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A numerical study of the unsteady flow phenomena in human swimming

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Abstract

Vortex dynamics around the body of a female swimmer was investigated for several successive underwater Dolphin kicks. This is a typical motion sequence of swimmers after they have pushed off the wall. The method of Computational Fluid Dynamics (CFD) was used in combination with a digital reproduction of the kinematics of the body surface to investigate the unsteady flow phenomena involved therein. The results showed the formation of larger vortices near the swimmer’s body, part of it being used to enhance thrust generation at the legs (vortex re-capturing). At each downstroke, a vortex ring was shed into the wake forming a street of vortices behind the swimmer. Further downstream these rings re-combined into streamwise oriented parallel vortex tubes. Within the motion cycle a distinct variation of drag and thrust force were observed as a characteristic footprint of the kinematics. Mean drag force over the complete cycle was about twelve times higher during dolphin kick when compared to passive, gliding swimming. Maximum mean thrust was reached in 3 motion cycles after the swimmer has pushed off the wall and remained constant from thereon.

[199 words]

Introduction

A more in-depth understanding of the unsteady flow phenomena and vortex dynamics in human undulatory underwater swimming can bring about innovations in both sports and engineering. A prominent example in swimming is the so-called dolphin kick, an undulatory movement similar to that of a fish, typically used after a swimmer's start or turn. Therein, a wave-like body motion is generated, running from the fingertips to the toes. While much research has been carried out for vortex dynamics and interaction in wave-like undulatory fish locomotion (e.g. Hanke, Brücker, & Bleckmann, 2000; Przybilla, Kunze, Rudert, Bleckmann, & Brücker, 2010), only little is known about its importance to undulatory human swimming. Earlier studies mainly focussed on kinematics and overall performance. As a result, adopting a more lateral body position during the dolphin kick led to an increase in stroke amplitude. This caused higher amount of ankle plantar flexion and higher thrust (Alves, Lopes, Veloso, and Martins-Silva (2006). Futhermore, humans performed higher kick frequencies than the cetaceans, resulting in higher Strouhal numbers (von Loebbecks, Mittal, Fish and Mark, 2009a), which indicated that human's Dolphin kick in general is less efficient than undulatory fish locomotion. This is because drag forces are seemingly excessively increased for the active propulsive motion (active drag). Unfortunately there is no satisfactory experimental method for a direct measure of the active drag without altering the swimmer's natural gait. Only for front crawl swimming did the MAD-system (Measure Active Drag; Hollander et al., 1986; Toussaint, 2000) judge the forces. However this method cannot be used for the dolphin kick.

Alternatively, computational fluid dynamics (CFD) offers the potential to calculate the swimmer's forces out of the simulated time-dependent 3D flow field around a swimmer. Such numerical flow simulations were carried out to quantify the forces on an isolated forearm in steady underwater motion (Bixler and Riewald 2002). The flow behind a rigid swimmer model in gliding phase was investigated by Bixler, Pease, and Fairhurst (2007). They compared their numerical results with experimental data of a towed body to quantify the accuracy of their simulated drag forces. Individual states within the dolphin kick cycle were studied by Lyttle and Keys (2006) in a quasi-steady simulation. They argued that propulsion is mainly generated by the forces acting on the legs. Later, these results were confirmed by simulations for the undulatory dolphin kick cycle (von Loebbecke, Mittal, Fish, and Mark (2009b). Recently, Cohen, Cleary, and Mason (2012) extended the numerical work on the Dolphin kick using the simulation method called 'smoothed particle hydrodynamics'. They claimed the strong need for parametric studies of different kick frequencies and the influence of hand oscillations on drag forces.

The purpose of this study was the detailed understanding of vortex dynamics and the generated time-traces of forces acting on the swimmer during successive Dolphin kicks after push-off from the wall. The major interest was the formation and interaction of vortices near the swimmer's surface and in the swimmer's wake. Therefore, a multiple hinged 5-ankle model was generated, where each segment represents the segmented shape of a digitized swimmer body (hand, arm, body, upper legs, lower legs and feed). The segments of the model were moved in a prescribed motion function to replicate the motion cycle of a Dolphin kick. Numerical simulations of the three-dimensional unsteady flow were carried for the phase of 6 successive Dolphin kick cycles. As a reference, the motion and body shape were taken from the same swimmer as used in the study by Hochstein and Blickhan (2011). Therefore, it allowed us to validate our numerical results with their flow visualization studies. Special focus was laid on possible relevance of any energy-saving mechanisms which might help to increase efficiency of propulsion such as vortex preformation or vortex re-capturing within the different motion cycles. The flow phenomena were correlated with the time-traces of the propulsion, as well as drag and lift forces in comparison to a passive gliding motion cycle.

