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INVITED CONTRIBUTION

FUNDAMENTAL HYDRODYNAMICS OF SWIMMING PROPULSION.

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The purpose will be to describe the different methods applied in swimming research to visualize and understand water movements around the propulsive limbs and their application to improving swimming technique. A compilation of flow visualization methods applied in human swimming research is presented. Simple propulsive actions will be analyzed combining the kinematic analysis with the flow visualization: underwater undulatory swimming and sculling propulsion. The analysis of vortices generated and 3D analysis of the pulling path seems the most adequate method to develop a new understanding of swimming propulsion. The development of flexible and portable laser systems such as the recently incorporating fiber optics and fiberscopes, will enable the applicability of PIV in real swimming conditions to quantify the wake momentum and vorticity. New and attractive ideas are emerging: the possible use by the swimmer to his advantage of the vorticity if it is produced by an external source, such as the environment, another swimmer or the re-use of his own vortices during the stroke or after the turn will be topics for research in the near future.

Key Words: wake, sculling, undulatory, flow visualization, Strouhal number.

INTRODUCTION

The study of human swimming propulsion is one of the more complex areas of interest in sport biomechanics. Over the past decades, research in swimming biomechanics has evolved from the observation subject's kinematics to a basic flow dynamics approach, following the line of the scientists working on this subject in experimental biology (20, 56). As Dickinson stated (20) "at its most fundamental level, locomotion is deceptively simple, an organism exerts a force on the external environment and through Newton's laws, accelerate in the opposite direction", but the dynamics of force application are not as simple as they might at first appear, specially during swimming or flying where the force is applied to a fluid. In fact, it results from the complex three-dimensional interaction between a stationary fluid and a moving body with soft boundaries. The hydrodynamics of this phenomenon are yet not clear. The muscle contraction flexes or extends a particular joint, moving the limb though the water. The water previously occupied the limb's volume; the subsequent position required the displacement of its particles. At very slow limb displacement, the water particles will occupy steadily and in an orderly way, but at higher limb velocities the water is moving unsteadily, generating a turbulent wake behind. This subject was analyzed by Counsilman (18), who considered that "eddy resistance is more important than frontal resistance and that, at least theoretically, more propulsion is derived from the back of the hand than from the front of it".

In an ideal situation the hand is fixed in the water (no displacement and zero velocity) and the net shoulder muscles contraction produces a full body displacement forward of the swimmer's body (for example using the MAD system); there is no interaction between the hand and the water around it. In a real situation the hand interacts with the water and its velocity is increased. But increasing the backward velocity of the hand alone will not produce the desired forward velocity (similar to a caterpillar paddlewheel); a combination of curvilinear hand movements (up-down, left-right and backward) will produce the desired effect on body velocity (46). The propulsive force is a vector addition of lift (L) and drag (D) forces generated by the hand and they are proportional to velocity squared (see eq. 1,2)

$$L = 1/2\ \rho\ u^2\ C_L\ S \qquad \text{(Eq. 1)}$$

$$D = 1/2\ \rho\ u^2\ C_D\ S \qquad \text{(Eq. 2)}$$

Where u is the relative velocity with respect to the fluid (m/s), S is the hand's surface area (m^2), ρ is the water density (kg/m^3), C_L is the lift coefficient and C_D is the drag coefficient. The values of these coefficients are characteristic of the object tested and are a function of the angle of attack (α) and the sweep-back angle (ψ) as Schleihauf (44, 45) and Berger (7, 37) investigated. Maximum values of C_L (about 0.8-1.0) are obtained between 35° and 45°-attack angle, and maximum values of C_D (about 1.3) are obtained at 90°. The values of C_L and C_D are more similar when all possibilities of sweep-back (different "leading edges" orientations of the hand) angles are considered. This indirect method of propulsive force calculation is based on the proper knowledge of the hand position and its velocity in a three-dimensional reference system (water volume) and in conditions of extreme accuracy the coefficients can be calculated (26, 37) and the water refraction controlled in order to apply adapted DLT methods (25). Considering these limitations some index characteristic have been defined in the 3D pulling path (47):

a) Diagonality index: the average angle of the negative hand line motion and the forward direction at the points of first, second and third maximal resultant force production (57);

b) Scull index or lift-drag index: the average ratio of lift and drag forces (C_L / C_D) at the three greatest occurrences of resultant force (57);

c) Force distribution index: is the average location of the three greatest resultant forces expressed as a percentage of the total duration of the underwater phase of the arm pull (57).

