FREESTYLE SWIMMING: AN INSIGHT INTO PROPULSIVE AND RESISTIVE MECHANISMS

Koji Honda[1,2], Matt Keys[1], Andrew Lyttle[1,2], Jacqueline Alderson[1], Mohammed Bennamoun[1], Amar El-Sallam[1].

The University of Western Australia, Australia[1]
Western Australian Institute of Sport, Australia[2]

The mechanisms behind propulsion and drag generation in swimming have proven difficult to accurately and comprehensively measure. With fluid effects being the major contributing factor for swimming performance, the ability to accurately determine these effects is of great importance. Computational Fluid Dynamics (CFD) modelling provides a solution to this problem. CFD can not only quantify the net effect of the forces acting on a swimmer, but also that observed at each individual segment. CFD modelling allows complex fluid flow regimes and geometry to be simulated. The results of a CFD analysis allowed for the distribution of the forces across the body throughout the freestyle stroke to be examined. The results of this analysis include an increased level of foundational knowledge with applied outcomes that may be used to improve swimming performance.

KEY WORDS: computational fluid dynamics, free swim, swimming, drag, propulsion.

It is clear that aquatic sports pose unique challenges for biomechanists, with the medium of water proving to be the greatest obstacle in the measurement of performance. Swimming is a sport further complicated by the changing nature of the human form, when compared with the rigid paddles and boat hulls used in aquatic sports such as sailing, rowing and kayaking. Although a number of theories are postulated in the literature to help understand swimming mechanics, many have lacked the necessary supporting evidence. Current free swim techniques are derived from a mix of natural genetics, feel for the water, knowledge of experienced coaches, and trial and error methods. Although this is considered to be effective, little is known of the hydrodynamic factors making one technique more efficient than another.

What is known is that there exists a complex interaction of forces as swimmers move through the water. To date, understanding the exact mechanisms surrounding the creation of propulsion and active drag minimisation during swimming is unresolved. In general terms, the three options available to increase swimming velocity are: to increase the total propulsive forces; minimise the total resistive forces; or a combination both. For coaches and sports scientists to effectively apply technique changes via these options; a thorough knowledge of the mechanisms of propulsion generation and drag force development is essential.

In order to understand these possible mechanisms, it is necessary to examine the methods used to determine the forces generated by swimmers in the water. Force in each direction on a body, with respect to time, is best described using Morrison's equation (Figure1; Barltrop & Adams, 1991), which combines inertial and drag terms:

$$F(t) = \underbrace{\rho C_m V \dot{U}}_{\text{Unsteady-state inertial term}} + \underbrace{\tfrac{1}{2}\rho C_d A U|U|}_{\text{Steady-state drag term}}$$

Figure 1: Morrison's Equation where ρ is the density of the fluid, U is the velocity of the object relative to the fluid, U.|U| is utilised to maintain the direction of velocity, A is the object area in the direction of the force, V is the object volume; and C_m and C_d, are the inertial and drag coefficients, respectively (Barltrop & Adams, 1991).

Without going into a thorough examination of fluid dynamics theory, there are two parts to this equation: the steady-state (or velocity-dependent) portion; and the unsteady-state (acceleration-dependent) component. As can be seen in Figure 1, the steady-state component is related to both the velocity and the frontal surface area of the segments;

whereas the unsteady-state component is related to the acceleration and volume of the segments. In human swimming, the inertial forces (unsteady-state) are often more important due to the relatively high accelerations of the segments during the stroke when compared with relatively low velocities. These unsteady-state inertial forces are the main cause of propulsion generation during the arm catch, and the commencement of the down-sweep and upsweep of the kick (due to the high accelerations of the arm and feet segments at these points) which highlights the importance of acceleration during these phases.

Research investigating swimming starts and turns has been relatively prolific due to the ability to apply instrumentation directly to walls and starting blocks. However, free swimming has to date had relatively few testing tools available to facilitate a comprehensive non-invasive biomechanical analysis. Past research has utilised one, or a combination of the following methods, to estimate what is happening throughout the swimming stroke;

- Video based kinematic analysis,
- Inertial sensors,
- Instrumented tethered swimming analysis,
- Numerical modelling and analysis of recorded flow lines and vortex patterns.

Each of these systems has provided valuable information and some empirical data to address questions surrounding 'the best way to swim'. However, due to these methods inherent limitations, and the highly complex nature of fluid flows around the irregularly shaped human body that is always a changing shape and position, none of these techniques have enabled a full understanding of what is occurring across different body segments throughout a full swimming stroke cycle.

