RELATION OF SWIMMING PROPULSION AND MUSCLE FORCE MOMENT

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Based on 3D video analyses of swimming movements new hypotheses on the mechanisms of propulsion could be deduced. Applying the hydrodynamic basic equation the forces at the limbs were estimated and the joint moments were calculated by summing across the body segments. These muscle force moments are related to the velocity of the centre of gravity of the body (CG) as a measure for the propulsion within a movement cycle. Simultaneously they serve as controlling data for dry land strength training.

KEY WORDS: 3D, hydrodynamics, swimming, muscle force moment, propulsion.

INTRODUCTION: More than 30 years researchers have intensively investigated into a better understanding of propulsion in swimming. Thus the swimming flume in the Olympic Training Centre Hamburg has been equipped with technology and software elaborated by the Institute for Applied Training Science Leipzig to analyse swimming movements (Drenk, Hildebrand, Kindler & Kliche). On a regular basis the swimming flume is used for technique training and for the preparation for international competitions by top swimmers.
Propulsion in swimming is reflected by the course of velocity of the CG. Such a calculation can be supplied by a good video analysis. From the standpoint of training methodology and its goal to improve swimming technique it is interesting to know in which way propulsion is related to swimming technique. To understand this relation the resistance forces acting on the limbs as well as the total resistance acting on the body have to be known. This represents a difficult problem. The paper deals with the results of a study which we did over a period of several years. The project consisted of the following elements: Design of a feasible measuring system, determination of the propulsion velocity with a 3D video analysis, explanation of propulsion from a phenomenological point of view based on measuring data, quantification of the subjectively applied net muscle force moments for propulsion by solving the hydrodynamic basic equation and finally deducing recommendations for the improvement of the individually possible propulsion.

METHODS: Methods of video frame analysis have to be completed by model development and measuring technology. Body point co-ordinates and their derivatives represent the basis to calculate pressure forces. For the access to the quantification of propulsion the hydrodynamic equations have to applied. Within the fluid there are three different forces: inertial force, resistance force and – in contradiction to solid bodies – also pressure force. Here it is important to underline that pressure does not alter the volume of non-compressible fluids. The development and effect of pressure does not become directly visible. This makes it even more complicated to understand the processes within the fluid. In addition vortexes are developed in the water in a more complicated manner than one could expect from the dynamics of the mass points. The majority of the vortexes is immediately left behind the swimmer and it is impossible to regain their energy. But those investigations have not been part of our study.
The hydrodynamic basic equation involving force on a volume element and its velocity **v**, for example the limbs, is as follows (Budo, p. 443):

$$\rho \mathbf{F} = \rho \frac{d\mathbf{v}}{dt} + \text{grad } p.$$

F is the strength related to the mass element, p the pressure, ρ the fluid density and d**v**/dt the sum of inertial and friction forces. Symbols in bold types characterize vectors. In another

version of the basic equation the vortex share can be determined. This makes additional investigations possible which should be done in future.
Because of the unknown velocity field and the pressure in the vicinity of a moving body and other border conditions the basic equation cannot be solved without further ado. In our case we did not consider the whole swimmer, but only the limbs which produce propulsion. Thus we could apply the assumption that only water in the immediate vicinity of the propulsive areas is moved (the hands do only catch standstill water and there are no shearing forces). Consequently we can work with two simplifications:

1. For the calculation of the shearing force we take the effect of the vortexes which is due to the running of the water on the edge of the limbs into account by designing an experimental form factor (Sommerfeld, p. 214-215).
2. For the hydrodynamic pressure we use the hydrostatic pressure $p = p_o + \rho gz$, z being the depth of the water, p_o the atmospheric pressure and g the acceleration due to gravity.

The simplification refers to the part of the unknown border conditions and to the definition of "local environment", for example the surface of the hand.
For the sake of completeness we have to say that the continuity equation div **v** = 0 also has to be considered. This condition is an expression for the fact that in with water is circulating close to body segments no sources and hollows can develop. The equation is a consequence of the incompressibility of water. But because of the fact that the basic equation in our case is only solved as an numerical approximation, one can explicitly disclaim this equation. Implicitly this equation supports the above mentioned assumption that water only locally is put into motion.
Analogous to the physical the hydrodynamic basic equation for the force **F** related to the mass unit has three terms seen from the mathematical point of view: the partial derivative by time of all three components of the velocity, the value of the spatial partial derivative of velocity and one term coming from the pressure change. The partial derivative by the time are identical to the acceleration of the body points considered. They are obtained from the analysis of frames.
For the second term, the gradient of the flow velocity in the spatial directions, approximation values are calculated, since there is no laminar flow on the edge of, for example the hand. Here we have to rely on experimental findings under theoretical ideal conditions (compare assumption 1) that prove an approximately double value of the force on the areas which are object to flow. It is surprising that the unknown distance, from which on the water remains unaffected, cancels during an integration over all mass elements. That means that it is not necessary to know this value. In the first approximation the resistance force resulting from friction is proportional to the square of the velocity of the moved body segments.
With respect to the third term, the pressure gradient, there is not such much information. We have the assumption that the hydrostatic pressure condition might be considered to be critical. In future measurements of the pressure in an immediate vicinity of the limbs, but not touched to the body, are indispensable.
From findings on the resulting force on the mass elements on the body surface one can calculate net muscle force moments for the shoulder, hip and knee with the help of cross products by a summation over all mass particles from the co-ordinates and the velocities via 3D frame analysis.