Methods

A female swimmer (personal best 200m butterfly: 2:12.9) was the template to generate the digital swimmer model with a realistic shape. Therefore, her body was scanned with a 3D laser body scanner (VITUS Smart XXL 3D, Human Solutions GmbH, Kaiserslautern, Germany) and the surface contour data were saved into a digital file format. The surface of the digital body is then subdivided into separate segments, which belong to the regions: hands, arms, head, body, legs and feeds. Those segments are connected at the corresponding ankles. The undulatory motion function of the swimmer for successive Dolphin kicks after push-off has been recorded in a test pool earlier (published in Hochstein & Blickhan, 2011). If no relative angular motion of the segments is applied and the body is in stretched state, this surface then represents that of the swimmer in gliding phase. This is named in the following the static swimmer model. Based on this model, the dynamic model was generated by transferring the recorded undulatory motion function of the swimmer to the individual segments of the digital swimmer model. After discretising the ambient fluid domain, the governing equations of fluid dynamics were solved in OpenFOAM, and the main forces influencing the swimmer segments were determined. The coordinate system was chosen in a co-moving reference frame such that the axial position of the swimmer remained constant in the flow domain.

The following table provides the necessary data of the swimmer and the parameter of the motion cycle from which we estimated the charateristic flow parameters in form of the Reynolds-number and the Strouhal-number.

(1)

$$\mathrm{St} = \mathrm{f} \cdot \mathrm{a} / |\mathbf{v}| \tag{2}$$

The former represents the ratio of characteristic inertia forces to viscous forces in the flow and the latter the ratio of time-scales between the undulatory motion and the time a fluid particles needs to travel the distance equal to the body length of the swimmer. These flow parameters are useful for comparison of the forces with other body shapes and swimming (towing) speeds. The highest deflection was located at the feet with an amplitude of $a = 0.53$ m at a steady frequency of $f = 2.20$ Hz. This resulted in $\mathrm{St} \approx 1$ at a velocity of $|\mathbf{v}| = 1.18$ m/s corresponding to the swimmer's speed as recorded in the test pool. This is well in the range documented for human undulatory swimming at $0.8 \le \mathrm{St} \le 1$ depending on the style of swimming and the athlete's physical attributes (e.g. Hochstein & Blickhan, 2011).

Table 1:

Static swimmer model

To remove holes and sharp corners as a consequence of inaccuracies of the scanning process, original surface contour data of the swimmer needed to be processed in a first step with a triangulation and smoothing procedure. Therein, the number of triangles representing the surface was reduced from 200,000 down to 12,000. This allowed a more convenient data transfer and time-efficient grid generation of the fluid domain for dynamic mesh conditions. Non-essential details such as swimsuit and face composition were smoothed during this process, too. The details of the mathematics of the smoothing procedure are given in Appendix A.

INSERT Figure 1 HERE!

As a result of this procedure, a smooth surface geometry of the female swimmer was reproduced as a digital surface. This surface represents the geometry of the swimmer in stretched form during gliding motion. It is used for reference and as a start for the segmentation process. In a second step, the main pivots (shoulder, hip, knee, and ankle) were assigned to the swimmer model. All pivots were used also as reference points for implementation of the swimmer kinematics (Pacholak, Rudert & Brücker, 2011b). Finally, the data points along the surface of the swimmer next to the pivots were assigned to individual segments of the body (arms, body, upper and lower legs, feeds).

