A review of experimental and numerical investigations about the unsteady flow in human swimming motions

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Abstract

This paper reviews the experimental and numerical investigations on unsteady flow conditions caused by swimming. To increase the understanding about swimming research, we summarize the progress and identify the limitations and future potential of the methodologies being applied. The accuracy of Computational Fluid Dynamics (CFD) continues to improve, but more research and validation of the experimental data are required to optimize and validate CFD simulations. Experimental data gathered by particle image velocimetry are limited, because at present the observation is restricted to a 2D, 1-m square area; this limitation could be removed if the output range of the laser sheet is improved. The swimming human simulation model is very useful and user-friendly; thus, we can expect that it will be applied to improve competitive swimming and swimming by handicapped individuals.

Key words: CFD, PIV, Swimming simulation model, Unsteady fluid force

Introduction

Previous studies have emphasized the importance of unsteady phenomena in swimming by humans.[2,52] Thus, we now know that quasi-steady hydrodynamic theory is insufficient to describe the mechanisms by which humans propel themselves through water. To address such problems, computational fluid dynamics (CFD) is used, because it includes the effects of unsteady fluid flow. CFD has been making a major contribution toward the increased understanding of complicated hydrodynamic phenomena[3−5,9,14,18−21,26,43,45,46,48,53,55,56]. Experimentally, particle image velocimetry (PIV) has proven to be a powerful tool for measuring the actual flow fields around human swimmers. On the basis of PIV measurements, several researchers have reported that vortices might play an important role in generating unsteady fluid forces[11,13,22−24,27−29,42,47,51,54]. Combining the results from CFD and PIV should aid in visual and theoretical understanding of complicated hydrodynamic mechanisms. Moreover, actual experiment data such as measurements of forces and pressures are valuable to verify CFD results and to interpret PIV images. Several experiments have been conducted to measure unsteady fluid forces or pressures on a mechanical arm, swimming robot, and pressure sensors attached to human swimmers[15−17,32,37,39,40,49,50]. Moreover, Nakashima et al.[32−34,38] have developed a swimming human simulation model (SWUM) that uses parameters from experimental data. The SWUM model considers the rigid body dynamics and unsteady fluid forces for the whole body, and is a much-anticipated tool for optimizing swimming movements as well as maximizing velocity or mechanical efficiency. If we can combine novel and sophisticated methodologies, such as CFD, PIV, and SWUM then we may be able to uncover the complex mechanisms that generate unsteady fluid forces while swimming.

However, it has only been about 10 years since these methodologies have come into practical use in swimming research. In fact, we have very less information of the progress that has been made or the inherent limitations and potential of these methodologies. Therefore, this paper reviews experimental and numerical investigations on unsteady flow conditions caused by swimming, and discusses future research areas and an appropriate

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methodology to resolve persisting problems. Moreover, there is a need to integrate knowledge from different methodologies to increase our understanding of unknown complicated hydrodynamic phenomena. Therefore, we focus on underwater undulation swimming (UUS) analyses and attempt to integrate the results obtained from UUS analysis.

Computational Fluid Dynamics

Computational fluid dynamics (CFD) is a numerical method used to simulate fluid flows by solving the discretized form of the Navier-Stokes equations in well-defined geometries with flow-specific boundary conditions. The first work using computers to model fluid flow was performed at Los Alamos National Labs, in the T3 group (1950s) to develop airfoils[10]. The accuracy of the method relies on the density of discretization employed and on the turbulence model selected for the flow.

In swimming, CFD analysis was originally applied by Bixler and Schloder[3] in 1996 to evaluate the effects of a 2D flat circular plate that was of the same size as a human hand accelerating through water. As the technology improved, the plate was adjusted to create a model of the hand and forearm that optimized the pitch angle of the hand in water[4]. Five years later, Bixler et al.[5] simulated the full body of a swimmer with CFD; they compared the passive drag computed experimentally in a flume with the passive drag computed by CFD. The resulting data shows a difference of 4% and 18% between the experimental and computational approach for a mannequin and human swimmer, respectively.

