An alternative technique for investigating fluid flow around the hand during front crawl

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Abstract

This paper presents the novel application of a technique for measuring flow around the hand during a simulated swim stroke with a view to enable a better understanding of propulsion generation in swimming. The technique relies on the instantaneous, non-intrusive, volumetric measurement of 3D velocity fields using a commercially available optical measurement system. A hand and forearm model was towed through a water tank to replicate the pull phase with fluid flow data being captured at regular intervals in a fixed volume through which the model moved. The measurement system included a single body, three-sensor probe for capturing pairs of images which were then processed to determine particle velocities and to characterise the flow. The results were used to investigate changes in mean velocity for six experimental cases based on three different angles of attack and two towing speeds. The results showed that the V3V system could be used to capture velocity data around the hand and for a 45° increase in angle of attack, the velocity magnitude of the flow reduced by half, indicating the presence of lift forces.

1. Introduction

There are five phases of the front crawl stroke cycle: entry, catch, pull, push and recovery. The hand *entry* and *catch* are the phases where the swimmer's hand enters and gets 'hold' of the water. The *pull* defines the first half of the stroke where the arm moves from a position stretched out in front of the body to a medial point; the *push* describes the hand as it moves from this point towards the feet of the swimmer. *Recovery*, the final phase, is where the arm leaves the water and returns to the re-entry point. It is generally agreed that the arms provide more than 85% of the total thrust in the front crawl stroke [1], with the *pull* phase generating the most power through the stroke. The success of a competitive swimmer depends on many factors; one of the most prominent is technique, and within this the hand orientation during each phase of the stroke. The coefficients of lift and drag are strongly dependent on the angle of attack, illustrated in Fig. 1; small changes in angle of attack can change the resulting propelling force, which is a vector product of the lift and drag force [1]. Swimmers are able to direct the propelling force by varying the lift and drag component by means of angle of attack. The optimal angle of attack can be seen to vary throughout the swim motion depending on the phase of the stroke [1].

Hand position and finger separation are important considerations when investigating the effect of hand orientation on performance. Computational Fluid Dynamic and physical modelling studies have determined the optimal finger separation to be between 10-12°, equivalent to a relaxed hand position. This is found to improve performance compared to a fully open or completely closed hand [2,3]. In addition to understanding the movements and angles of the arms during a stroke it is also necessary to consider body and hand velocity. The stroke slip rate of an elite swimmer is the relative velocity between the hand and the water in the direction of the swimmer's forward motion and varies from 0.1 to 0.6 m.s^{-1} [3]. Velocities of the underwater phases of swimming have also been reported by Maglischo [4], however these consider the hand velocity in three dimensions thereby resulting in higher values.

Theories in propulsion have evolved through continued research and better understanding of fluid behaviour. Arellano [5] discusses the relationship between these theories and swimmer technique and highlights the need for further research in this field. Many studies have been based on steady flow theory [6]; flow fields around swimmers are, however, typically unsteady and, therefore, inherently difficult to predict and measure. Particle Image Velocimetry (PIV) has been used to analyse the motion of swimmers, allowing velocity vector

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measurements to be taken in a region of flow while being non-intrusive to the swimmer. Studies have investigated areas such as the flow around the hands [7] and also investigated the area behind the feet during undulatory swimming [8–10], allowing for correlations between propulsion and vortex generation.

Techniques presented in reviewed literature have been limited to two-dimensional studies, investigating flow in either the sagittal or the frontal plane, with no research to date reporting data collection simultaneously in multiple planes. For this reason, flow generated from an arm model towed through water was studied here by examining a volumetric flow field using a volumetric PIV system.

2. Methodology

2.1. Hand model and rig

Experiments were conducted in a water filled tank sized 800 x 450 x 350 mm, using a bespoke mechanical rig towing an end-effecter. A model of a female forearm (hand length 185 mm, hand breadth 80 mm, hand circumference 190 mm), produced from a water resistant Jesmonite acrylic resin, with the hand at the correct orientation and finger spread, was mounted to a double-acting pneumatic actuator, allowing only linear motion with total travel range 750 mm. The air pressures at the inlet and outlet ports of the actuator governed the velocity of the arm. The average velocity of the end-effecter was captured with two optical switches arranged as light gates separated by 232 mm.