A similar approach was used by Sanders (43) to obtain the propulsive forces alternative vertical breaststroke kicking applied by the water-polo goalkeepers.

Under this methodology four basic hand propulsive movements were defined (31, 32): Downsweep, insweep, upsweep and outsweep. Each stroke was therefore composed of a combination of these movements. For example, breaststroke is composed of outsweep and insweep.

The previous paragraphs based the understanding of swimming propulsion on steady-state flow mechanics that has left many questions unanswered. Some trials observing the flow behaviour around the swimmer's body lead us to try to apply unsteady mechanisms of force production to resolve them. However, such approach needs to analyze the flow behaviour around the propulsive limbs to identify the phenomena, a difficult task in a swimming pool, but quite common in fluid dynamic laboratories.

The traditional semantic classification of the propulsive forces in terms of drag and lift is not relevant when applying a non-

steady hydrodynamic analysis and it is probably more useful to investigate the momentum and the vorticity or their respective scalar indicators the energy and the enstrophy applied by the swimmers limbs on the water.
Our purpose will be to describe the different methods applied in swimming research to visualize and understand water movements around the propulsive limbs and their application to improving swimming technique.

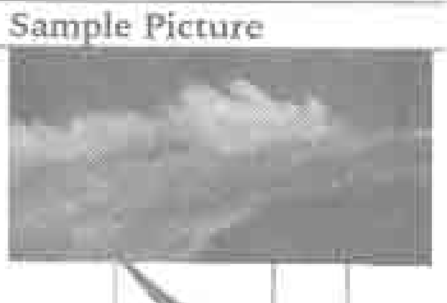
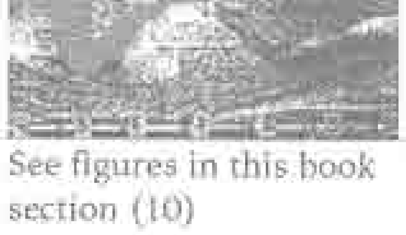
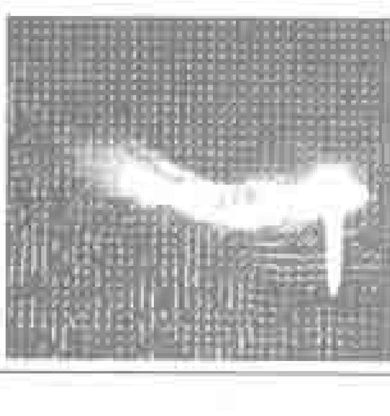
OBSERVING WATER MOVEMENTS

During aquatic locomotion forces are exerted by the body and limbs against the surrounding water, which is not fixed in position but instead yields in response to the action of propulsive surfaces (27). Colwin (12, 13) and Ungerechts (54) suggested new ways of analysing the swimming propulsive movements based on the observation of water around the propulsive limbs. All bodies (including propulsive limbs) displacing water will create vortices (rotating water masses) in their wakes; they carry a fairly high momentum, which can transfer a strong propulsive impulse to the body (55). As Bixler (9) stated when an object accelerates, decelerates, or changes its shape or orientation as it moves through a fluid, the flow will be unsteady. Thus, the resulting pressure field exerted by the fluid on the body's surface, responsible for the propulsion, will be again unsteady, varying differently with both time and position. In this conditions the propulsive drag and lift forces developed by a swimmer's hand at a given time are dependant not only upon the velocity at that time, but also the acceleration at that time and the acceleration history of the hand prior to that time. Under these criteria the calculated ***D*** need to be updated in unsteady flow conditions, for example, through a quasi-steady approach (9):

$$D = 1/2\, \rho\, u^2\, C_D\, S + k\, \rho\, \forall\, a \qquad \text{(Eq. 3)}$$