One area that has gained significant momentum in recent years to investigate the fluid flow effects around swimmers has been Computational Fluid Dynamics (CFD) modelling. Based on fundamental fluid mechanics principles, CFD allows complex fluid flow regimes and geometry to be simulated, allowing the resultant fluid flow effects to be quantified. As such CFD can measure a number of variables such as velocity and acceleration, along with the propulsive and resistive forces acting on a swimmer as a whole or of specific body segments. This can provide insight into problems thus far unobtainable via known physical testing techniques and has been identified as the key to future developments by the international scientific swimming community (Vilas-Boas 2010).

The increasing interest in the use of CFD analysis in determining the mechanisms for the swimming stroke has progressed from an initial investigation in 1996 by Bixler and Schloder, who used a disk of the same size as a human hand to estimate the forces throughout the freestyle stroke. With improvements in technology, studies have utilised CFD analysis to examine hand motion through the water (Sato & Hino, 2002); the hand and arm acceleration through the water (Rouboa et al., 2006); the propulsion created by the hand and forearm in steady flow (Bixler & Riewald, 2002); the effect of finger spread on propulsion (Marinho et al., 2010); and underwater kicking (Lyttle & Keys, 2006; Cohen, Cleary & Mason, 2009). CFD analysis has further progressed to a single case study of a complete full body dynamic analysis of the freestyle stroke conducted by Keys (2010) in an unsteady flow. This paper will discuss the outcomes of the work by Keys (2010) and discuss a novel technique to obtain the accurate 3D kinematics needed for further CFD analysis to be conducted.

While this paper does not comprehensively detail how to run a CFD analysis, it is important to identify some of the technologies and methodologies that make this type of simulation a reality. More information on general CFD theory is covered in the work of Versteeg and Malalasekera (1995), while more in-depth information on the dynamic CFD model developed for this work can be found in Keys (2010). In general, any dynamic CFD model requires two important components.

1. A detailed 3D mapping of the swimmer's body shape using a 3D laser or video scanner. This is used to create the domain in which the CFD model is run, where the subsequent mesh is made more 'dense' in critical areas (e.g. areas of great curvature) to accurately define the fluid flow characteristics and forces acting at each point on the swimmer.
2. An accurate description of the 3D kinematics (technique) of the swimmer performing the stroke. In Keys (2010), 3D kinematics were derived through manual digitising. While this is

the standard method for obtaining kinematic data in aquatic motion, there are limitations that are tied to inherent inaccuracies associated with this measurement technique underwater. The dynamic CFD model then calculates the fluid flow effects across each body segment resulting from the 3D swimmer's animation (produced by the 2 CFD inputs). The CFD model by Keys (2010), on an ex-world 50m freestyle world record holder, allowed the net propulsive and resistive forces to be calculated, as displayed in Figure 2. The temporal phases of the stroke are listed in Table 1.

