ANALYSIS OF SWIMMING TECHNIQUES USING VORTEX TRACES

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Propulsion in water is based on the interaction of motion body and water, respectively *(under the condition of limited energy reservoir*). The swimming movements are transmitting momentum creating a flow in the aquatic surrounding. Self-propulsion is a mutual result of a transfer of momentum from the propelling parts of the body on the water as well as a transfer of impulse from the water on the body, producing a *counter bearing* (a term indicating the application of Newton's 3rd Law) and leaving thereby some traces. In water the traces are useful for discussions about the efficiency of swimming techniques. Here the traces of *vortex* (a common term for *mass of whirling fluid*) are emphasised. Vortices occur in different organized patterns, as *trailing vortex* next to the hands (front driven body) or *rolling vortex* in the wake of the feet (rear driven body). *Trailing vortex* create a zone of underpressure: it is hypothised that the hand is resited by this suction from the intended pull through the water and thus the action of the trunk-arm muscles propels the body past the hand. *Rolling vortex* may transfer a power stroke to the body in case the sense of its rotation is altered.

KEY WORDS: self propulsion, flow visualisation, hydrodynamics, vortex, front/rear driven propulsion, ecconomy

INTRODUCTION: Swimming means the combination of buoyancy and translation through the water by self propulsion. The explanation of self propulsion is still a matter of controvery. The development of new research technologies have led to discussions of the model: propulsion by Bernouilli's Principle (Counsilman, 1971). No doubt, this concept contributed much for a better understanding of the interaction between the movements of the body (or parts of it) and of the water.

Models of propulsion which are to be used to analyse swimming techniques should consider the following aspects (i) non-steady state flow conditions, (ii) mutual interactions of body and water motions[1] and (iii) the total energy balance. The 'interactive bio-fluiddynamic' model used for explanation of the propulsion of swimming animals (Ungerechts, 1985) reflects the creation of momentum[2] and transfer of impulse[3] and the energy transfer involved *under the condition of a limited energy reservoir*.

This approach may be integrated in the test set-up like the 'expertsystem' described by Persyn et al. (1988). It provides physiological and biomechanical information in order to steer the individual training process. The structure of *complex mutual body-water motion* has to be introduced to the swimmer and the coach, respectively. In this case, swimmers and coaches should be introduced into the same hydrodynamic laws, however, adapted to their needs.

HYDRODYNAMICAL CONCEPTS:

VORTEX, DRAG AND ENERGY BALANCE. Hydrodynamics is, to a large extent, a matter of theoretical axioms of people knowing physics. Swimming experts may be part of this community. However, experimental proofs of hyotheses are still rare, partly because of the non-steady state nature. In any case, the search for new concepts in swimming is still going on. New concepts consider water to be a medium (i) for movements as well as (ii) for transfer of impulse/momentum. Water, as a medium for movements is known since long and mostly attributed with velocity terms. However, by the motion of (parts) of the body masses of water

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[1] The process of changing position; a gesture.

[2] a) the impetus gained by movement, b) the quantity of motion of a moving body = mass x u, c) strength or continuity derived from an initial effort (*lat)*.

[3] An indefinitely large force acting for a very short time but producing a finite change of momentum by the change of momentum produced by this or any force.

gain a change in velocity and in reaction, a powerful thrust on the body can be exerted. It seems to be an art to optimize the masses involved and their changes in velocity. I seems that traces, left behind during the mutual motions may act as indicators of aspects which are in theory much more advanced.

In theory, thrust opposes the braking effect of the pressure and frictional drag and inertial properties of the water. However, at present in regard to self-propulsion no experimental set-up is available to distinguish between forces *in* and *against* swimming direction. Forces *in* and *against* the swimming direction are occurring simultaneously (thrust and drag are like *Siamese Twins*, both 'reactions' of the same flow). However, they are distinguished by their effect felt by the swimmer.

From a hydrodynamical point of view the total cyclic situation is a non-stationary one. Since no constant velocity is existing the effect of the intertia of (wobbling) water masses needs to be considered (provided velocity changes are large in relation to the speed; if it is so, can be checked by *Strouhal Number*). The effects may be surprisingly. Studies in which external masses were applied to swimmers while swimming in a flume revealed unexpected changes of oxygen uptake: more masses result in smaller oxygen consumption. The effect of the additional masses is expressed as *acceleration reaction*. The additional masses can be imagined as 'how many kg of water is moved via 1m', the unit of this non-steady state factor is [kg/m].