Kinematic swimmer model

All parameters of the swimmer's kinematics during the dolphin kick cycle were previously captured by video analysis in a test pool (Hochstein & Blickhan, 2011). Each pivot of the female swimmer was marked with a self-luminous marker (Fig. 1a) and tracked with a video camera (Basler A602fc, Basler AG, Ahrensburg, Germany) at 30 Hz. The marker positions over time were curve-fitted with MATLAB 2010b (The MathWorks, Natick, MA, USA) and transferred into kinematic functions for each joint. Undulatory motion was then considered as a segmented coupled motion where each segment behaves like a rigid body whose length remains constant and whose time-trace of the angle is known. The origin of the coordinate system in the co-moving reference frame was chosen as the average vertical position of the shoulder pivot. The axial position of the shoulder pivot (y-coordinate) remained therefore fixed at the origin, while the vertical position (z-coordinate) was oscillating with the amplitude A_z around the zero-position z_0 in a harmonic manner as follows:

$$z = z_0 + A_z \cdot \sin(\omega t + \varphi_z) \qquad (4)$$

Then, the positions of the other pivots $\mathbf{P}_t$ could be calculated iteratively from one joint to the next joint, starting with the pivot point nearest to the shoulder (hip) and terminating with the ankle. The relative angles θ_i and absolute pivot angles α_i around the x-axis were interrelated as follows:

$$\theta_i = \theta_{0i} + A_i \cdot \sin(\omega t + \alpha_i), \qquad \alpha_i = \sum_{k=2}^{i} \theta_k \tag{5}$$

All absolute angles and the lengths of the segments were known from previous video measurements. The new pivot positions $\mathbf{P_t}$ of pivot points $\mathbf{P_0}$ (Fig. 2) were then determined with the rotation matrix $\mathbf{R_x}$ (around the x-axis) which contained the relative pivot angles θ from Equation (5).

$$\mathbf{P_t} = \mathbf{R_x} \mathbf{P}_0 \,. \tag{6}$$

INSERT Figure 2 HERE !

Actually, this rigid transformation rule holds only for the pivot positions and surface patches in the middle of the rigid segments. However, at larger angles θ_i the surface points near to the joints start to overlap leading to an unnatural deformation of the surface. This problem could be overcome by adding an additional translational and rotational shift of the patches relative to each other plus a smoothing kernel which scales with the distance r_{Patch} of the patch to the pivot. The surface coordinates were then determined as follows:

$$\mathbf{p_t} = \mathbf{R_x}(\mathbf{p}_0 - \mathbf{P}_0) + \mathbf{P_t} + \mathbf{r}_{\text{smooth}} + \mathbf{r}_{\text{patch}} \,. \tag{7}$$

As a consequence, surface points near to joints were shifted to a larger amount relative to their neighbours than points close to the middle of the rigid segments. This finally led to a realistic skin-like surface motion in good qualitative agreement with the video recordings of the swimmer.

$$. \qquad (8)$$

Computational fluid dynamics

As fluid, water was assumed herein to have constant density ρ and constant viscosity η. The governing equations of mass (9) and momentum conservation (10) for an unsteady three-dimensional flow (named in fluid mechanics the Navier-Stokes equations) then read (see e.g., Schade & Kunz, 1989):

$$\nabla \cdot \mathbf{v} = \mathbf{0} \qquad (9)$$

$$\frac{\partial \mathbf{v}}{\partial \mathrm{t}} + (\mathbf{v} \cdot \nabla)\mathbf{v} = -\frac{1}{\rho}\nabla \mathrm{p} + \frac{\eta}{\rho}\Delta \mathbf{v} \qquad (10)$$

with pressure p and fluid velocity **v**. The open source CFD program OpenFOAM was used to solve the equations using the finite volume method with 2nd order discretization in space and implicit discretisation in time (see e.g. Ferziger & Peric 2002; Versteeg & Malalasekera 2007). The solver is able to treat deforming mesh geometries in 2D and 3D and thus is well suited for the simulations of the unsteady flow around the swimmer model. No turbulence model was applied.

INSERT Figure 3 HERE !

The basis for highly resolved results was a combination of an outer block mesh consisting of hexahedral cells with a finer central structure which was adapted to the shape of the swimmer model with the OpenFOAM tool SnappyHexMesh. Cells inside the swimmer model were deleted and cells containing a part of the surface structure were sub-divided into smaller units until a specified cell size or cell number was reached. Additionally, surface layers were added along the contour of the swimmer model to get better wall resolution (Fig. 3). The final mesh size was $2.5\times7\times2.5$ m³ (x-y-z) containing about one million cells.

INSERT Figure 4 HERE !