2.2. Data capture

A TSI Volumetric 3-Component Velocimetry (V3V) System was used to capture the region of flow on the dorsal side of the hand as it moved through the tank with the centre of the arm model approximately 215 mm from the edge of the tank, as illustrated in Fig.1b.The flow was illuminated by a dual head 200 mJ/pulse Nd:YAG laser with a pulse separation time (Δt) of 1250 µs. Two negative 25 mm cylindrical lenses were mounted in perpendicular orientations to produce an ellipsoidal cone of illumination which was expanded to cover a larger region. A flat mirror was used to reflect the beam back through the water tank towards the measurement region to increase illumination intensity. Screens were used on
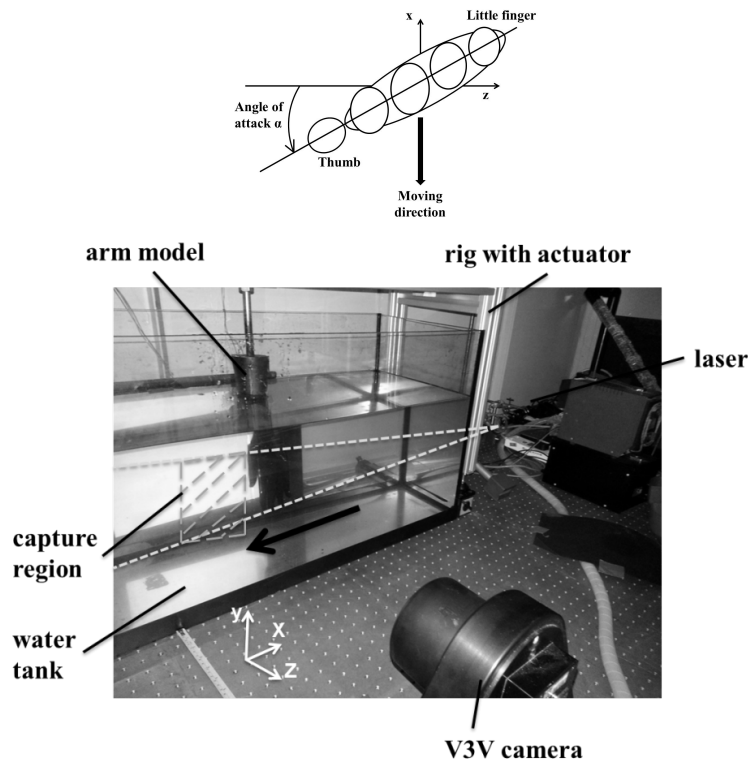

Figure 1: (a) Hand angle of attack; (b) Image of the experimental setup; arrow indicating the direction the arm was towed

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Table 1: Angle of attack and arm mean velocity

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
angle of attack (°)	0	20	45	0	20	45
mean velocity (mm.s^{-1}) (SD)	184 (0.9)	184 (0.6)	187 (0.8)	243 (1.0)	276 (1.0)	279 (0.7)

the side of the tank to limit the illumination volume to the area of interest. Polycrystalline particles with a mean diameter of 50 µm were used as tracers. The volumetric camera sensor consisted of three apertures, each containing a four-megapixel CCD, arranged in an equilateral triangle of side length 170 mm. The camera sensor was mounted 675 mm from the rear of the measurement region and perpendicular to the illuminating light. This arrangement allowed for a measurement region of 135 mm x 110 mm in the horizontal and vertical directions respectively and with a depth of 100 mm. The V3V camera frames and laser pulses were triggered by a synchroniser with each of the three CCD's capturing a pair of images. The two laser-emitted pulses are timed to straddle neighbouring camera frames in order to produce images for 3D particle tracking. The synchroniser was triggered externally to coincide with the arm passing through the optical timing switch. The velocities of the arm through the capture region were based on a slow velocity of 185 mm.s^{-1}, and a faster velocity in the region of 260 mm.s^{-1} as shown in Table 1. Image sets were captured at 7.25Hz giving 15 image sets per stroke, each with three image pairs. The parameters used during image capture are detailed in Table 1.