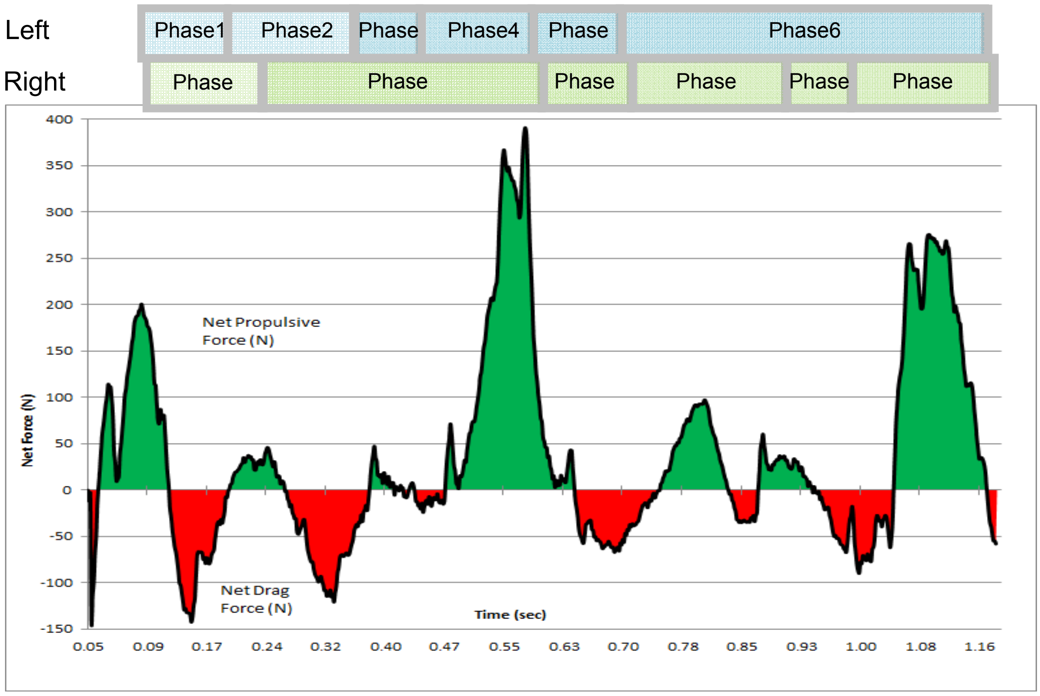

Figure 2: Overall propulsion/drag throughout a full stroke cycle (net drag force are displayed in red and net propulsive force in green).

Table 2
Timing for the temporal phases of the left and right arms through the freestyle stroke.

Phase	**Left Hand (s)**	**Right Hand (s)**
1. Initial hand entry and outstretching of the arm	0.09-0.21	0.61-0.70
2. Acceleration at the start of the stroke pushing outwards	0.21-0.38	0.70-0.91
3. The change of direction from pushing outwards to bringing the arm back in towards the centre of the body	0.38-0.45	0.92-0.98
4. The main propulsion phase along the base of the body when the forearm is close to perpendicular to the direction of travel	0.45-0.59	0.98-1.14
5. Hand exit	0.59-0.67	0.10-0.24
6. Arm recovery	0.67-1.13	0.24-0.61

An examination of the breakdown in the distribution of forces revealed that the arms and legs create significant amounts of propulsion, with the trunk contributing the majority of the drag. The hands provided a total propulsive momentum of 23.8 Ns while the combined contribution of the wrist, forearm and elbow was 27.6 Ns. This highlights that the forearm position during the underwater arm stroke is as critical as that of the hands. The head was found to contribute less drag than the upper and lower trunk components. This finding could be related to both; the fact that it is occasionally positioned in only a semi-submerged state, and secondly has less volume to influence the potential amount of wave drag experienced. The thighs, knees and calves also contributed a greater percentage of the propulsion than the feet. This reinforces the importance of entire leg movements and positioning (pose and orientation), as opposed to just focusing on feet positioning. However, this result may also be

attributable to the feet coming out of the water regularly, and the possibility of wave assistance.
The overall changes in forces throughout the stroke were characterised by six clear cycles, containing four small peaks and two large peaks. These peaks represent the six beat kick pattern that is adopted, with the two large peaks correlating with the peak propulsion of the left and right arm strokes; occurring simultaneously with two of the kick cycles. These peaks, and in particular the peaks associated with the arm stroke propulsion, were reflected in increases in the swimmer's instantaneous velocity. The two highest velocity peaks of the swimmer occurred immediately following presence of peak propulsive forces, namely at 0.64s and 1.14s, where the swimmer's velocity surged to $2.3 m.s^{-1}$. There are definitive peaks associated with the left and right arms as they move through the cycle. The left arm peak occurs at 0.55s and the right at 1.07s. There is a secondary lower peak that occurs prior to these at 0.33s for the left, and 0.89s for the right.
An area of major focus for the enhancement of CFD methodology has been identified as the improvement in 3D kinematic generation. Obtaining reliable and accurate 3D kinematic data of swimmers' techniques will provide unparalleled insight into the swimmers' movement patterns and will maximise the potential of CFD to provide useful and valid information for swimmers and coaches. To this end, an investigation of image reconstruction techniques using visual hull recognition has been initiated by the research group from the University of Western Australia, Swimming Australia and the Western Australian Institute of Sport.

CONCLUSION: Though in its infancy, CFD analysis is an emerging tool which can be used to provide practical information for swimmers, coaches and sports scientists. The major difficulty using CFD as an analysis tool is that the program is both labour and computationally expensive. However the ever increasing capacity in computing power and the continued development of CFD programs will allow for a more streamline analysis process. The outcome of this CFD analysis provides an increased level of technical understanding related to the production of net thrust forces during the freestyle stroke, leading to an improved technical proficiency of the freestyle performance. Further development of the swimming kinematic methodologies using visual hull techniques have been identified as a key to maximising the benefits of the CFD methodology.

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