Where: ***k*** is the added mass coefficient, ∀ is the characteristic volume of the body on which ***k*** is based and ***a*** is the instantaneous acceleration at time ***t***. The first term is equation 2, which is the drag due to steady state motion. The more water that is "grabbed" by the swimmer's hands the larger the added mass and the larger the propulsive drag. Such quasi-steady model theory is of common practice when investigating fluid forces on structures (49).
Based on the observation of flow movements it is possible to measure the total locomotor force (in fishes). It is calculated by dividing the fluid momentum of the vortex ring (or rings) shed over a fin beat cycle by the duration of the fin beat. The momentum of each vortex ring is itself calculated as the product of the water density, the area of the vortex ring and the mean ring circulation (27). The described procedure, simple in essence but complex in its applicability in human motion, encourages us to apply sophisticated methods of flow measurement such as Particle Image Velocimetry (P.I.V.). This methodology broadly used in fish propulsion studies has been recently applied in human swimming in a very controlled situation (2, 35). Nevertheless, we must improve the methods used to visualize the flow around the swimmer's limbs before applying this advanced methodology.
A compilation of flow visualization methods applied in human swimming research is presented in Table 1. The capabilities and limitations of each method are very different and are adapted to research conditions: laboratory (small water tanks), swimming flume or swimming pool. Under very controlled conditions it is relatively easy to observe and measure water movements; however in real swimming the observations are more complex and less accurate, as it is only possible to analyze the problem in a qualitative and descriptive way at the moment.
The approach developed in Tsukuba University is a first trial to apply PIV in freestyle swimming. A sophisticated swimming flume, a tool similar to that the applied in fish swimming research, is being used. The flume is filled with small close-to-buoyant particles. A laser light sheet within the working area illuminates a horizontal plane, parallel to the water surface. The arm pull action of the swimmer enables his hand to cross the illuminated slice of the flow during the insweep and outsweep. A triggered high-speed camera records the illuminated plane while the hand crosses this specific zone, so that it is possible to observe the hand displacement and water particles movements. Pairs of consecutive images from the video sequences are then input into a cross-correlation processing algorithm, which takes a small, user-defined area of the image and calculates the direction and magnitude of each particle's velocity within that region. This yields a single velocity vector representing the average flow within that small area. Repeating this analysis at each location, a map of velocity vectors can be calculated that provides a snapshot of wake structure and strength (27, 35, 49) [see figure 1.7].

Table 1. Flow visualization methods applied in swimming research (PIV listed bellow is not a flow visualization technique but a mechanism one).

Method	Description	Authors	Sample Picture
1. Natural or spontaneous bubbles	As a result of accidental air entrapment (16)	Colwin (12-16) Ungerescht (54)	
2. Tuft	Observing the direction and motion of the tufts made of thread or lod of an appropriate length and material (36)	Hay (24), Ferrell (22), Toussaint (51), Nakayama (36)	 (52)
3. Reflective particles	Particles of solid tracer are distributed uniformly in the fluid (36)	Arellano (1) Redondo (40)	
4. Injected bubbles and bubbles wall (Path line method)	Fluid tracer (air) is injected continuously into the flow though fine tubes or holes (36)	Arellano (1, 3, 4)	
5. Coloured dye	Fluid tracer (dye) is injected continuously into the flow though fine tubes or holes (36)	Colman (11) Persyn (38)	
6. Sodium Fluorescelnate powder	The flow is visualized using a chemical reaction between the fluid and surface substance (36)	Colman (10)	See figures in this book section (10)
7. PIV	A picture capturing movements of tracer particle is analyzed through some optical and /or mathematical procedure to get velocity information (36)	Arellano (2) Matssuchi (35)	

As Colwin (16) stated "vortices are the muscles and sinews of propulsion, and the activity, seen here in the flow field, represents a history of the swimmer's propulsion". The application of injected bubble enables us to observe the wake produced by a swimmer after the propulsive limb movements; this history tells us about the efficiency of the energy transfer mechanism between the swimmer and the water and his control of propulsive actions. Swimmers of different levels generate very different wakes during simple and complex aquatic movements. In some cases, better swimmers generate bigger vortices that rotate quicker and are kept stationary in the water after the swimmer's stroke or kick, enhancing more efficient energy transfer mechanisms. Simple propulsive actions will be analyzed combining the kinematic analysis with the flow visualization: underwater undulatory swimming and sculling propulsion.