After image capture, the V3V software was used to determine the velocity vector fields in four steps: i) 2D particle identification in each of the individual images, ii) 3D particle location in the measurement volume iii) 3D velocity vector generation based on particle tracking and, finally, iv) interpolation of the vectors onto a regularly spaced grid. Each of the four stages are summarised below, with more details found in Troolin and Longmire [11]. The locations of the tracer particles in each image were determined by setting a baseline intensity threshold out of 4096 grey scales, a minimum and maximum 2D particle diameter (1 mm and 3-3.5 mm used for the data collected) and a maximum particle overlap size of 75%.

The process of identifying particles from one image and its corresponding image in the pair required the use of the volumetric spatial calibration, which was achieved in advance of making measurements by traversing a single planar target through the measurement region and capturing images at regular, pre-defined intervals. The target surface consists of a series of holes spaced on a 5 mm square grid; the target was traversed towards the camera in the *z*-direction at 5 mm intervals over a range of 100 mm resulting in 63 images per calibration. Once the calibration information was obtained, the locations of the 2D particles were compared with it, in order to determine 3D particle locations or triplets [12]. The centroids of the 2D particle locations were forced to match the calibration within a tolerance of four pixels. After particle clouds were achieved in both frames a relaxation method of particle tracking is performed [13]. Vectors found were spaced within the volume dependent upon particle locations. It is useful to have vectors on a Cartesian grid; these vectors are found through regular Gaussian-weighted interpolation. A typical single capture yielded approximately 300 independent arbitrarily spaced vectors and 22000 interpolated vectors per velocity field.

2.3. Data Analysis

Data was obtained for the six cases under investigation and, within each, multiple runs were completed; each run resulted in 15 pairs of images, each pair separated by 0.138 sec. The data obtained was not phase averaged at this time; the preliminary study focused on investigating the mean flow in the three vector components for a single instance in time; this was the period immediately after the hand had passed through the capture region. It is predicted that this instance would be of most interest and allowed for the largest volume of water to be processed without being obscured by the arm. Initially, only 10 trails from each case were processed using the V3V software and the vector files further processed using MATLAB to investigate the averaged flow and the results presented within.

3. Results and discussion

This research was carried out to investigate if the pull phase of the swimming stroke could be analysed using the V3V system. Figures 2a-c show the individual components of velocity averaged across the entire volume at a single time instance, for each of the three angles of attack at a low arm tow speed (cases 1-3). The data highlights significant variation between runs, with average and standard deviation values being shown in Table 2. In general the average velocity magnitude ($\bar{V}$) of the water behind the hand was found to decrease with increased angle of attack. Considering the components of velocity, in the first three cases in which the arm was

towed at the same velocity though the measurement region, the average *x*-component, ($\bar{u}$), reduced in magnitude with an increased angle of attack. However, the *z*-component ($\bar{w}$) increased, indicating the presence of a lift force across the hand with increased angle of attack. This trend is less significant in the second group of trials, conducted at a higher tow speed, probably due greater to fluctuations in the speed across the three angles of attack.

