Motion analysis in water sports

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Abstract

Historically the analysis of water based sports techniques has been isolated to the means of scientific investigation by a barrier. This barrier has been the water itself and it is only in recent years that the developments in technology have allowed a more scientific approach to the analysis of water-based activities. These activities include those within the water such as swimming and those on the water such as rowing, kayaking and sailing. This chapter will review how technology has aided the scientific analysis of water-based activities and how this technology has been used to develop the theoretical underpinnings of techniques, as well as being used as an integral tool for the performer in developing their own technique.

Keywords: kinematics, swimming, kayaking, hydrodynamics

1 Introduction

The medium of water has presented scientists over the years with problems in the design and implementation of analytical and experimental methods, which will enable an adequate evaluation of a performer’s technique. For the ‘dry-land’ researcher, methods have been developed that allow detailed qualitative and quantitative analyses of technique to be undertaken. Such methods have been invaluable to both the sport scientist and performer in understanding key components of technique. However, as a direct consequence of the nature of the environment, many methods of biomechanical analysis have not been directly transferable. Similarly, research in these fields has not taken advantage of the opportunities that developments in technologies have presented. This has meant that it is only within the last 5–10 years that researchers have made great strides into the understanding of water-based activities, in particular, swimming and kayaking. This chapter will focus on principles of technological development in these two main water-based activities.
2 Technology in swimming research

In swimming, particularly at the elite level, the major determinant of performance is technique [1]. Improvements in performance therefore are likely to be the result of recommendations made from a detailed understanding of technique. Early assessments of technique were through observation and intuition. Up until Counsilman’s 1971 paper [2] it was generally assumed (and coached) that swimmers should pull their hands directly backwards in a straight-line utilizing drag forces for propulsion. The application of film in swimming led Counsilman [2] to identify that skilled swimmers executed a ‘S’ shaped pull pattern in the front crawl. He inferred from this that lift forces could be generated by the hand in skilled swimming and that these forces could contribute to propulsion. As such a curved or ‘S’ shaped pull pattern was coached. This application of technology led to a significant change in the way swimming technique was viewed.

Over the past few years the evaluation of technique through methods or procedures that provide objective quantitative data has been at the forefront of much scientific research. Methods that have been used to evaluate swimming technique quantitatively include measures of velocity [3], acceleration [4], stroke parameters [5], power [6], the estimation of hand forces [7, 8] and swimming efficiency [9]. As technology has advanced the analysis and understanding of swimming propulsion has developed to the point where theories of propulsion commonly accepted only a decade ago are being challenged. What follows here is a brief history of how technology has shaped research and understanding of swimming technique.

2.1 The application of film

To date, arguably the most valuable tool available to the sports biomechanist has been the motion picture. Video (or cine, though rarely used) enables both qualitative and quantitative analyses to be undertaken. Certainly video has been used in almost all of the quantitative methods described above and today the use of underwater video recording is perhaps the most accessible method of technique analysis. Its use is facilitated by the fact that a frame rate of 25 Hz is sufficient to capture the swimming stroke which, compared to other sporting movements is relatively slow [10].

The quantitative assessment of swimming technique using video can essentially take two forms, two-dimensional and three-dimensional kinematic analysis. In most cases both approaches require a modification to the experimental set up because of the nature of the dual-media environment. When using standard video and digital video cameras, invariably they have to be set behind a transparent barrier of either perspex or glass (with perspex the quality of the image is reduced as a greater quantity of light is absorbed). Previous literature indicates that a variety of methods have been used for mounting and positioning cameras used in the evaluation of swimming technique.

A limited number of studies have used cameras placed on the pool-side or in some way suspended above the swimmer e.g. Ref. [11]. This method is almost exclusively reserved for quantitative assessments of variables such as average
swim speed, stroke frequency and stroke length, particularly for assessments made during competition races [1].

It is reasonable to assume that kinematic measures of stroke technique which occur during the recovery phase of front crawl can adequately be measured by a pool-side camera. Such variables can also give valuable information on the overall effectiveness of a swimmer’s technique. For example, stroke length is a function of the propulsive and resistive forces exerted on a swimmer [12] and has been identified as being an important factor in determining performance [1]. Of course the first two phases (block time and flight time) of the race starts can also be adequately evaluated using a pool-side camera.

Using a pool-side camera to measure underwater variables cannot be deemed sufficiently accurate. The combined effects of refraction at the water’s surface and wave turbulence created by the swimmer make the following path of the hand almost impossible. The filming of the underwater stroke has been achieved by a number of different protocols. Underwater housings provide a cheap and portable method of gathering underwater video. Their widespread use in underwater photography has been well documented since the first underwater housing introduced by Louis Boutan in the 1890s, illustrated in Figure 1 [13].