UNDERWATER UNDULATORY SWIMMING

At certain Reynolds numbers, when a wake is generated, a double row of vortices is visualized. Their characteristics depend on the situation of the immersed body, stationary (like a hand following a rectilinear path) or oscillating (like a fish tail). The vortex street shed from stationary bodies produces drag and a staggered Kárman vortex street. An oscillating tail or foil produces a vortex trail shed where the sense of each vortex in the trail is opposite to that of the Kárman 'natural' shedding case (see figure 2); it can be considered as 'thrust-type' trails as the induced momentum produces thrust upon the disturbing body initiating the trail (58).

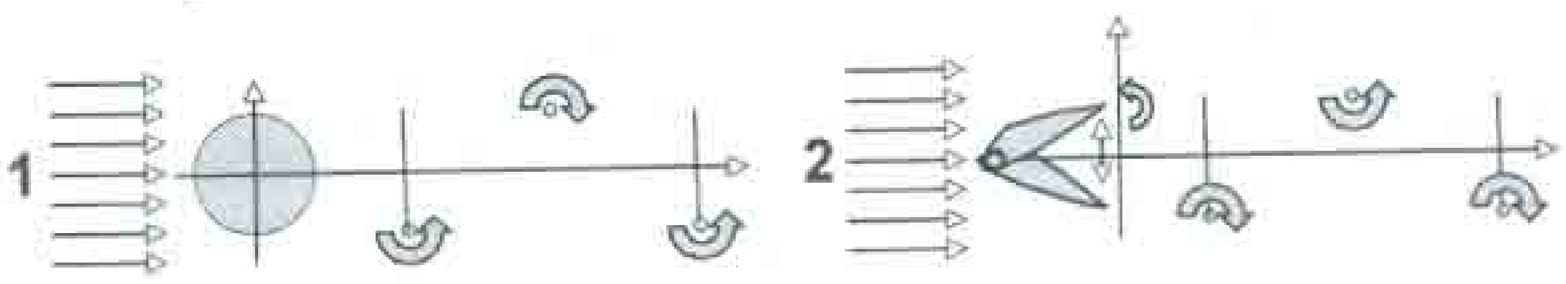


Figure 2. 1. A vortex street shed from a stationary body that produces drag. 2. A vortex trail shed produced by an oscillating foil that produces thrust. Adapted from Weihs (58).

When a fish undulates and propels itself with its tail fin, it produces a water displacement that can be observed: wake vortices. Every vortex generated after each stroke has a different rotation (clockwise or anti-clockwise), producing a jet of water undulating between vortices and flows in the direction opposite to the swimming direction (56). What makes the high efficiency and high thrust of a foil is the manner in which the vortices are arranged behind the foil, the oscillating tail is a more efficient method of propulsion than a classical propeller (42). Before starting to study complex strokes such as the freestyle-pulling path, we decided to begin with underwater undulatory swimming (UUS). The UUS is fully underwater (wave drag can be considered negligible), the body is extended horizontally with the arms stationary, legs and body movements can be considered symmetrical and displacement is obtained with leg and body propulsive undulations or oscillations.