The disturbed and displaced water results in a wake of different configurations leaving traces. Among others the water is set into rotation. Vortex[4] flow formations in general carry a certain amount of momentum (mass x velocity) which was transferred from the body to the water. The transfer of an impulse back to the body coming with the motion of water occurs 'online'.

It is known that the organisation of the wake, which can be different, is closely related to the drag a body experiences. Geometrically large wakes, characterised by a pool of eddies and a high velocity field (equivalent to low pressure) indicate large distribution of energy and high drag values. Vortices, if unstable waste some energy. According to the theory of 'non-resistant' fluid, no pressure - or form drag is acting on a moving body provided the flow velocity/pressure in front and in the wake are the same (in still water this means zero velocity). In reality, Gliding and self propelling bodies experience to a different extend some flow velocity in the wake, hence there is some form drag.

In the gliding situation the wake follows the body in the swimming direction due to frictional effects. In the self propelling situation, however, the flow along the body is accelerated (periodically) partly due to the creation of rotational flow, filling the zone of underpressure (Ungerechts, 1981). This means that, due to self propelling actions the velocity/pressure in the wake is more alike the velocity/pressure in front of the body decrasing form drag. The velocity change of the vortex formation disminishes (periodically) the pressure difference across the body.

The rolling up (of waterparticles) plays a supporting role in the energy balance. The energy, which has to be spent to accelerate the flow along the body, is partly compensated for by a decrease of the form drag. An exellent timing of body movements and vortex formation can (i) strengthen the couple and (ii) effect energy balance.

EXAMPLES OF SELF PROPULSION. Self-propulsion is a result of a transfer of momentum from the propelling parts of the body on the aquatic surrounding as well as a transfer of impulse from the water on the body, producing a mutual *counter bearing*,. Essentially, swimming movements[5] create a flow by disturbing the water. The flow pattern is decisive for the amount of momentum transferred from the body to the water and for the amount of energy wasted. The *counter bearing*, a brief passing construct, needs permanent work to be created (in addition to the work needed to overcome the always opposing drag). Principles of

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4 coiled chain of whirling water loop.

5 the moving parts of a mechanism (e.g. clock); being caused to change position.

propulsion as known from the realm of aquatic animals are closely related to the way how the *counter bearing* is produced (Webb, 1988):

- via use of pressure differences, e.g. paddling of Ducks;
- via use of *vortex - induced momentum* in conjunction with *acceleration reaction*, e.g. whip lash like movement of 'profiled' flukes or fins of Dolphins, Sharks or true Seals;
- via use of hydrodynamic lift, e.g. flying through the water of Mantas, Penguins.

The difference in producing the *counter bearing* is related to the different morphological properties of the animals.

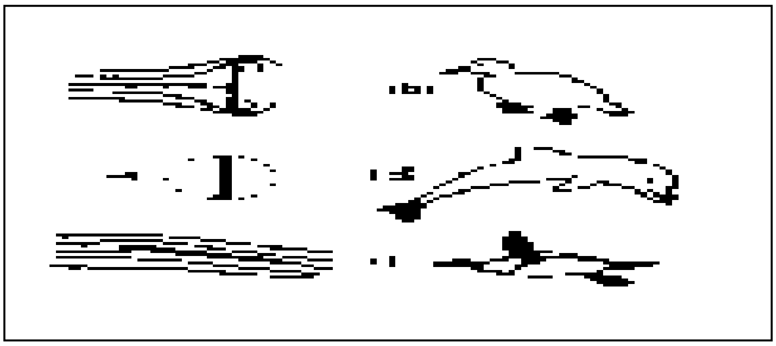

Figure 1 - Examples of self-propulsion in swimming animals emphasing the flow conditions.

PRODUCTION OF *COUNTER BEARING* IN HUMAN SWIMMING. The 'easiest' and 'cheapest' way to create propulsion is to find pads below the waterline where the hand can be fixed and the body moved pass the hand, like with the MAD-System (Toussaint et al, 1988). It is easiest because no power has to be spent to produce the *counter bearing*.