After 2006, CFD analysis was applied to various types of swimming research because of the growing capabilities of the commercial CFD software, FLUENT. Subjects of analysis, turbulence models, CFD software, etc. in previous studies are summarized in Table 1. In most of those studies, attempts to assess swimming performance involved steady-state analyses of the whole body or sections of it; few studies have employed transient analysis. Moreover, earlier studies particularly, were based on 2D analyses, which led to results of questionable accuracy, because complex 3D flows were approximated by 2D simulations. Furthermore, except for the work by Bixler et al.[5] and Machtsiras[19], most of those studies have not been validated against

Table 1 Summary of subjects of analysis, turbulence models, CFD software in previous studies

Author	Subjects of analysis	2D/3D	Turbulence model	Type	Software
Bixler and Schloder (1996)	Two dimensional flat circular plate	2D	standard k-ε& RNG & RM	steady state	Fluent
Bixler and Riewald (2002)	Swimmer's hand/forearm	3D	standard k-ε	steady state	Fluent
Sato and Hino (2003)	Comparing two elite freestyle swimmers' arm stroke pattern	3D	N/A	transient	in-house software
Gardano and Dabnichki (200	Swimmer's arm	3D	N/A	steady state	Fluent
Rouboa et al. (2006)	Swimmer's hand/forearm	2D	standard k-ε	transient	Fluent
Bixler et al. (2007)	Validation of CFD analysis comparing to an actual passive drag measurement	3D	standard k-ε	steady state	Fluent
Lecrivain et al. (2008)	Handicapped swimmer's amputee arm	3D	N/A	transient	Fluent 6.3
Silva et al. (2008)	Effect of drafting distance	2D	standard k-ε	steady state	Fluent
Zaidi et al. (2008)	Changing swimmer's head position	2D	standard k-ε	steady state	Fluent
Marinho et al. (2009)	Gliding position for arms along the trunk and arms extended at the front	3D	standard k-ε	steady state	Fluent
Minetti et al. (2009)	Optimum finger spacing of a hand	3D	SST	steady state	CFX
von Loebbeke et al. (2009)	Underwater dolphin kick	3D	IBM	transient	Fluent
Keys (2010)	Simulation of dolphin kick, free style kick and breaststroke kick	3D	realizable k-ε	transient	Fluent
Sato and Hino (2010)	Gliding position in different depth	3D	N/A	transient	SURF
Zaidi et al. (2010)	Stream-lined position	3D	standard k-ε& standard k-	steady state	Fluent
Machtsiras (2012)	An effect of head position, depth and swimsuit on glide performance	3D	LES & RANS type k-ε	transient	STAR-CCM

Where RNG is the Renormalized Group turbulence model, RSM is the Reynolds Stress model, SST is the Shear Stress Turbulence model, IBM is the Immersed Boundary method and LES is the Large eddy simulation model computational findings.

For CFD calculations, FLUENT has been the mainstream software, while the standard k-ε turbulence model has been the turbulence model that has been applied most often. The standard k-ε model was thought to be the best turbulence model for examining passive and active drag in swimming[5,48,55]; however, the model has some inherent limitations. Recently, advances in CFD software have resulted in better performance in flows involving rotation, boundary layers under strong adverse pressure gradients, and separation. Consequently, the realizable k-ε model may provide better turbulence results[56]. Another possible alternative for these applications is the shear-stress transport k-ω turbulence models developed by Menter, Kuntz & Langtry[25]. The latest results obtained by Machtsiras[19] concluded that the Large Eddy Simulation (LES) model performs significantly better than the standard k-ε model. For example, a difference between experimental and computational results of 2.73% was obtained when the LES model was employed; this was significantly less than the 18% difference previously reported by Bixler et al.[5]. Although the accuracy of CFD analysis continues to improve, more research and testing is required to optimize and validate CFD simulations; nevertheless, using current "best practices" should provide some insight into swimming techniques[14].

Another numerical simulation approach, somewhat different from CFD, has been developed by Cohen et al.[6,7]; the approach is called smoothed particle hydrodynamics (SPH). This is a meshless method for simulating swimming movements, but it may take considerable time before swimming movements can be analyzed by this method.

