COMPUTATION OF HIP AND SHOULDER TORQUES IN COMPETITIVE SWIMMING

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The mechanisms of propulsion can be deduced from 3D video analysis of swimming. The basic hydrodynamic equation can be used to compute the total force for those particles. The shoulder torque was calculated by summation over hand, lower arm and upper arm of infinitesimal torques of displaced water particles. These muscle force moments were related to the velocity of the mass centre as a measure of the propulsion. However, a direct interrelation between velocity and torques cannot be established since the total resistance of the body in motion is unknown. Therefore, the aim was to determine individual differences in swimming technique, controlled by shoulder, hip torques and swimming velocity, at any state of one movement cycle. Recommendations for best propulsion techniques are derived.

KEYWORDS: 3D analysis, hydrodynamics, swimming, muscle force moment, propulsion.

INTRODUCTION: For more than 40 years researchers have invested much work into a better understanding of propulsion in swimming. Propulsion is reflected by the velocity of the mass centre, which can be calculated by 3D video analysis. For training methodology it is interesting to know in which way propulsion is related to swimming technique. To understand this relation the drag forces acting on the limbs as well as the total drag acting on the body have to be known. This is a difficult problem. The paper presents the results of a six year study which consisted of the following elements: Design of a feasible measuring system, determination of the limb velocity by 3D video analysis, explanation of propulsion from a phenomenological point of view based on measuring data, quantification of the net muscle force moments by using the basic hydrodynamic equation (1) and, finally, deducing recommendations for the improvement of the individually best propulsion techniques. Our main aim was to indicate individual differences in swimming technique depending on hip and shoulder torques and on swimming velocity.

The calculation of forces is based on 22 body point coordinates and their derivatives. There are three different forces in fluids: inertial force, convective force and – in contrast to solid bodies – also pressure force. In international scientific literature there are no publications paying attention to this distinction of three forces; application of the basic hydrodynamic equation for the calculation of propulsion forces has yet to be used. Sanders (1997), for example, applied the following formula to compute the force on the hand $\mathbf{F} = \rho\, A\, (C_X, C_Y, C_Z)\cdot\mathbf{v}^2 + \rho\, A\, (D_X, D_Y, D_Z)\cdot\mathbf{a}$, where **C** is a constant referring to drag and lift and **D** is a vector including the effective mass accelerated by the hand with acceleration **a**. The acceleration term is quite similar to the first term in the basic hydrodynamic equation, the velocity term however is different. Explanations for movement in the water run from the mechanics of the paddle steamer (Schleihauf, 1979), or that of the ship's propeller up to undulations, like vibrations of the fins of fishes. Currently the vortex theory by Matsuuchi et al. (2009) is most popular. To move quickly in water we use our relatively large hands and feet to find water resistance and we repel ourselves like from a soft solid. In crawl stroke this happens directly with the hands when they are moved against the swimming direction. When swimming crawl stroke or butterfly with high speed, no part of the legs can push the water against the swimming direction. The feet are moved forward all of the time (Hildebrand, 2001). In the downstroke of the legs the streaming water (viewed from the swimmer) generates an acceleration force. Since the legs are bent in the knee and the hip joints, the muscle force moments cause a stretching of the body, pushing the mass centre while the joints are opening. The upstroke is even more complicated. The feet are coming up close to the surface. One can see the formation of a water peak at the highest point of the feet. Muscle forces cause a lift of the legs which in turn induces a negative drag. In other words, if the upstroke is strong enough the inflowing water sliding upwards along the legs will be accelerated. By Bernoulli's equation, a slipstream arises at the lower legs, which can be transformed into propulsion at the beginning of the downward movement. This tricky technique must be learned.

METHOD: The experiment was carried out at the swimming flume at the Olympic Training Centre in Hamburg. Technology and software were elaborated by Drenk, Hildebrand, Kindler and Kliche (1999) at the Institute for Applied Training Science Leipzig. Two 50 Hz cameras were used. We recorded the performances of four elite swimmers of height 182.0 ± 3.5 cm and of age 23.8 ± 4.3 years; one male breaststroke swimmer and three female swimmers. We calculated the forces at the limbs and moreover the joint torques at elbow, shoulder, knee and hip joint. The flow speed ranged from 1.15 m/s to 1.65 m/s. From 3D analyses we obtain velocities and accelerations of all model points. Using velocities, accelerations and coordinates of the joints by linear interpolation we calculate the velocity distribution of arms and legs (Drenk et al., 1999).