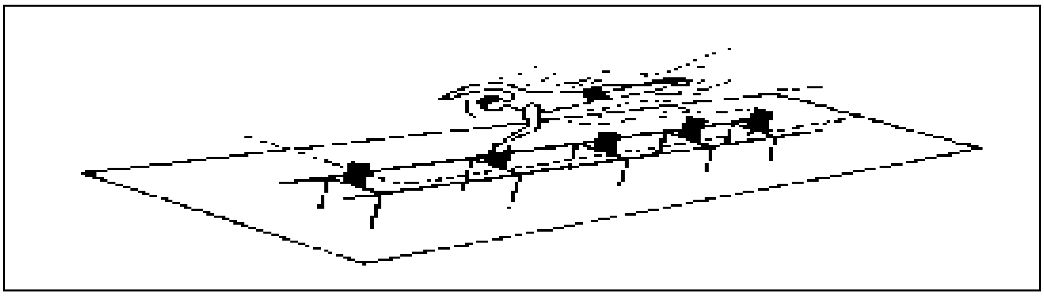

Figure 2 - A device (MADS-like), serving as a counter bearing to the hand.

This example also demonstrates how the body is propelled. The hand is resisted from pulling through the water because it is fixed. Since the muscles between trunk and arm are active, their contraction cause a motion of the body instead of moving the arm backwards (*Law of Approximation*). The distance the body can be moved forward (per cycle) depends on the arm-length. The velocity by which the distance is covered depends on the capacity to empower the muscle contraction in regard to the load (resistance) acting on the body.
In the 'unsupported' swimming situation the *counter bearing* has to be created by the swimmer. According to the functional-morphological properties of the human body the *counter bearing* can be created using the different hydrodynamical effects:

- A swimmer may use drag (pressure differences) as a primary source of thrust production. By moving the hand perpendicular and parallel to the body through the water, a pressure difference between the front and the back of the hand retards the upper extremity from being pulled backwards. The flow conditions are characterized by large formation of eddies in the wake of the hand and arms.

- A swimmer may use hydrodynamic lift as a primary source of thrust production. By moving the hand at a certain angle of attack to its path through the water, which is orientated perpendicular to the swimming direction, a pressure difference in front and on the back of the hand may by directed in swimming direction. The flow conditions are characterised by circularly flow around the hand. However, the creation of lift needs some steady state flow conditions and some time interval to develop. However, the duration to get the strongest lift effect last longer than the duration of underwater action lasts. Since long it is known that lift is fully developed if the wing has travelled 8 x its chord length (in case of the hand it means a distance of 0.6 to 0.8 m and 1.2 - 1.6 m for the feet).

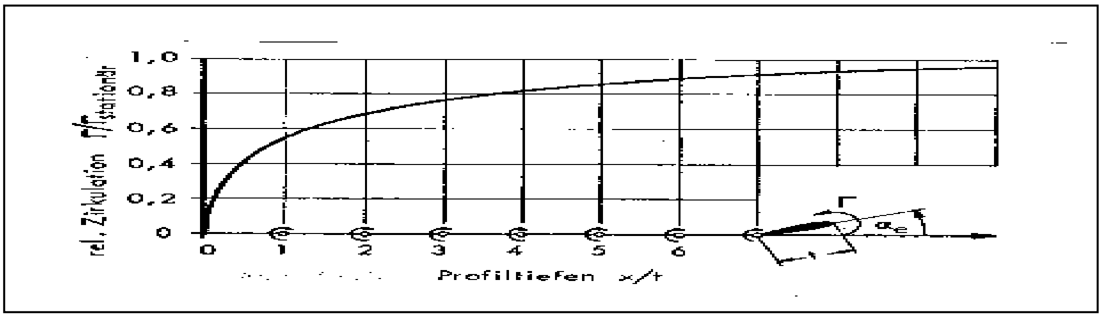

Figure 3 - Development of hydrodynamic lift depending on the distance travelled.

- A swimmer may use *vortex - induced momentum* in conjunction with *acceleration reaction* as a primary source of *counter bearing* and thrust production. Notice, hands and feet create different vortex formation, characterised by rotation.

THRUST PRODUCTION VIA VORTEX:

FLOW VISUALISATION. Flow visualising techniques revealed since long that water masses, when disturbed by a movement of a body are set into rotation, showing various rotational patterns (Ungerechts, 1981). A mass of whirling fluid is called *vortex*. An 'induced' vortex can be seen in the wake of a swimming animal.