Particle Image Velocimetry

Particle Image Velocimetry (PIV) is an optical method of flow visualization that can be used to measure instantaneous velocities and related properties in fluids. The initial groundwork for a PIV theory was laid down in 1988 by Adrian[1] who is a theoretical hydrodynamics researcher. The method has been successfully used to study locomotion of fish[31,44] and insects[8]. However, even with the use of this sophisticated method, at present the difficulty is in directly measuring the entire flow field around a human hand and/or foot.

In 2004, Matsuuchi et al.[22] first demonstrated the use of PIV in swimming research by measuring the flow field that develops around a moving hand while swimming, which may be the main source of propulsion for the crawl stroke. A remarkable amount of momentum was observed during the transition from in-sweep to out-sweep motions at the latter part of the stroke because of the action of a pair of counter-rotating vortices.

Table 2 Summary of merits and demerits about PIV

Merit	Demerit
Non-disturbing swimming motion owing to its contact-free setup	Calibration is necessary
Because of fast response and, it is possible to capture changes of velocity and temperature quickly	Tracer particles have to be diffused in water
Instantaneous velocity, vorticity, and heat flux rates can be measured	The time resolution is poor
Lagrangean measurement is possible including Lagrangean correlation and Lagrangean vector measurements	The dynamic range of the velocity is low
Because measurement probes such as hot wires are not necessary, the mean velocity and temperature are obtained easily	
Multi-dimensional measurements are possible	

Matsuuchi et al. suggested that this increase in momentum directly led to the unsteady fluid force generated according to Newton's second law of motion[23]. Subsequently, Matsuuchi and his research group[30] developed a new PIV system combined with motion analysis. This system synchronizes PIV images with 3D human motion data by using two high-speed cameras to simultaneously capture the velocity and vorticity fields with the geometrical configuration of the hand. The results obtained reveal that when the hand orientation was changed rapidly, vortex generation, shedding, and momentum generation were observed in the flow field. Such vortex behavior might contribute to a large part of the generated thrust[24]. In addition to the front crawl, Kamata et al.[13] attempted to demonstrate the flow field during sculling movements, and concluded that after the change in direction of hand motion, a pair of vortices formed with a jet flow induced between the vortices. This jet flow increased momentum, and accordingly a lift force acting on the hand was thought to be generated.

We can expect that PIV will contribute to identify previously unknown mechanisms that generate unsteady fluid forces, but PIV is not without drawbacks. The merits and demerits of PIV are summarized in Table 2. The most serious issue with PIV seems to be the inherent limitations in the area of observation. Even in the latest study, the observation area is limited the two dimensional and 1 m square, it is not enough to cover a whole swimming motion at once. To solve this problem, improvements in the output range of the laser sheet might be essential.

Swimming human simulation models

Nakashima et al.[33–36,38] have developed SWUM to analyze swimming by humans; the model accounts for the unsteady fluid forces, including buoyancy and gravity. In the SWUM model, the whole human body is divided into 21 parts of a truncated elliptic cone, and the unsteady fluid forces acting on each part are computed from the local motion of the part, i.e., from its position, velocity, acceleration, direction, etc. Notably, unlike CFD, SWUM does not compute flow-field conditions, because the computation time is shorter. Thus, an optimized swimming motion could be developed on a personal computer. Nakashima and his research group have conducted simulations of various swimming motions by using SWUM, e.g., the front crawl[33,38], breaststroke[41], underwater undulation swimming[35], and monofin swimming[36]. These simulations have provided very practical information for adjusting movements that enable a human to swim faster. Since SWUM seems to be very useful and has a user-friendly interface, various applications can be expected for competitive swimming and swimming by handicapped individuals. However, SWUM considers neither the effect of surrounding walls nor the mutual intervention of limbs, hence the computational result of SWUM might differ from CFD; this seems to be a limitation of SWUM.

Direct measurement of unsteady fluid forces and other methods

Although sophisticated methodologies, such as CFD, PIV, and SWUM have come into practical use in swimming research, the direct measurement of forces and pressures is still important to verify the results by these methodologies. Kudo et al.[17] used a hand-forearm model to investigate the acceleration effects of hydrodynamic forces on the hand. They determined that hydrodynamic forces on an accelerating hand were 1.9–10 times and 1.7–25 times greater than that for a non-accelerating hand in angular motion and general motion, respectively. These large increases occurred during positive and negative acceleration phases, which might be due to the added mass effect and a vortex that forms on the dorsal side of the hand.