![Illustration of the underwater housing used by Boutan in the 1890s and the method he used to manoeuvre it. (Copyright Dobbs (1962) reprinted with permission.)](image)

**Figure 1:** Illustration of the underwater housing used by Boutan in the 1890s and the method he used to manoeuvre it. (Copyright Dobbs (1962) reprinted with permission.)
From the literature it seems that the construction of the housing is dependent on its purpose and the size of the camera, which is placed in it. Lauder et al [14] used a housing constructed of perspex and fixed to the pool-side to film underwater movements in a direction towards the camera (Figure 2). Variations on this have been developed for individual purposes and, although details are rarely reported in the literature, the general construction is the same. The camera is mounted behind a glass or perspex sheet or a dome port hole. Other examples include housings that allow a panning technique to be used and housings that are fixed to run on tracks down the length of the pool. The ease with which such housings can be installed and transported has led to an increase in their use for swimming research over recent years.

Another approach makes use of underwater windows. Underwater windows were initially used for observation of swimmers’ techniques. With the introduction of cinematography in swimming research there has been an increased use of underwater windows for filming rather than observation. A large number of studies have used underwater windows and many new pools, especially those used specifically for research, have underwater windows installed as part of the design. One limitation of underwater windows though, often owing to their location, is that they have a limited flexibility. Particularly for three-dimensional analyses, when ideally the windows should be positioned orthogonally to one another.
Periscope systems have also been used for filming the underwater movements of the swimmer [15]. The idea was first introduced in a presentation to the First International Symposium on Swimming by Dal Monte [16]. Hay and Gerot [17] much later presented a technical note on ‘distortion-free’ periscope systems for recording underwater motions of the swimmer. The basic design enabled the camera lens to be held vertically downwards, a mirror and mirror support system that reflects the image of the swimmer’s movements up to the camera and a wave deflector to stop surface wave distortions caused by the swimmer’s motion. Periscope systems are still in use today, however they do not directly deal with the effect of refraction at the air–water interface and it has been suggested that they severely limit the field-width [18].

The problem of refraction is not only limited to the use of periscope systems. Recordings of motion through underwater housings and underwater windows are also subject to the effects of refraction, as invariably there is an interface between the camera and object of materials with different refractive indices.

Refraction at a flat surface is readily understood on the basis of Huygens’ Principle [19]. If light travels from a less dense medium to a more dense one (e.g. air to water or water to glass) its speed is reduced. The effect of this when light rays strike the interface at an angle is defined by Snell’s Law as given below.

\[
\sin \phi n = \sin \phi' n' \tag{1}
\]

Where \( n = c/v \) and \( n' = c/v' \)

\( c \) is the speed of light in a vacuum \( v \) and \( v' \) the speed of light in the respective mediums.

It was this relationship that McIntyre and Hay [20] used to produce their transformation equation for dual media filming. The problem is that the light rays invariably travel from water to glass (less dense to more dense) and then from glass to air (more dense to less dense), thus being refracted twice. Therefore, any transformation equation for matching underwater and ‘in air’ objects should take into account the refraction at each surface. Practically the effect of refraction can be corrected by assuming that the object plane is perfectly aligned with the interface between the media. Based on this assumption, it is possible to calculate object coordinates in the water with the use of two cameras. These methods have been used in photogrammetry to map underwater objects [21].

The key condition that arises from dual-media research is that the camera lens and the refracting surfaces should be perpendicular to one another. The same condition should be met for three-dimensional reconstructions using the Direct Linear Transformation (DLT) algorithm [22], where the conditions of co-linearity and co-planarity have to be met. If a flat sheet of glass (or a dome) was placed in front of the lens to form the air–water interface, it essentially becomes an element of the lens itself. Theoretically the ‘outer element’ can be placed such that the problem of refraction is eliminated. In practice, this is not
readily achievable [23]. Therefore, by placing a video camera arbitrarily behind a sheet of glass or perspex, as in an underwater housing or behind an underwater window, a direct violation of the co-linearity assumption of the DLT algorithm occurs. The overall effect is that there is an added level of distortion to the image. If the optical system contains many refracting (or reflecting) surfaces, it should be assumed that the level of distortion increases.

Two approaches exist that could be used to correct for refraction, a mathematical approach and a physical approach. Walton [23] essentially presented the first physical method to correct for the effect of refraction where the image is viewed in both media. The solution was to place a semi-circular dome in front of the camera lens and to align the optical axis of the camera lens with the centre of curvature of the dome. The procedure then was to visually correct for refraction by changing the distance between the lens and the dome until the effect of refraction had been removed from the image. The image used for this procedure is illustrated in Figure 3 below [23] and consisted of vertically aligned ‘stripes’. When the image was affected by refraction the stripes do not align but when the refraction has been corrected the stripes do align.