Figure 4 shows the boundary conditions of the system of Equations (9) and (10). The motion functions that deform the computational mesh in a prescribed way over time were implemented as moving mesh boundary conditions. Note that the origin of the swimmer' coordinate system remains at the same position within the grid as if the swimmer is observed in a co-moving reference frame. Therefore, flow is imposed at the inflow boundary conditions with a prescribed constant velocity that is equal to the mean swimming velocity of the swimmer. This situation resembles a swimmer in a counter-flow pool who is forced to keep his streamwise position constant over time. Each supporting geometry and surface motion was created by applying the boundary condition on the static swimmer model. A phase of steady gliding was chosen as initial conditions for the equation system. It simulated the swimmer's push-off from the wall after a short period of gliding to reach the terminal swim speed of $|\mathbf{v}|=1.18$ m/s where the cycles of Dolphin kick start. One single kick cycle of period T consisted of more than 4,550 time steps in the simulation. After every tenth time step the old mesh was updated with a new deformed one and the data of $\mathbf{v}$ and p were interpolated onto the new one using bilinear interpolation. The Courant number Co defined as

$$\mathrm{Co} = |\mathbf{v}|\,\mathrm{dt}/\mathrm{dx}\,. \tag{11}$$

with the minimal cell size dx and time step dt was always in the range $\mathrm{Co} < 0.5$ throughout the simulations.

Force calculation

The total force acting on the body of the swimmer is in general the sum of a steady component $\mathbf{F}_{\text{Static}}$ which does not change with time and a time-varying component $\mathbf{F}_{\textbf{Motion}}$ related to the swimmer’s motion cycle:

$$\mathbf{F}_{\text{Result}} = \mathbf{F}_{\text{Static}} + \mathbf{F}_{\text{Motion}} \qquad (12)$$

The static force consisted of the gravitation component $\mathbf{F}_{\text{G}} = \mathrm{m}\mathbf{g}$ and the opposing Archimedes force $\mathbf{F}_{\mathbf{A}} = -\mathrm{V}\rho_{\text{W}}\mathbf{g}$, where $\mathbf{g}$ was gravitation, m and V were the mass and volume of the swimmer, respectively, and ρ_{W} was the density of water. Those are not further considered herein and were left out in the following discussion. In addition, any lateral force $\mathrm{F}_{\text{x}} = \mathrm{F}_{\text{Drift}}$ representing a side-drift of the swimmer was neglected, too. Finally, the dynamic force $\mathbf{F}_{\text{Motion}}$ varied during a kick cycle and was determined by integration of the pressure p over the swimmer’s total surface area A_{S}:

$$\mathbf{F}_{\text{Motion}} = \int_{\mathrm{A}_{\text{S}}} \mathrm{p}\mathbf{n}\,\mathrm{dA}_{\text{S}} \qquad (15)$$

Note that the contribution of the viscous wall friction was herein neglected, since the wake effect and the unsteady propulsion dominated the generated forces. The vertical component of $\mathbf{F}_{\text{Motion}}$ represented the lift force $\mathrm{F}_{\text{z}} = \mathrm{F}_{\text{Lift}}$ which is the hydrodynamic counterpart to aerodynamic lift generated with an airfoil. In swimming direction (y-direction), the resulting force $\mathrm{F}_{\text{y}} = \mathrm{F}_{\text{Propulsion}} + \mathrm{F}_{\text{Drag}}$ was the sum of thrust and drag. The former was calculated via the axial momentum added into the wake by the balance across two planes A_{p} (Fig. 4) normal to the swimming direction $\mathbf{v}$ (Schade & Kunz, 1989):

$$\mathbf{F}_{\text{Propulsion}} \cong \int_{\mathbf{A}_1}^{\mathbf{A}_2} \rho_{\text{W}}\mathbf{v}(\mathbf{v}\cdot\mathbf{n})\,\mathrm{dA}_{\text{p}} + \int_{\mathbf{A}_1}^{\mathbf{A}_2} \mathrm{p}\mathbf{n}\,\mathrm{dA}_{\text{p}} \qquad (16)$$

The first plane was 1.1 m in front of the swimmer and the second plane cut the swimming domain 0.1 m behind the swimmer. A non-dimensional representation of the drag and lift forces was given in form of coefficients which relate the forces to the dynamic pressure of the flow multiplied with the projection area of the swimmer in swimming direction.