Nakashima et al.[39,40] developed an underwater robotic arm that has five degrees of freedom to perform various complicated limb motions for swimming. Using the robotic arm, unsteady fluid force actions on a hand or a foot were directly measured, and the resulting data were analyzed with the SWUM model to improve computational results. Recently, Takagi collaborated with Matsuuchi and Nakashima who used their own methodology to measure fluid forces, pressures, and flow fields around a robotic hand during the breaststroke[51]. Takagi et al.[51] concluded that when the maximum resultant force acted on the hand, a pair of counter-rotating vortices appeared on the dorsal surface of the hand. The vortex attached to the hand increased the flow velocity, which led to a decreased surface pressure and an increase in hydrodynamic force. This phenomenon is known as the unsteady mechanism of force generation. Takagi et al.[51] determined that the drag force and lift force was 72% and 4.8 times greater than the values estimated under steady-flow conditions, respectively.

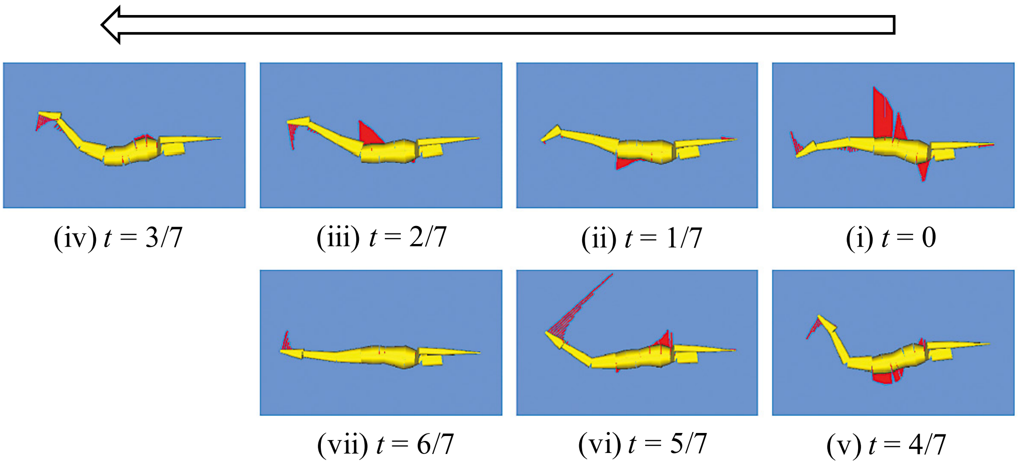
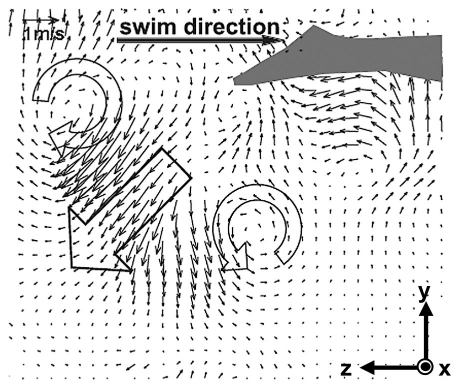


Fig. 1 Computed results of the unsteady fluid force acting on a body during underwater undulation swimming by using SWUM. Red histogram demonstrates the fluid force generated on each body part and its direction of action and magnitude. (Modified from Nakashima et al., 2007)

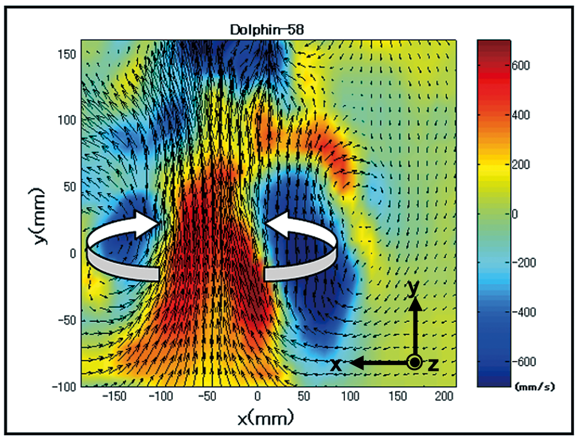
Integration of knowledge in underwater undulation swimming analyses

Although each of the above methodologies has its own merits, we need to integrate knowledge from different methodologies. Therefore, we attempt to integrate the results obtained from UUS analyses because UUS is comparatively easy to adopt it as an experimental object.