The basic hydrodynamic equation involving force **F** on a volume element and its velocity **v** is

$$\mathbf{F} = \rho\, \partial\mathbf{v}/\partial t + \rho\, (\mathbf{v}\ \mathrm{grad})\, \mathbf{v} + \mathrm{grad}\ p, \quad (1)$$

where p denotes the pressure, ρ the fluid density $\rho\, \partial\mathbf{v}/\partial t$ the inertial force and $\rho\, (\mathbf{v}\ \mathrm{grad})\mathbf{v}$ the convective force. Explicitly, this reads as follows

$$\mathbf{F}_1 = \rho\, (\partial u/\partial t + u\cdot\partial u/\partial x + v\cdot\partial u/\partial y + w\cdot\partial u/\partial z) + \partial p/\partial x$$
$$\mathbf{F}_2 = \rho\, (\partial v/\partial t + u\cdot\partial v/\partial x + v\cdot\partial v/\partial y + w\cdot\partial v/\partial z) + \partial p/\partial y$$
$$\mathbf{F}_3 = \rho\, (\partial w/\partial t + u\cdot\partial w/\partial x + v\cdot\partial w/\partial y + w\cdot\partial w/\partial z) + \partial p/\partial z.$$

Since velocity distribution and pressure close to a moving body and other boundary conditions are not known, the boundary value problem cannot be solved.
We use these equations as a definition of the force. We do not consider the whole swimmer, but only limbs which produce propulsion. Thus we can assume that water particle displacement occurs only close to the propulsive areas, and there are no shearing forces. The hands move on an S-shaped curve in a way that the hands catch into stationary water all the time. The resulting velocity, acceleration and velocity gradient are put into the right hand side of the basic hydrodynamic equation. On the left hand side we then obtain the force acting on a single mass element. Finally we can compute the torques via cross product of force and distance vector to the joints. We apply the following three simplifying assumptions:

1. To calculate the force at the edge of limbs we take the effect of the vortices into account by designing an experimental form factor equal to two (Sommerfeld, 1954).

2. Instead of the hydrodynamic pressure we use the hydrostatic pressure $p = p_o + \rho\, g\, z$, z being the depth of the water, p_o the atmospheric pressure and g the gravitational acceleration.

3. The unknown velocity at some inner point of the limb is the linear interpolation of the velocities at the end points. The velocity in a small area close to the limb is constant in any plane orthogonal to the vector from one endpoint to the other. The same applies to accelerations.

These simplifications refer to the unknown local environment, the area close to the hand, shank and so on. The force **F** related to the mass unit has three terms: the partial time derivative $\rho\, \partial\mathbf{v}/\partial t$, the inner product $\rho\, (\mathbf{v}\ \mathrm{grad})\, \mathbf{v}$ and the gradient of the pressure grad p. The partial time derivative is the acceleration of the replaced particle. To compute the second term $(\mathbf{v}\ \mathrm{grad})\, \mathbf{v}$, including $u\cdot\partial u/\partial x$, $v\cdot\partial u/\partial y$, $w\cdot\partial w/\partial z$, we apply assumption 3: the gradient of velocity is constant and multiple of the endpoint vector. Here we also take the above mentioned form factor two from assumption 1 into account. In the first approximation the convective force is proportional to the square of the velocity of the moved body segments. Net muscle force moments for shoulder and hip joints can be calculated from the resulting force on mass particles. This is done by taking cross products of forces and distance vectors to the joints and summation over all mass particles.

RESULTS: The principle which is used to produce propulsion with arms is a little bit different from the principle for legs. In breaststroke initially, after diving into the water, the arms move in swimming direction and against the water. The water is flowing upward towards 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 swimming direction on the unmoved water resulting in a reverse of the streaming direction of the water. Obviously, just in these phases the drag force can be completely transformed into propulsion. It does not matter if the hands are led exclusively against the swimming direction, since the resulting force is always created against the local streaming direction. In the crawl stroke the hands are mainly led backward towards the hip. Especially in breaststroke swimming they are also led laterally. The drag 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 to crawl stroke one could imagine a hold at an anchor in the water from which one is pushing off. 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 (Fig. 2). 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 (Fig. 1, left). In case the forearm is quickly moved into a perpendicular position towards the swimming direction drag is created at the whole forearm. This force lasts longer (Fig. 1, right).