Visualisation of flow structures

Illustrations of the numerical results were given in form of a series of vector field plots or isosurfaces representing the shape of vortical structures. Reconstruction of vortical structures out of the flow field is often based on post-processing to obtain either the so called Q-value or the λ_2 value (Hussein XXX). Herein, the Q-value was used for visualization of the flow structures. However, an isosurface with a single Q-value was not suitable to highlight both the vortex structures near the swimmer's body as well as the structures in the near- and far wake. The body vortices would be overshadowed if the isosurface was chosen with a low Q-value while the wake vortices would disappear if the Q-value was high. This problem was overcome by normalizing the Q-values by the magnitude of slip-velocity of the vortex relative to the swimming speed $|\mathbf{v}-\mathbf{v}_\infty|$:

$$Q_{\mathrm{mod}} = \frac{Q}{|\mathbf{v}-\mathbf{v}_\infty|}, \tag{18}$$

where $\mathbf{v}$ was the local velocity and $\mathbf{v}_\infty$ was the swimmer's mean velocity. In the wake, the vortices decayed slowly but slip velocity decayed, too. Thus, the quotient remained nearly constant. In comparison, near the body the vortices were strong but slip velocity was high, too, therefore the quotient did not change. Hence, isosurfaces of constant normalized Q-value gave good impression of the shape of the vortex structures and their interaction in the wake.

Additional colouring of the surfaces with the Q-value in logarithmic scaling resulted in suitable information about vortex strength (Fig. 6b).

INSERT Figure 6 HERE !

The results of the numerical simulations were qualitatively compared with results from previous 2D flow-field measurements around the same swimmer in our group (Hochstein, Pacholak, Brücker and Blickhan 2012). Main focus was laid on comparison of location and evolution of characteristic flow structures in the saggital plane of the swimmer.

Results

Forces on the swimmer

The amount of (passive) drag for gliding is $F_D = 15.9$ N at a velocity of $|\mathbf{v}| = 1.18$ m/s (Table I). For an active dolphin kick the (active) drag is 200.8 N for period 2 and 216.8 N for period 6. As a result, the drag force of a moving swimmer is about 12 times higher than for the swimmer in gliding phase. In addition, the results indicate a slight increase in propulsion of 8% during the four periods which means that maximum performance is only reached after a fey kick cycles. Average lift force and average net thrust/drag remain close to zero. Fig. 12 shows the time-varying traces of the propulsion and drag forces.

INSERT Table I HERE !

Vortex structures

Various flow structures were identified during the successive dolphin-kick cycles as illustrated by the isosurfaces in Figs. 7 and 8 which show a comparison of the results for kick cycle #2 and kick cycle #6. At cycle #2 there exist vortex structures (Fig. 7a) in the swimmer’s wake which are the remainder of the transition from the gliding phase (after push off from the wall) to the first kick cycle. These vortices resemble horse-shoe type vortices. In addition, one can recognize two ring-type vortices which were generated in the first cycle by the upstroke (upper ring) and downstroke (lower ring) of the feet (Fig. 7a). Thus each stroke generates a separate ring-type vortex which is shed into the wake of the swimmer.

INSERT Figure 7 HERE !

The dynamics of the vortex formation and shedding process is shown in Fig 8 and fig 9 by means of a series of flow states in the kick cycle. Vortex structures and their three-dimensional shape are indicated by isosurfaces of Q_{mod} (Fig. 8). Additional information is given by a cut through the isosurfaces in the sagittal plane of the swimmer shown in Fig. 9 which illustrates the vortex positions along the body more in detail. First we focus on the vortices generated along the main body. Close to the shoulder, a larger vortex structures is seen dorsally (A). When the shoulder blades move up while the arms push down (B), this vortex structure is transported along the upper body surface to the hip (C). Due to the flexion of the knee joint another vortex structure is generated dorsal of the knee (B). While the hip moves up (C-D), both vortex structure merge together and extended into a horse-shoe vortex, gaining strength through the lowering of the legs (D). On the ventral side, a larger vortex structure is formed near the shoulder and breast at state B,C. It moves further downstream (D), grows in size and strength and finally forms a horse-shoe type vortex below the legs (A). Both body vortices the dorsal and the ventral one interact with the pedal region in such a way, that they induce a strong fluid motion relative to the feeds at the state where the down- and upstroke start. At the end of upstroke and start of the downstroke in C, the shear layer is being shed into the wake and rolls up in form of a vortex ring (start vortex) that is left behind the feed on the upper side. On the other hand, at the end of downstroke and start of upstroke in A, another vortex ring is shed on the lower side. Due to the induced relative motion by the presence of the body vortices near the feed the relative velocity between body and fluid is increased at the up- and downstroke. This generates higher thrust since the generated momentum depends only on the relative velocity.