First, we study the results obtained from SWUM by Nakashima et al[35], which are shown in Fig. 1. The figure contains a series of body diagrams that forms a sequence of stages in UUS from the basic position (streamlined position) to the upbeat and downbeat phase. The red histogram shows the fluid force generated on each body part, including its magnitude and direction of action. The largest thrust force occurred at $t = 5/7$ (Fig. 1(vi)), which is the moment when the direction changed from upbeat to downbeat phase. The velocity distributions in the flow field were obtained by PIV for that moment; those distributions are illustrated in Fig. 2. The upper figure[11] shows a side view of velocity vectors around the feet to the direction of travel; a strong oblique downward jet flow appears with a pair of counter-rotating vortices. The lower figure[28] shows a vertical section of velocity vectors in a flow field downstream from the feet. The red and blue colors represent backward and forward velocities, respectively. A strong backward flow and a pair of forward flows on each side of the backward flow occur. Both the upper and lower figures represent the flow structure on a 2D plane; however, since the flow structure is actually 3D, it seems to be difficult to understand the actual structure of the unsteady flow. Therefore, a 3D flow visualization of the unsteady flow structure obtained



Modified from Hochstein et al. (2011)



Modified from Miwa et al. (2005)

Fig. 2 Velocity vectors in the flow field when large thrust force generated by feet during underwater undulation swimming in PIV analysis. The upper figure indicates a side view of velocity vectors around the feet to the direction of travel (Z direction). The lower figure indicates a vertical sectional view (x-y plane) of velocity vectors at a downstream location from the feet. The color bar indicates the velocity of z-axis direction, which means representative flow direction. (Modified from Hochstein et al., 2011 and Miwa et al., 2005) by the CFD method[12] is shown in Fig. 3. As shown in Fig. 3(b), donut-shaped vortices were generated by the upbeat (upper ring) and downbeat phase (lower ring). Comparing the CFD results with findings from PIV and SWUM models for the same phases of the motion shows some similarities in vortex generation.

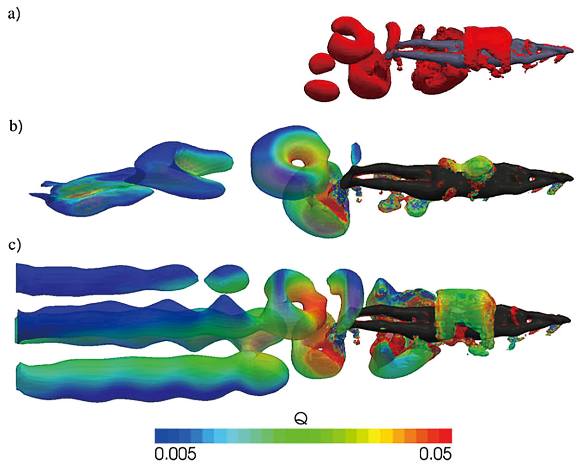


Fig. 3 Flow visualization of unsteady structures for underwater undulation swimming by CFD. a) a discrete value (Q=0.5 s-2) with standard Q-Criterion, b) a steady interval of Q with modified Q-Criterion at logarithmic scaling and c) after period one. (Hochestein et al., 2012)

Future research areas and appropriate methodologies

Studies based on CFD have the potential to provide new insights and information that cannot be obtained by testing and measurement. Similarly, SWUM simulations offer practical benefits to coaches and swimmers by providing information about the optimal movements for improved training and performance. In addition, PIV measurements play a vital role in verifying results from numerical simulations. Furthermore, applying a combination of these methods will be a powerful tool to further advance research in swimming. Currently, it seems to be difficult to analyze the broad range of 3D motions that constitute any one of the standard strokes: front crawl, breaststroke, backstroke, or butterfly. For now, a feasible research area seems to be underwater undulation kicking or sculling movements. In any case, as we move forward with new research, we will have to identify the appropriate turbulence models for use in CFD and expand the range of PIV to include 3D analyses.

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