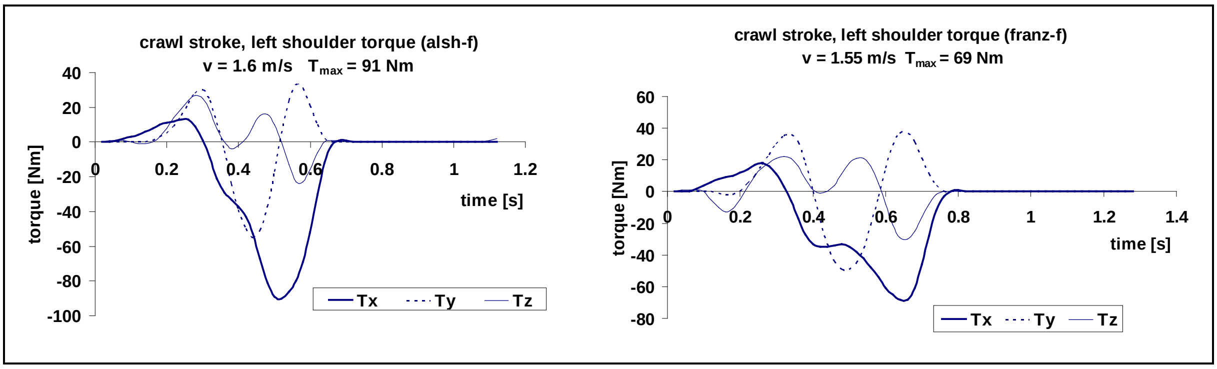

Figure 1. Left shoulder torque of two elite crawl stroke swimmers. Left figure: deep arm pull, v-flow = 1.6 m/s, Right figure: perpendicular lower and upper arm and pressure on forearm until the arm is leaving the water, v-flow = 1.55 m/s.

The thick solid line T_x represents the shoulder torque around the transverse axis, on the left with a maximum of 91 Nm and on the right with a maximum of 69 Nm. The dotted line T_y represents the torque component around the longitudinal axis and finally the thin solid line T_z with the smallest amplitude represents the component around the vertical axis. The technique shown on the left picture requires both higher force values and higher joint performances. These two swimming techniques require different dry land training.

In breaststroke the movement of arms differs between women and men. Men swim about 0.5 m/s faster than women. For men, by lack of time, a backward movement of the hands against the water is impossible. The very first technique of women breaststroke, in which hands create pressure against the swimming direction, becomes more and more ineffective with increasing swimming speed. Men develop the following strategy: when the outward movement of the hands is completed they are immediately put together below the breast. This move generates a drag transversal to the swimming direction.

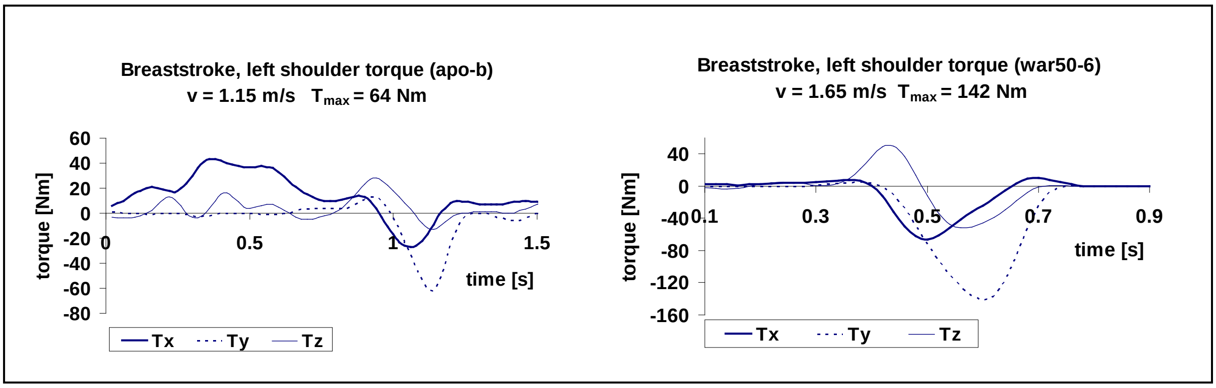

Figure 2. Breaststroke, left arm torques. Left figure: swimming technique at v-flow = 1.15 m/s. Right figure: swimming technique at v-flow = 1.65 m/s.

The result is a much greater torque about the body axis, as shown in Figure 2 (dotted line, right figure). This technique therefore requires different control of arm and shoulder muscles, and a training that is different from the one for the classical technique.

CONCLUSION: The quantification of the individual propulsion moments improved our understanding of the propulsion processes. We can prove that there are different ways of creating propulsion depending on swimming velocity. This has to be taken into account especially in long and short distance breaststroke swimming as well as when learning swimming techniques. As expected, the contribution of the moments 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 moments. At this point the swimming technique can be optimized. Compared to earlier estimations (Hildebrand, 2001) the torque in the shoulder joint is 50 percent larger. The significance of the three terms in the basic equation is of great interest. The greatest gain is produced by the convective force, while the effect of the pressure gradient is significantly smaller (that could affirm assumption 2). Inertial force has only the same significance for long breaststroke distances. In breaststroke swimming, with a velocity of 1.60 m/s, arm propulsion is dominating, but when swimming with about 1 m/s, leg propulsion dominates. The dolphin stroke in butterfly swimming and crawl stroke 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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