INSERT Figure 8 HERE !

INSERT Figure 9 HERE !

In the wake of the swimmer, vortex interaction leads to re-configuration of the flow structure in form of longitudinal vortex tubes (Fig. 7b). This process is illustrated in more detail in Fig. 10. The successively shed upstroke vortex rings split and form two upper longitudinal vortex tubes (Fig. 10) while successively shed downstroke vortex rings form two lower longitudinal vortex tubes. Split-up and merging happens at the region, where the counter-rotating parts of the two successive vortex rings are next to each other. As a consequence, the vorticity cancels out to zero, the vortex lines break-up and recombine into column-like vortex tubes (Fig. 10 B2-B3).

INSERT Figure 10 HERE !

Comparison to experiments

The comparison of the numerical results (Figs. 8, 9 and 10) with the experimental observations (Fig. 11) for similar time steps shows similar dynamics of vortex generation and vortex transport. The capital letters represent the movement time steps assigned in Figure 5. Due to the flexion of the knee joint a vortex is generated dorsal of the knee (compare Fig. 11B and Fig. 8B). After the downstroke (Figs. 9D and 9A vs. Figs. 11A and 11A') both results show the generation and the pedal transport of a vortex dorsal of the knee (Fig. 9B vs. Figs. 11B and 11D). These vortex structures are comparable in size and location.

INSERT Figure 11 HERE !

Discussion and implications

High level swimmers usually perform about 5–8 periods after the start and turn. In our simulation the start is a simple push-off that might be a simplification of the actual competitive swimming start or turn. Thus the following motion cycles have to be examined separately to investigate the progress of unsteady structures and their constructive or destructive influence on the flow.

Forces on the swimmer

If the fluid velocity and swimmer's silhouette match the used motion function, all components of the resultant force acting on the swimmer must be balanced. In this study the resultant force in the swim direction (net thrust/drag; F_y) and perpendicular to the swim direction (lift; F_z) differ from zero (Table I). There is about a 3% difference between the drag and propulsion, which depends on the varying reference amount caused by the time shift and calculation impreciseness. Both the average lift force and the average net thrust/drag are (slightly) different from zero, indicating that the motion cycle of the swimmer is not exactly balanced. Reasons for this difference could be the inaccuracy of the motion function used (sinusoidal fit of swimmer's tracked motion). Furthermore, during undulatory motion there are intra-cyclic variations in the swimming speed. In contrast, this study used a constant flow velocity of $v \approx 1.18$ m/s (average swimming speed). Additionally, the shape of the body (mainly the legs) varies during the kick cycle (more open or more closed). The frontal area during the kick cycle (Fig. 12a) is similar to that of the underwater undulatory backstroke motion of Cohen et al. (2012).

The drag and lift forces over a complete period have a similar progression for period 2 and period 6 (Fig. 12b). In detail the dolphin kick in period 6 generates more propulsion in the first part of the motion cycle $\left(0 \le t \le 0.4T\right)$, between $0.4T \le t \le 0.8T$ the propulsion of period 2 becomes more effective but decreases after this short phase below the level of period 6. The mean drag and mean propulsion of period 6 is about 8% higher than in period 2 (Table I). This means that vortex re-capturing is only achieved after several kick cycles. As a consequence, fine-tuning of push-off velocity, body kinematics and vortex preformation is necessary to obtain a constructive body-vortex interaction. In contrast a mismatch between the swimmer's motion and swimming speed may lead to destructive interferences.

INSERT Figure 12 HERE !

Vortex structures

Our investigations discussed herein differ from former studies that we have run the simulations for 6 successive kick cycles with an additional initial gliding phase. Other studies were focussing only on a single cycle without any starting phase (Loebbecke et al. 2009b, Cohen et al. 2012). Therefore, we are able to investigate the transient from the gliding to the kicking phase and possible cycle-to-cycle variations. As the results have shown there is an increase of 8% of propulsion when comparing cycle #2 and cycle #6. The reason therefore is assumed to be related to the mechanism of vortex re-capturing as discussed in the following. The basic idea of vortex re-capturing in locomotion is to use the kinetic energy of vortices generated near the body to enhance propulsion (Hochstein & Blickhan, 2011). As documented herein, vortex re-capturing occurs at the swimming cycle when the body vortex is transported caudally along the body's surface (circle in Fig. 9) to a position where the legs in the next kick within the cycle would cross the vortex (B). Due to the presence of this body vortex in the region near the feet, there is an induced fluid motion which – in case of constructive interaction - is counter to the stroke motion of the feet. In consequence, there is a higher relative velocity between feet and fluid during the stroke. This causes an increase of momentum added to the fluid.