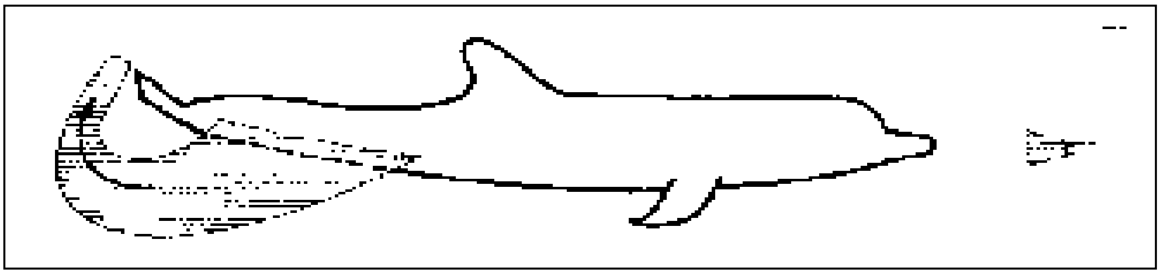

Figure 4 - Water set into rotation during the first quarter of the down-stroke of a dolphin's fluke.

In the beginning of the down-stroke water starts to move from the leading side of the fluke to its trailing side, while the body translates through water. Later on, more and more preformed water (passed already the body) is set into rotation. Essentially, the displaced water stays in place and so do the vortices (until water has come to 'rest') leaving back some traces (like foot- or fingerprints). Although it is known that vortex is mostly confined to the wake behind a body, its induced velocity field is influencing the flow 'in front' of it.

In human swimming similar vortex traces can be detected in the wake of the feet. Methods to make the flow along a swimmer (swimming with dolphin kicks below waterline) visible are still under development (Colman et al., 1999). First attempts showed that the water is moved aside by the increasing amplitude of the moving leg. When the feet travel through this field, water is set into rotation (during the downward action with a rotational sense towards the sole of the feet). This can be imagined like rolling up a carpet, which is an excellent means to “hide“ displaced water masses (it looks as if the body is translating through the water like between rollers). These traces are of ’barrel’ like shape. These *rolling* vortex are characteristic for a rear driven body.

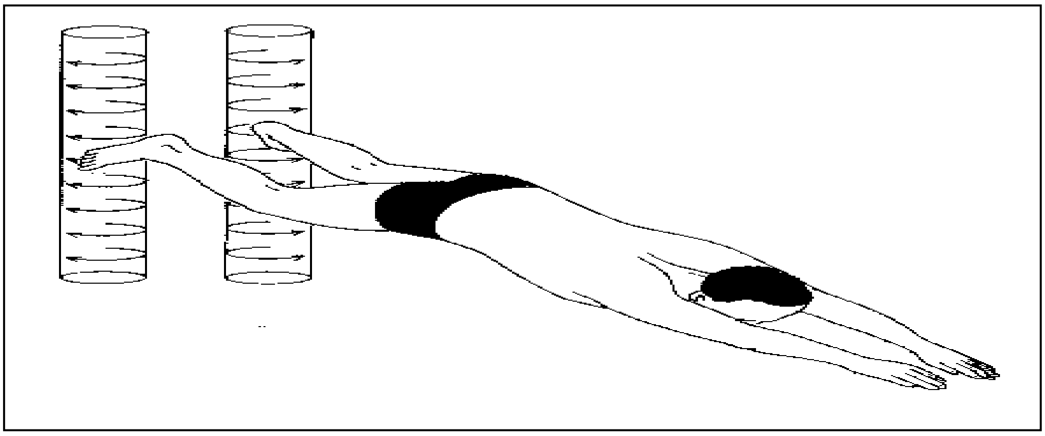

Figure 5 - Water set into rotation by breaststroke kick of a human swimmer.

The vortex traces of the hands shows a completely different pattern. Here the flow-pattern is characterised by a coiled chain of whirling water loops and indicates a front driven body. These *vortex loops* materialize on the trailing side of the back hands and are expanding, the more the arm is flexed in the shoulder joint (remember, the hand is more or less fixed relative to the water but allowing for some local acceleration).