The Strouhal number is a dimensionless number, representing the ratio of unsteady and steady motion (23). Strouhal number (St) can be defined by the equation:

$$St = A_{p\text{-}p}f \,/\, U \qquad \text{(Eq. 4)}$$

Where $A_{p\text{-}p}$ is the tail-beat peak-to-peak amplitude (the distance from the peak of the tail fluke upstroke to the peak of the tail fluke downstroke), f is the tail-beat frequency and U is the mean body velocity. It can be interpreted as well as a reduced frequency, providing a ratio between the momentum caused by the tail oscillation and that due the forward motion of the swimmer. It is then an estimate of the relevance of the unsteadiness in the fluid-body interaction to the overall fluid structure. In our previous studies (4, 5) swimmers with less experience obtained values higher than 1, while top performers obtained values around 0,80. These values are far from the results of efficient water animals (between 0,25 and 0,35 (53)). The practical use of this number is to play with its variables in order to bring its value closer to the more efficient range without decreasing the swimmer's speed, in this case with modifications in frequency and amplitude values. In that sense, it appears to be part of an indicator of the efficiency in the aforementioned energy transfer mechanism. Parameters such as the timing of the change of direction of the tail (acceleration-deceleration), the tail's curvature and its performance in generating circulation or the synchronization between vorticity creation and tail, knees and hip motion appear to be linked to the obtained performance for a given thrust.

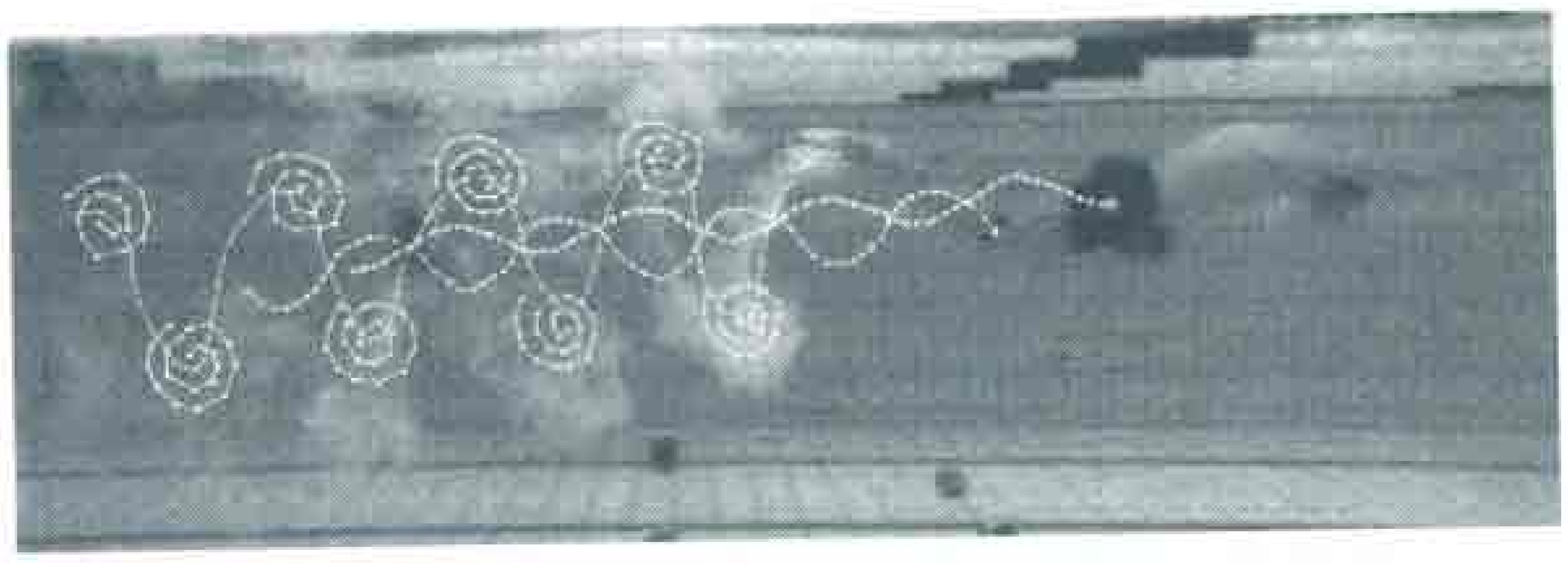


Figure 3. Spiral drawing representing the size and rotation direction of the vortices generated after each change in the kick movement. Some authors have suggested the thrusting impulse is a reaction to the jet stream away from the body, moving between the counter-rotating vortices (28, 53, 59). The trajectories represent hip, knee and big toe. The vortices drawn represented an instant after the change of direction in the big toe trajectory. All the traces were performed with the computer programme GraphClick v2.8.1 (Arizona Software).