It is important to note that the formation of the body vortices needs a certain number of cycles to be established in full strength. As shown in Fig. xxx. after push-off from the wall, flow at the cycle #2 is still influenced largely by the presence of vortices generated in the starting phase and the body vortices are not yet fully developed. Thus there is only limited use of any vortex-recapturing in the initial phase. In contrast, the illustrated vortex dynamics in the later cycles clearly revealed the presence of vortex re-capturing. We therefore conclude that the increase of propulsion about 8% from cycle #2 to cycle #6 is due to vortex re-capturing in the later kick cycles.

Comparison to experiments

we validate the results of the numerical simulation of the 3D flow field with the experimental results of the same swimmer with the same motion (Hochstein & Blickhan, 2011; Hochstein et al., 2012). In fact this comparison is limited by the constraint that the experimental method of Particle Image Velocimetry only provides a 2D flow field in a single plane, the sagittal midplane. The good qualitative agreement between the results from experiment and numerical simulations in the saggital plane supports the herein deduced discussions about the three-dimensional nature of the vortex structure and the resulting forces.

Conclusion

This paper shows a complete approach from the scanning of a real swimmer with a body scanner and reconstructing the surface data in order to implement the motion functions and conduct open source CFD simulation with the dynamic model. This offers great advantages when using steady moving models with implemented motion functions instead of fitting a model position to some given image frames. Parametric studies are easier to implement through varying the parameters, such as joint angle, phase or frequency. This methodology allows greater influence on running calculations and the implementation of new numeric solvers. The discovery of vortex merging in the swimmer's wake visualised by a modified Q-criterion and the reusing (re-capturing) of vortices shows the great potential for further studies on this topic, which will lead to a better understanding of the entire process of human undulatory swimming. The study shows that the propulsion through underwater undulatory swimming increases with a longer diving phase. Another important aspect is the calculation of the active and passive drag. It is well known that the main propulsion is realised by the legs and feet, but the questions of what percentage of overall forces are generated by undulatory body motion and what detailed effect results from active drag have still not been determined.

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Fig. 1: Steps in model construction: the human model (a), the entire data scan of the 3D body scanner (b), and the completed surface model of the human swimmer at three different instants within the dolphin kick cycle movement steps (c).

Fig. 2: Mathematical model of human swimmer at an optional point in time *t*, the pivot point $\mathbf{P}_0$ and the surface data $\mathbf{p}_0$ in rest position are rotated around the x-axis by angle α to gain the time-dependent positions of $\mathbf{P}_t$ and $\mathbf{p}_t$.

Fig. 3: Slice through calculation mesh with finer core around the swimmer's surface from side view (a), from the front (b), and an enlarged subsection showing layers near the surface (c).

Fig. 4: Boundary conditions of calculation mesh: fluid intake (inlet), fluid cleanout (outlet) and remaining boundaries (boundary), and two additional planes $\mathbf{A}_p$ for propulsion calculation.

Fig. 5: Single motion cycle of human dolphin swimming showing the significant time steps (A: gliding position at the beginning and the end (t=0=T), B: maximum upper transversal excursion of feet (t=0.25T), C: maximum downstroke velocity of feet (t=0.5T), D: maximum lower transversal excursion of feet (t=0.75T). In the following these indicating time steps are symbolised by their capital letter (A-D).

Fig. 6: Comparison of standard and modified *Q*-Criterion: Vortex evolution and interaction cannot be visualised with a finite threshold value of iso-surfaces of *Q* (a). Modifying *Q* with the magnitude of slip-velocity leads to a chronological characteristics Q_{mod} of vortex evolution (b).

Fig. 7: Generation of upper and lower ring-vortex structures (visualised by the modified *Q*-Criterion) behind the swimmer (a) at the beginning of period 2 (initial structures after push off from the wall and one kick cycle) and (b) at the beginning of period 6 (vortex

rings merge into four longitudinal vortices). (c) Slices through swimmer’s wake at three different positions. The black arrows stand for die flow velocity.

