subjects use their arms only for propulsion; their legs are floated with a small buoy. If a constant swimming velocity is maintained, the mean propelling force equals the mean total drag force. Hence, swimming one lap on the system yields one data-point for the velocity-drag-curve. To estimate the effect of wave drag it was assumed that below a certain swimming speed, drag is predominantly determined by pressure drag. Hence, friction drag is assumed to be negligible which given the Reynolds number (>1,000,000) swimming at speeds >0.8 $m \cdot s^{-1}$ seems justified. This implies that at swimming speeds (0.8 – 1.7 $m \cdot s^{-1}$), total drag would be proportional to velocity squared (Amar, 1920) :

$$F_d = F_p = K_1 . v^2 \qquad (3)$$

while at swimming speeds near and above the hull speed, wave drag would become more important such that total drag would increase stronger than v^2. Thus at high speed swimming total drag can be considered as being the sum of pressure drag and wave drag:

$$F_d = F_p + F_w = K_1 . v^2 + K_2 . v^b \qquad (4)$$

For 8 swimmers, drag was determined in a range of speeds (0.8 – 2 $m \cdot s^{-1}$), such that at least 12 data points of drag dependent on velocity were determined. These velocity/drag data were least square fitted using a Levenberg-Marquardt algorithm to the function:

$$F_d = A \cdot v^n \qquad (5)$$

where F_d represents total active drag, v equals swimming velocity and A and n are parameters of the power function. After discarding the fastest run of the (remaining) data-set, this fitting procedure was repeated until the coefficient n was reduced to about 2. The resulting fit was assumed to reflect the pressure drag of the swimmer, hence $F_d = F_p = K_1 \cdot v^2$. The wave drag was estimated from the difference between the measured drag and the fit for pressure drag (see Figure 3).

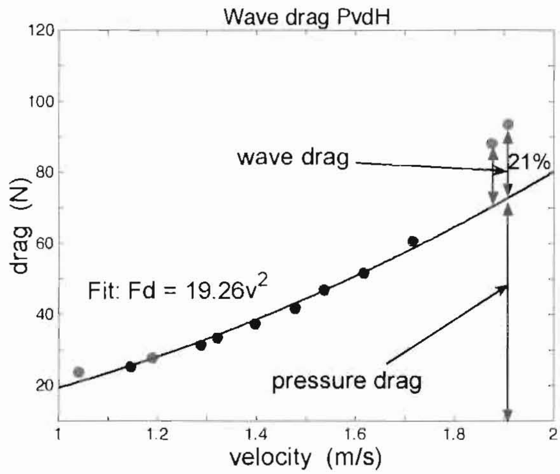

Figure 3. Typical example of drag dependent on velocity. Up to 1.7 $m \cdot s^{-1}$ drag is dependent on the velocity squared. The drag dependent on velocity (below 1.7 $m \cdot s^{-1}$) is $F_d = 19.26\ v^2$. Above 1.7 $m \cdot s^{-1}$ wave drag becomes more important. At 1.9 $m \cdot s^{-1}$ wave drag is 21% of total drag.

Table 1. Individual data for the swimmers for Wave drag, wave drag expressed as percentage of total drag (%drag), and the speed reached on the MAD-system for which the magnitude of wave drag was determined.

Subject	Total drag (N)	K_1 ($kg \cdot m^{-1}$)	Wave drag (N)	%drag	Speed ($m \cdot s^{-1}$)
Ewout	116	25.9	13.2	11.4	1.98
Thijs	97	29.3	5.9	6.0	1.76
Benno	109	25.6	9.6	8.8	1.96
Robin	99	19.5	23.0	23.2	1.92
Chantal	66	18.9	10.1	15.3	1.70
Sander	82	21.6	8.4	10.2	1.90
Mark	107	25.7	14.5	15.6	1.89
Johan	110	26.5	7.2	6.5	2.02
Mean:	98.3	24.125	11.49	12.13	1.89

RESULTS AND DISCUSSION: Using their arms only, some swimmers could reach speeds up to 2 $m \cdot s^{-1}$ when swimming on the MAD-system (Table 1). Total drag at maximal speed was on average 98.3 N. The average coefficient (K_1) relating pressure drag to velocity squared was 24.125 $kg \cdot m^{-1}$. Using the individual coefficients wave drag was estimated to be 11.49 N on average. This is 12.13% of total drag. 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; Bober & Czabanski, 1975; Maglischo, 1982; Toussaint & Beek, 1992). 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 below the water-line in large ships (Larsen, Yancher & Bear, 1981). In line with these suggestions it has been observed that proficient swimmers create waves of lower amplitude than less skilled swimmers (Takamoto, Ohmichi & Miyashita, 1985).
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 suggest that there may be a performance advantage when the swimmer 'dives under' the wave-making-resistance at the short competitive distances where a high swimming speed can be developed (Toussaint, Hollander, Berg & Vorontsov, 2000).

CONCLUSION: The magnitude of wave drag is less than might be expected given that competitive swimming speeds exceed the hull speed by more than 10%. This suggests that wave drag might be reduced by swimming technique. Nevertheless, wave drag amounted to 12 % of total drag. This makes it worthwhile to 'dive under' the wave drag after start and turns.

REFERENCES:

Aigeldinger T.L. & Fish F.E. (1995) Hydroplaning by ducklings: Overcoming limitations to swimming at the water surface. *Journal of Experimental Biology*, **198**, 1567-1574.
Amar J. (1920). *The human motor* London: G. Routledge & Sons, Ltd.
Bober T. & Czabanski B. (1975). Changes in breaststroke techniques under different speed conditions. In Clarys J.P., Lewillie L. (Eds.), *Swimming II,* 188-193. Baltimore: University Park Press.
Counsilman J.E. (1968). *Science of Swimming* Englewood Cliffs, N.J.: Prentice-Hall.
Fish F.E. & Baudinette R.V. (1999) Energetics of locomotion by the Australian water rat (hydromys chrysogaster): A comparison of swimming and running in a semi-aquatic mammal. *Journal of Experimental Biology*, **202**, 353-363.
Larsen O.W., Yancher R.P. & Bear C.L.H. (1981) Boat design and swimming performance. *Swimming Technique*, **18**, 38-44.
Maglischo E.W. (1982). *Swimming Faster* Palo Alto: Mayfield Publishing Cy.
Prange H.D. & Schmidt-Nielsen K. (1970) The metabolic cost of swimming in ducks. *Journal of Experimental Biology*, **53**, 763-777.
Takamoto M., Ohmichi H. & Miyashita M. (1985). Wave height in relation to swimming velocity and proficiency in front crawl stroke. In Winter D.A., Norman R.W., Wells R.P., Hayes K.C., Patla A.E. (Eds.), *Biomechanics IX-B,* 486-491. Champaign, Ill.: Human Kinetics Publishers.
Toussaint H.M. & Beek P.J. (1992) Biomechanics of competitive front crawl swimming. *Sports Medicine*, **13**, 8-24.
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.v.d. & Vorontsov A. (2000). Biomechanics of swimming. In Garrett W.E., Kirkendall D.T. (Eds.), *Exercise and Sport Science,* 639-660. Philadelphia: Lippincott, Williams & Wilkins.
Vogel S. (1994). *Life in Moving Fluids; The physical biology of flow*, 2nd ed. Princeton, N.J.: Princeton University Press.