The combination of the body landmarks kinematics and flow visualization demonstrated in UUS:

a) A wake of counter-rotation vortices is clearly observed after kick-up and down (see figure 3)

b) The feet leave the vortex behind after each change in their trajectory, maintaining their rotation for several seconds while its size is expanding (see figure 3)

c) The vortex wake pushes a hypothesised jet stream (see figure 3)

To think that the vortex creation *is not related* to the forward displacement of the swimmer's body seems unrealistic considering the controlled circumstances of the UUS displacement studied. The analysis of undulatory displacement of the body land-marks using Fourier analysis demonstrated in UUS a coordinated sequence and increase of amplitude and peak vertical velocities from shoulder to feet. The body landmarks are phases of a simple sinusoid oscillation with very rhythmical motion. The high mean velocities of centre of mass (about 2 m/s) measured in top swimmers are obtained with smaller ranges of c.m. velocities than we expected (about 0,4 m/s) and similar ranges to the most continuous stroke: freestyle (33). In spite of the limits recently imposed by the FINA regulations the applicability of this stroke in the underwater phase of the starts and turns is clear (17, 34).

THE SECRETS OF SCULLING

Another basic propulsive movement is horizontal scull. This short propulsive action of the hand is applied specially in synchro swimming or water-polo (goal-keeper) to keep some part of the body out of the water stationary and high and in the insweep phase (bending the elbow) of all the competitive swimming strokes (6). It is characterised by an important application of hydrodynamic lift force (6, 45). The basic movement is performed using a trajectory similar to an ellipse in the front view and an elliptical-figure eight trajectory in the horizontal plane (see figure 4).

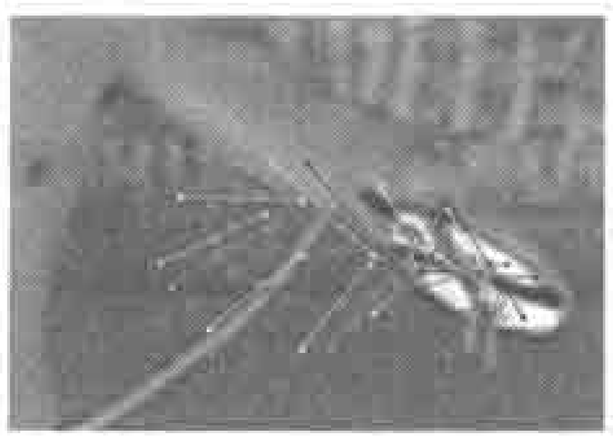


Figure 4: Trajectory and plane position during a cycle of vertical sculling movement (50 Hz). It can be observed the changes in the attack angle, leading edge and trailing edge (sweep back angles) every half stroke (stroke reversal).

The analysis of this movement under the steady or quasy-steady theories would lead us to find that the continuity of propulsive force application could be stopped during the stroke reversal actions. This phenomenon has been analysed by biologists that studied the insects and birds flight finding that the conventional mechanisms (steady) simply do not provide enough lift for a flying insect to stay in the air (8). Delayed stall, rotational lift and wake recapture represent three distinct, yet interactive, mechanisms of unsteady lift generation which are necessary for flying insects to achieve the flight forces needed to support their weight and carry loads (21). An advance in biofoil rotation not only generates circulatory forces at the end of each stroke, it also increases the strength of the wake and ensures that the wing has the proper orientation to use the shed vorticity for generating positive lift at the start of the next stroke (21). It can be hypothesized that sculling actions observed in the figure 4 use the previously mentioned mechanisms. The movement is composed by four kinematic portions: two translational phases (insweep and outsweep), when the hands move through the water with efficient angle of attack (about 40°), and two rotational phases (pronation and supination), when the hands rapidly rotate and reverse direction. The *delayed stall* can be an addition to the forces generated during the hand translation with high angles of attack. Our observations demonstrated that big vortex is generated and de-attached after the start of each translational phase. During the stroke reversal and based in the *rotational circulation* mechanism (a specific application of the Magnus effect) it is necessary an early hand flip, before reversing the direction, then the leading edge rotates backward relative to translation and should produce an upward component of lift. Depending on the timing of the referred stroke reversal one can expect *cumulative Wagner effect* acting in attenuating the generated lift (19). One additional lift force can be obtained with the *wake capture*. The hand benefits from the shed vorticity of the previous stroke. If rotation precedes stroke reversal, the hand intercepts its own wake so as to generate positive lift. It is possible to argue in this case the swimmer's ability to extract energy from its own wake. What is also possible provided a sufficiently high Strouhal number is achieved is to produce wakes consisting on maximum backwards momentum vortices, as is frequent in animal swimming (29, 30). Using particle tracking on the wake of a hand stroke it is possible to delimit the regions of positive (anticlockwise) and negative (clockwise) vorticity on the plane of the laser sheet used. It is also possible to apply unsteady Kutta-Joukovsky theory to relate pressure and velocity measurements as discussed in Redondo et al. (39-42).