Fig. 8: Comparison of unsteady structures in period 2 (left column) and period 6 (right column) visualised with modified Q-Criterion. Main differences in intensity are located in the region of the hip and in the vortex transport in this area. Capital letters A-D represent the points in time defined in Figure 5.

Fig. 9: Comparison of unsteady structures in period 2 (left column) and period 6 (right column) visualised with modified Q-Criterion in sagittal plane at the midline of the swimmer. Light contours show the extrusion of these vortex structures in the x-direction, the circle labels the same unsteady structure and its transport during a complete period. Capital letters A-D represent the points in time defined in Figure 5.

Fig. 10: Top view on the swimmer’s wake. Process of ring-vortex merging into two longitudinal vortices (the legs form an elongated loop vortex) illustrated for the upper ring vortex release area from $t=T$ (A1) until $t=4.25T$ (B3). The same procedure occurs in the lower ring vortex release area with a phase shift of $0.5T$. Capital letters A-D represent the points in time defined in Figure 5.

Fig. 11: Validation of the numerical results with the experimental measured 2D flow field (black arrows stand for the direction and the magnitude of the flow) and vorticity (contour) of the swimmer’s sagittal plain (adapted from Hochstein et al., 2012) of the same swimmer and same motion observed in the present study. Each image is a combination (divided by the black vertical line) of the same phase during the motion cycle. The right part of the inset is always two motion periods before the left part. The large blue (clockwise) and red circles (anticlockwise) indicate vortex structures, and the black 3D structures stand for halved 3D vortex rings.

Fig. 12: Time dependency during a dolphin kick cycle of (a) the frontal area including characteristic time steps (dotted lines and its corresponding front view), and (b) the

propulsion and drag force of period 2 and period 6 over a complete motion cycle showing a vertical flip with a shift of 0.19*T* in time.

Appendix A

The smoothing procedure is described in detail in the following: first, to modify the surface resolution the scanned data were embedded into a minimum cube. For the three spatial directions this cube was divided recursively by two into eight sub-cubes. The more often this division was performed, the higher the final resolution of the model. It was not possible to gain a higher model resolution than the scan data without destroying surface closure (holes, bricks). Depending on the geometry of the scanned object, several created sub-cubes contained data points p_i. These data p_i were reduced into one balance point c_j for each cube:

$$c_j = \frac{1}{n}\sum_{i=1}^{n} p_i \qquad (1)$$

With Equation (1) it was possible to reduce the surface data to 8^b points, where b was the number of recursions used for cube division. This amount was just an upper boundary because not all cubes contained data.

The cube with balance point c_j obtaining the most neighbours of neighbours

$$N_j^2 = \left(\bigcup_{k \in N_j^1} N_k^1\right) / \{c_j\} \qquad (2)$$

was the starting point for the initial triangulation. Equation (2) determined a set of cubes, that were neighbours of at least one neighbour of c_j but without c_j itself. Two cubes were neighbours (N_j^1) if they had one side in common. There were at most six neighbours in 3D space. The amount N_j^2 contained all neighbours of the neighbours of cube c_j and had 18 items or less. The balance point of c_j and its N_j^2 were projected onto their regression plane and triangulated with the planar Delaunay triangulation algorithm (Pacholak, Rudert, & Brücker, 2011a). This method created regular triangles with interior angles close to 60°. After re-projecting the planar triangulation onto the original c_j and its N_j^2, the main triangulation started to add the remaining neighbouring balance points, step by step, to the existing triangulated surface.

$$c_l \subseteq N_j^2 \cap N_i^2 \qquad (3)$$

The points c_l had to fulfil the following conditions: (i) c_l was part of the outer border e_{ij} of the triangulation or was not already used, (ii) c_l was in the direction t of triangulation, (iii) the angle between the normals of the existing triangle and the triangle created was below 105°, (iv) the distance between c_l and the outer border e_{ij} was below $\sqrt{2q}$, where q was the length of a sub-cube, and (v) there was no faces crossing between the triangle created and already-existing triangles.

If more than one point fulfilled these conditions, the most regular triangle was created (the regularity condition meant that all interior angles are close to 60°). The edges of the created triangle were added to the outer border e_{ij} of the triangulation or deleted if they were already part of it. The procedure for adding new neighbouring points started again and lasted as long as any outer edges remained.

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