RESULTS: According to the basic equation resistance is developed via three forces (vis inertiae, frictional force and pressure force). The principle which is used to produce propulsion with the arms is a little bit different than the principle for the legs. Initially in swimming the arms are guided in swimming direction against the water after the entry into water. The water is flowing upward to the shoulder. When the arms are taken to the body there is one moment when the inner palm, the forearms and parts of the upper arms are pushing against the swimming direction on the resting water resulting in an reverse of the streaming direction of the water. Obviously just in these phases water force can be transformed into propulsion. Here it does not matter if the hands are led exclusively against the swimming direction, since the resulting force always is created against the local streaming direction. In freestyle swimming the hands mainly are led backward towards the hip. In breaststroke swimming especially they are also led laterally. The resistance that the hands are faced with is used with the help of the muscle force moment in shoulders and arms in such a way that the trunk pulls forward (Hildebrand, Drenk, Kliche 1999). Referring freestyle one could imagine a hold at an anchor in the water from which man is pushing away. In breaststroke swimming one is pushing the hands together against the imaginary anchor to pull the body forward over the shoulders. But in these two cases different muscle groups are working. The principles are implemented individually: In case the stretched arm catches deeply into the water a big torque is resulting from the long hand-lever (Figure 1 left). In case the forearm quickly is moved into a perpendicular position towards the swimming direction resistance is created at the whole forearm. This force lasts longer (Figure 2 right).

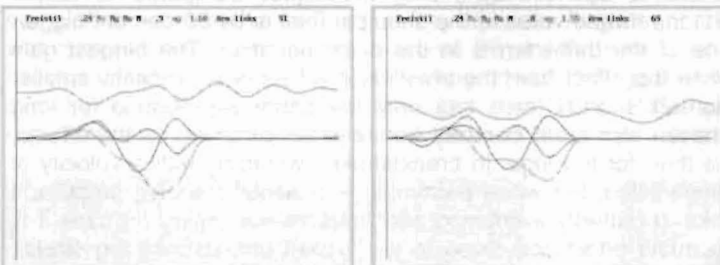

Figure 1 Shoulder moment in freestyle swimming. Left: deep arm pull with v-flume = 1.6 m/s, right perpendicular elbow and pressure on forearm until the arm is leaving the water, v-flume=1.55 m/s. The upper blue line represents the velocity of CG during the whole cycle. The yellow line that goes lowest represents the shoulder moment around the lateral axis (to left with a maximum of 91 Nm and to the right with a maximum of 69 Nm), the pink line represents the component around the longitudinal axis and the red line with the smallest amplitude represents the component around the vertical axis. The technique shown to the left requires both higher force values and higher joint performances. These swimming techniques also require a different dry-land training!

The propulsion with dolphin stroke (Figure 2 left) has explained in a different way. When swimming with very high speed at no moment any part of the body can push the water against the swimming direction, and the feet are moved exclusively forward (Hildebrand 2001, 2003). In the downward stroke the streaming water (sight from the swimmer) creates a resistance that, analogous to the arms, for a short period of time fixes foot and lower leg within the water. But because of the fact that the legs are bent in the knees and the hip the muscle force moments cause a stretching of the body, and the CG is moved in swimming direction. The upward stroke follows even more complicated mechanisms (Hildebrand 2001) since the feet are coming up close to the water surface. But nevertheless even here a big torque has to be created in the hips for an effective upward stroke. In the breaststroke leg stroke (Figure 2 right) propulsion is created in close relation with swimming speed. Thus in case of a high swimming speed there is a transformation into a dolphin-like upward leg stroke.

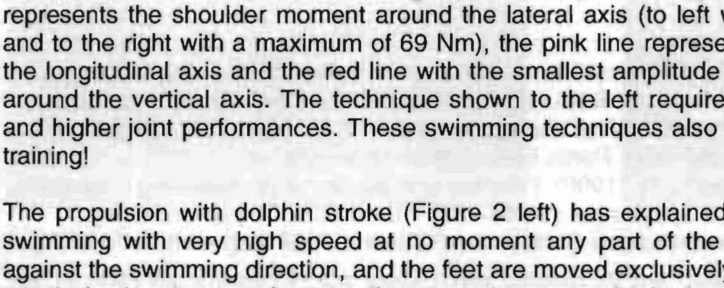

Figure 2 Hip joint moment for leg stroke. Left dolphin with v-flume = 1.78 m/s, right breaststroke with v-flume = 1.25 m/s. In the dolphin stroke the lateral component is dominating (maximum = 291 Nm in the first leg

stroke), the two other components being without significance. Even the upward stroke can have a propulsion effect (compare with the blue velocity line of CG). Right, in the breast stroke (in this individual case) beating together of the feet with the succeeding upward movement of the feet produces more propulsion than pushing the feet.

CONCLUSION: The quantification of the individual propulsion moment improved our understanding of the propulsion processes. We can prove that there are different ways of creating propulsion depending on swimming velocity. This circumstance has to be taken into account especially in breaststroke swimming over long and short distances and when learning swimming techniques. As expected the contribution of the moment arising from the upper arm and the thigh are small compared to the moments resulting from hand, foot and lower leg movements. In between we found individually different maximum forearm moment values. Here we see chances to optimise swimming technique. Compared to earlier estimations (Hildebrand 2001) the torque value in the shoulder joint is by 50 percent bigger. Of interest is the significance of the three terms in the basic equation. The biggest gain comes from friction force, while the effect from the pressure gradient is significantly smaller (that could affirm assumption 2). Inertial force has only the same significance for long breaststroke distances. There are also small contrary trends when summing up the effects. This refers more to the arms than for the legs. In breaststroke swimming with a velocity of 1.60m/s arm propulsion is dominating, but when swimming with about 1m/s leg propulsion dominates. The dolphin stroke in butterfly swimming and freestyle swimming (in case it is performed) has almost the double effect compared to the typical breaststroke leg stroke. Thus it has been possible to prove the great importance of the dolphin stroke for the performance trend in swimming.

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