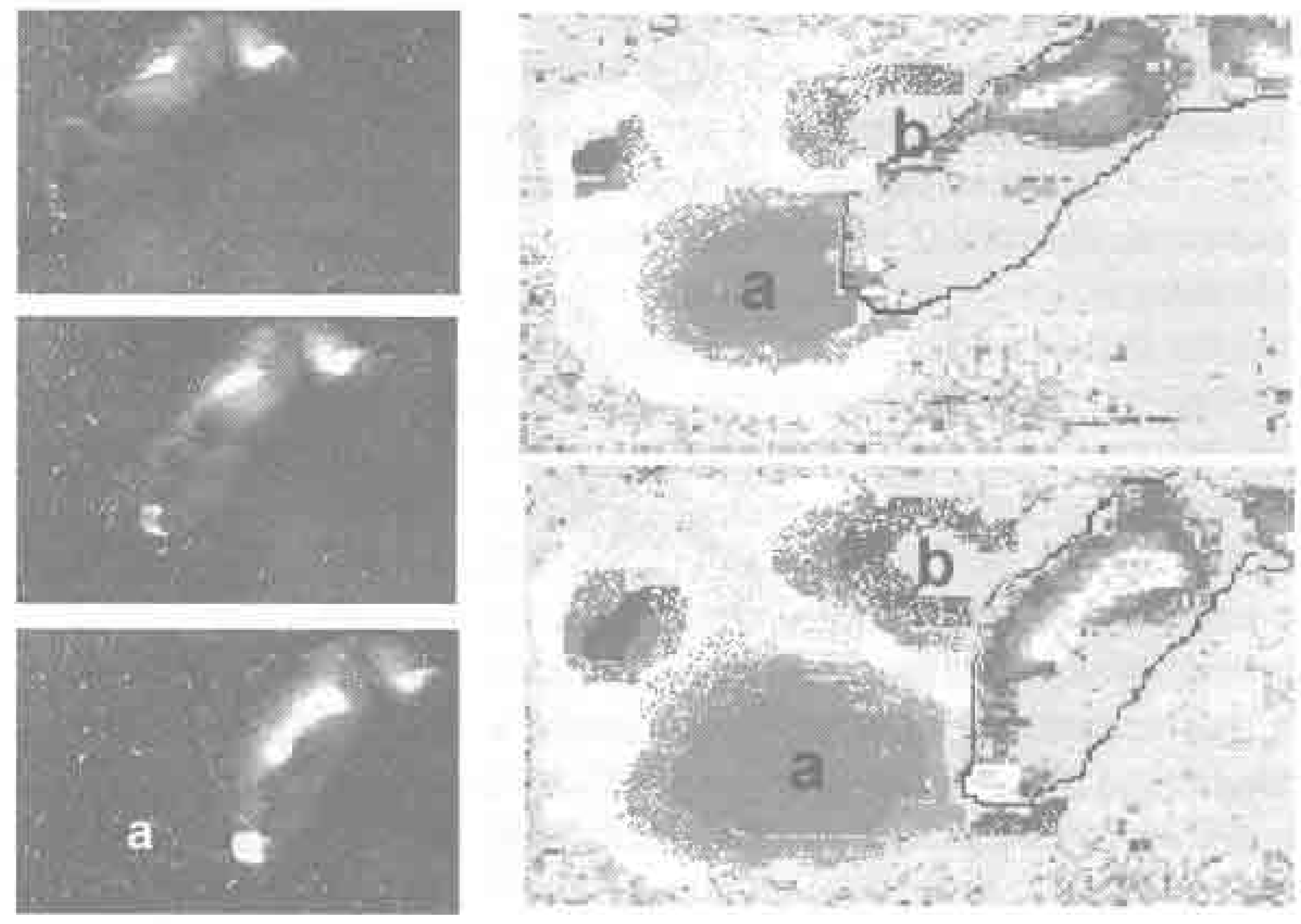


Figure 5: Trajectories of the seeded particles in an experimental tank as a hand stroke is performed. A vertical plane of laser light is used to film the wake at (50 Hz) left. Two maps of the vorticity are shown in the right images showing the shedding of positive (blue-b-) and negative (red-a-) vortices.

Hand drag coefficients obtained experimentally at different water speeds were related to the Reynolds number (Re) and compared with those obtained by Schleihauf, (45, 46), for a wide range of angles and speeds, which included the turbulent wake transition. The drag coefficient decreases when the Reynolds numbers increase near the transition with values of the drag and lift coefficients from 20° to 90°-sweep angle when Re is high [9.4×10^4] (39). The detailed analysis of velocity and vorticity balances in the wakes of swimmers limbs is still at large but figure 5 shows the strong dipole structure produced by a hand stroke (40).

CONCLUSIONS

The analysis of vortices generated and 3D analysis of the pulling path seems the most adequate method to develop a new understanding of swimming propulsion. The development of flexible and portable laser systems such as the recently incorporating fiber optics and fiberscopes, will enable the applicability of PIV in real swimming conditions to quantify the wake momentum and vorticity.

What may be obtained using an integral balance of the momentum and vorticity of swimmers wakes is the feedback necessary to obtain maximum propulsion, irrespectively if it is due to drag or lift projections of the limbs. This is clearly maximized when minimal balances of vorticity, which occur when coherent structures do not spread sideways, are coupled with maximum momentum and minimal energy. This is not an easy balance as demonstrated by a single vertical wake by Linden and Turner (30). For the simpler underwater undulatory swimming analysis on the Strouhal number on swimmers (4) shows that humans are still far from fish and dolphins, that obtain maximum propulsion at about St= 0.2-0.4, (50).