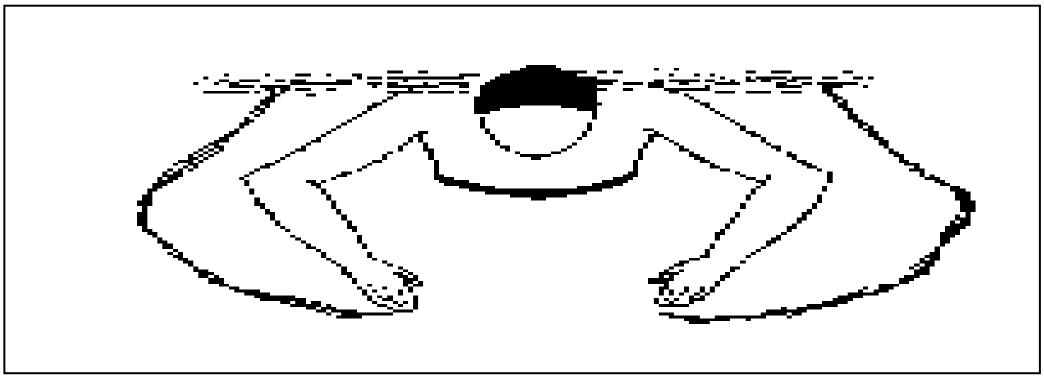

Figure 6 - View of two vortex loops in the wake of the hands of a butterfly swimmer.

The appearence of the vortex patterns does not explain the propulsive forces itself (they just indicates the possiblity of gaining some thrust) - or in other words, vortex patterns may also lead to drag. The central questions is, which physical property of the vortex mediates the transfer of momentum to the swimmer (a precondition for propulsion)?

THE MOMENTUM – IMPULSE COUPLE OF VORTEX of REAR DRIVEN BODIES. Thrust production by rear driven mechanisms differ between form - rigid bodies like ships and form – changing, self propelling bodies. In form - rigid bodies it is attributed with energy wasting ’pushing water backwards’, like the propeller. In form – changing, self propelling bodies the story is more complex: the rear body parts preform the aquatic surrounding by applying some work on the water, storing some energy. In this context, the particularity of whip lash like action (a combination of heaving and rotation) of the some parts of the body is a prerequisite.

As described, the preformed water masses flow around the trailing edge into the zone of underpressure creating a rolling vortex. Due to their high geometrical organisation vortex 'carry a high amount of momentum in relation to the energy spent for their production' (Lighthill, 1969). When, after a cycle, the trailing edge reverses direction the vortex is either shed in a *vortex street* or *annihilated*. In both cases some thrust is produced and can be calculated under some conditions (Ungerechts et al., 1999).
The vortex when shedded periodically into the vortex street is organised in a staggered manner, each side is rotating in an opposite sense (Blickhan, 1992). Due to the lasting rotation a jet stream (away from the body) is produced. The thrusting impulse is a reaction to this jet stream (similar to the jet stream behind rockets).
The other option is to stop the vortex by the reversal action of the trailing edge and its momentum is transferred to the body (Ahlborn et al., 1991). The thrusting impulse occurs just after the reversal action has taken place which means that peak acceleration of the body should occur after the tip of the fluke (or feet) has left the reversal point (Dubois et al., 1976; Ungerechts, 1988).

PRACTICAL IMPLICATIONS RELATED TO REAR DRIVEN BODIES.

- Vortex creation can be supported by whip-lash like action of the legs and the feet.
- The reversal actions of the feet need well developed ankle joint flexibility.
- The whip like action is more pronounced if the knees can be hyper-extended slightly.
- The organisation of the vortex in the wake can be bettered when the 'sideways' motion starts from the midst of the body and is increasing in amplitude towards to end.
- Slight recoil actions of the head are 'allowed'.
- It is energetically favourable to set large mass of water into rotation at moderate speed.
- The timing of vortex production should be adapted to the aspect of push and glide action resulting in a high mean swimming speed (depending on the individual drag factor).
- Vortex formation during the upward-kick in backstroke swimming is hampered by the interference with the surface, thus slightly inward rotation of the feet is recommended.
- The underwater action of the hand (or both) creates a (rotational) pressure field and left 'in place' (in all strokes): the reversal action of the tip of the feet should happen close to this 'place' (gain some speed from the remaining rotation).

THE MOMENTUM – IMPULSE CONTROL OF VORTEX in FRONT DRIVEN BODIES. The vortex traces of the hands are characterised by a coiled chain of whirling water loops. These loops originate from microvortex of the fingers (or rims of the hands). Microvortex, to some extend, are the first reactions to the displacement of (still) water by the finger(tips). Each microvortex is twisting (water follows itself permanently). Short period later, the number of microvortices merge and form a lasso type loop a certain distance from the back of the hand (the more distant regions of the loop may assist the work of the vortices in its vicinity).