Lift forces act perpendicular to the direction of hand movement and combined with drag forces are important for propulsion. However, the reaction force to lift must result in momentum in the fluid, as discussed in depth by Toussaint *et al*. [1]. Force in the direction of travel is generated by giving a mass of water a velocity change and consequently the pushed mass of water acquires a kinetic energy. This kinetic energy is a result of work done by the swimmer. However, not all of the work done by the swimmer generates force in the desired direction of travel; some of the energy is wasted moving the water in other directions. It is hypothesised that minimisation of this loss of energy that is an indicator of efficiency and good swimming technique. It is therefore clear that, to generate the same propulsive force at a given speed, by using an efficient technique the swimmer can reduce the work required. Both propulsion generation and energy losses to the water need to be considered together to understand swimming technique; quantifying this energy loss and efficiency is the next stage in understanding the propulsion forces generated in swimming.
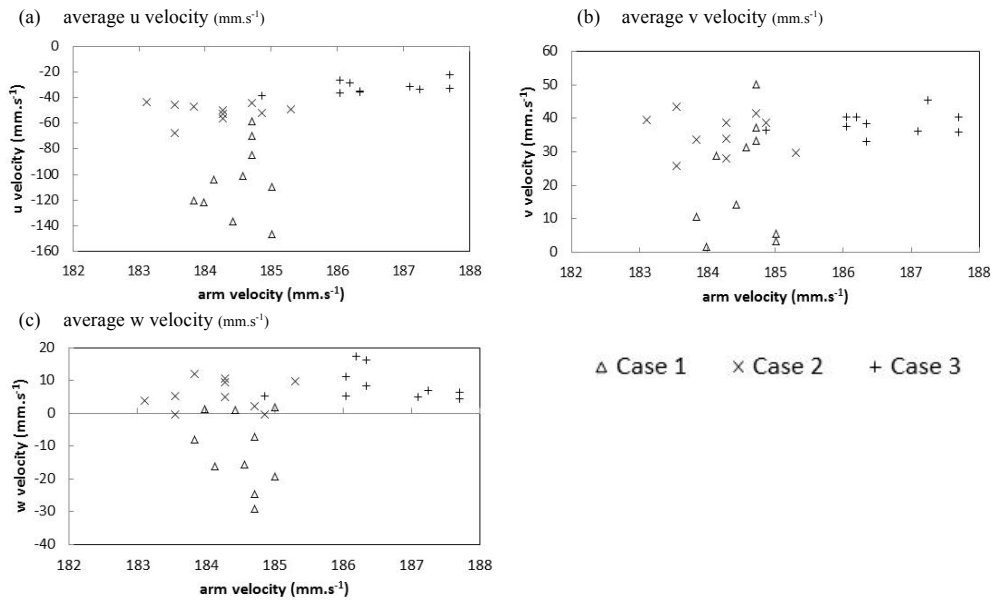

Figure 2: The average u v and w velcotiy in the measurement region against towed hand speed, for a single time instance for case 1-3, 0, 20 and 45° at low speed

Table 2: Average velocity data for each case (mm.s⁻¹), (standard deviation).

	Case 1 (0°)	Case 2 (20°)	Case 3 (45°)	Case 4 (0°)	Case 5 (20°)	Case 6 (45°)
$\bar{u}$ (mm.s⁻¹)	-105 (26)	-51 (7)	-33 (5)	-154 (12)	-107(16)	-51 (9)
$\bar{v}$ (mm.s⁻¹)	22 (16)	35 (6)	38 (3)	26 (13)	29 (7)	48 (4)
$\bar{w}$ (mm.s⁻¹)	-12(10)	6 (4)	9 (5)	-17 (12)	-34 (15)	13 (8)
$\bar{\nabla}$ (mm.s⁻¹)	108	62	51	157	117	71

4. Conclusions

Flow generated from an arm model towed through water was studied by examining volumetric flow fields. The current data shows that the pull phases of the front crawl stroke can be investigated using the V3V system. Previous studies investigating swimmers using PIV have focused on the size and location of vortices generated with only some links being made to the energy expenditure associated to this. Hochstein and Blickhan [9] discussed the need to recapture the energy associated with vortex generation, but they do not quantify the energy transfer to the water in the same way. The V3V technique was useful in providing velocity data to begin the process of understanding the momentum and energy transfer between the water and the swimmer. It allowed a

volume of flow to be investigated without the need for instrumentation within the water which could influence the results.

In order to investigate a human swimmer in a pool environment there is a need to further develop the technique to, firstly, use an illumination source which is suitable for a swimmer to traverse through and, secondly, move away from seeding of the flow with physical particles. These developments would allow the technique to be deployed with minimum invasion of the swimmer's training ensuring there are no adaptations in the athlete's technique.

Acknowledgements

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