New and attractive ideas are emerging: the possible use by the swimmer to his advantage of the vorticity if it is produced by an external source, such as the environment (48), another swimmer or the re-use of his own vortices during the stroke or after the turn will be topics for research in the near future.

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INVITED CONTRIBUTION

ANALYSIS OF SWIMMING TECHNIQUE: STATE OF THE ART: APPLICATIONS AND IMPLICATIONS.

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INTRODUCTION
Methods of analysing motion have advanced greatly in recent years due to improvement in technology as well as application of scientific approaches. Methods of analysis may involve video based techniques from which kinematics and kinetics can be derived or direct measurement of velocity and force using various velocities and force transducing devices. At the Centre for Aquatics Research and Education (CARE) we have developed methods based predominantly on analysis of video. Analysis based on video ranges from qualitative analysis without quantification of variables, to three-dimensional analysis of kinematics and kinetics from digitised body landmarks from several cameras.
The purpose of this paper is to present video-based methods of collecting data, analysing data, and presenting results for different levels of analysis including qualitative analysis and simple quantitative analysis for immediate feedback, two-dimensional (2D) and three-dimensional (3D) quantitative analysis of kinematics, and deriving forces from the whole body centre of mass. Examples of specific applications and implications are described.

STATE OF THE ART FACILITIES AND EQUIPMENT
In 2000 a six lane 25m swimming pool was planned to accommodate research in aquatics, education and training in aquatics in the Department of Physical Education Sport and Leisure