Figure 7 - Chains of whirling water. (adapted from Bannasch, 1998)

The condition why microvortex merge into a loop instead of developing an area of *dead*water zone (like after a paddle blade) might depend on the fetch of the flow (which preceeds the catch of the flow). Fetch is a term indicating that there is some time necessary to structure the chaotic flow conditions and to direct the microvortices towards the back of the hand in a highly organized manner leading to *trailing vortex.* The high rotational velocity of a small amount of water mass provides some momentum creating a *zone of underpressure* velocity of rotating water masses and pressure are inversely related), acting on the back of hand and arm. Thus, the vortex loop may be act as a *counter balance.*
The zone of underpressure has an effect on the water and an impact on the propulsion of the swimmer. On the water it induces a flow towards i ts center along the arm (just opposite the direction of arm motion). It supports thrust production by resisting the intended backwards movement of the arm and hand. As described for the MADS the *Law of Approximation* applies: instead of pulling the hand backwards the body is moved (this means: the drag of the body has to be smaller than -or at least equal to- the suction force on arm and hands). The hand is (from sagital view more or less) fixed and the body is passing by until the thighs reach the position of the hand(s).
After the fetch, the vortex loop needs to be 'feeded' during the underwater action of arm and hand. This will be provided by the continuing creation of microvortices at the tips (slightly spread fingers) an rims of the hand and a certain change in the acceleration pattern. On its way under water the hand is forced to change direction e.g. from outwards to inwards. These changes are critical for the continuing existence of the vortex loop and consequently for the *counter balance*. The change of direction can be executed either *briskly* or *gradually*. Briskly means: when the pronated hand is moving outwards (flow enters the hand via small finger side) and in the next tenth of a second the hand is moved inwards. In that case the vortex is shed (providing a strong, short lasting impulse). Gradually means: before the hands change direction they should start to supinate and the vortex loop remains in contact with the upper extremity (in addition the gradual rotation of the hand support the high/foreward elbow position). Thus the vortex loop is extending like a bundy rope the more the arm is flexed in the shoulder joint (remember, the hand is more or less fixed relative to the water).

PRACTIAL IMPLICATIONS RELATED TO FRONT DRIVEN ACTIONS.

- Vortex creation can be supported by spreading the fingers (slightly).
- Vortex loop is directed towards the back of hands (and arms) by slight dorsal flection of the hand in the wrist joint.
- Vortex loop is staying stable provided the change of direction is predeeded by the (gradual) rotation of the hand.

- The suction (from the underpressure) depends on speed of the ’sweeping’ actions of the hand (which is limited by the drag forces on the body which has to be overcome).

DISCUSSION: The vortex foot- and finger-prints are just a presentation of a small part of the whole vortex story. The theory of vortex demand closed lines like rings or contact to the waterline. The traces are as good as the applied method of flow visualisation is. The 3 - D gestalt of the vortex in self-propelling swimmers remains to be shown. Sometimes it is difficult to present a proof by audio-visual media. If and to what extend the vortex loops are moving backward (relative to a fixed background) after the action of the hand or feet remains to be clarified. Similar applies for the opinion that it looks as if the body is translating through the water like between rollers. Advanced methods of flow visualisation should provide information about the rotational aspects: the sense and the speed.
On the other hand, due to a combination of theoretical knowledge and visible proof, the traces tell the mutual story of drag and propulsion which are produced simultaneously (which is more than the propulsive aspect). The question is: which pattern of a swimming movement is best in terms of energy costs? Geometrically large wakes like behind a paddeling blade or hand moved perpendicular to its path create high drag values (equivalent to very low pressure) but is wasting large amount of energy. Vortex traces will assist to clarify if the vortex in the wake is rotating in place or moving backwards? Vortex rotating in place indicates least drag. This information is of some value as a feedback, since the swwimmer should strive not to push the vortex. Organized vortex will required much less energy than paddle like action of the hands. In fact, the aim is: “contolling energy, not just spending it“ and “do not execute the movements too forcefully“.

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Acknowledgements
We want to thank Huub M Toussaint and V.U. Amsterdam for critically reviewing this manuscript.