This is due to the dome essentially forming part of the lens as the incident node of the lens is coincident with the geometric centre of the dome. Although the author described the method for correcting for refraction he did not state if the proposed method was for correction of split media filming, i.e. above and below the water simultaneously (as indicated by the figure above) or for correcting solely underwater images where the plane glass is replaced by the domed glass. In the evaluation of the method only a written description of the tests was provided. The author indicated that the method correctly recovered valid ‘three-dimensional trajectories, correct limb lengths and several kinematic variables’. Unfortunately no data or specific methods were presented in the paper, so the accuracy of the method cannot be directly compared to other research on accuracy.

Reinhardt and Walton [24] and Reinhardt [25] used the methods of Walton [23] to correct for refraction in studies determining the range on motion of space
suits tested in an underwater environment. The procedure utilized ExpertVision, developed by Motion Analysis Corporation; an accuracy of $\pm 2.5$ mm was reported for a three-dimensional reconstruction of trajectories. This accuracy seems comparable with results from studies conducted in air, and the physical method of correcting for refraction is promising, particularly if incorporated into the design of underwater housings. Unfortunately the method does not account for the effect of refraction at plane glass underwater windows, which are more commonly used in underwater filming studies.

The only other study to investigate the effects of experimental set-up where filming occurs through a glass barrier is that reported by Lam et al [26]. These authors sought to determine the effects of various parameters relevant to test conditions on the calibration and accuracy of a video dimension analyser (VDA) used to assess strain in soft connective tissues. The set-up uses high-speed film to measure displacements on the surface of the connective tissue by digitizing markers placed on the surface. Typically soft tissue is mounted in a test apparatus and the surface of the tissue stained with parallel dye-lines. The surface is viewed through a TV monitor and an electronic dimension analyser places two ‘windows’ on the image. These windows are placed over two dye-lines and the apparatus scans the edges of the dye-lines when the tissue is put under strain. A timer records the time between any two edges which pass the windows. The scan time is converted to a voltage which corresponds to the distance between the two edges. Previous investigations into the accuracy of these systems [27] had shown that the calibration of the system was linear (voltage output against linear dimension) when the media filmed through were air and glass.

Lam et al [26] considered three further parameters. The first was to vary the distance between the object (tissue) and the lens, the second to show the refractive effects of the glass and physiological solutions and, finally, the dynamic response of the VDA. The experiments were carried out in two groups, a series of static experiments and a series of dynamic experiments. To evaluate the first parameter, three object distances were used (175, 230, 300 mm) and the results were reported as least squares regression lines for each distance showing the slope and intercept. The refractive effects of the set-up were shown through two experiments. One used a standard object distance of 175 mm and filmed the tissue under three conditions, just the object and lens, the object, glass and lens and finally the object, glass and water. The last static test consisted of the same object distance but the angle of incidence between the lens and the object was varied ($0^\circ$, $10^\circ$ and $20^\circ \pm 0.5^\circ$); one other set-up of 230 mm and $10^\circ$ was also reported. For the dynamic tests an Instron testing machine (Instron 1122, Canton, MA) was used to create a dimension that changed continuously with time. The experiment consisted of 10 trials of 0.1 mm simulated tissue displacements between 5.0 mm and 5.1 mm and then repeated 0.1 mm displacements up to 5.7 mm. The rate of displacement was 10 mm min$^{-1}$. All results were reported as best-fit regression lines giving the slope ($a$) and intercept ($b$).

The results showed that, for all parameters, increases in slope (voltage against linear dimension) occurred with increase in the size of the object. The VDA
system works on the basis that the line passes through the origin, i.e. the intercept is zero. The results for all experiments showed this not to be the case. The authors undertook an error analysis to investigate how sensitive error was to the parameters of the experimental set-up based on the slope and intercept of the line, the initial length $L_0$ and a standard deviation of the voltage from the regressed value (VDA output). The analysis showed that the error was sensitive to camera placement and orientation as well as the media through which the object is observed. The authors suggested that one way to reduce error would be to maximize the image size on the screen, by decreasing the object distance or increasing the magnification (presumably through changing the focal length of the lens or changing the curvature of the glass barrier). Suggestions that the larger the control length as a proportion of the screen, the more accurate the results, were mediated with warnings that field width is constrained by practice. Similar recommendations for filming analysis have been made previously [28]. Unfortunately the implications of the results were not fully discussed and the reader was left to interpret the significance of the experimental set-up on error. It would appear that, for any such set-up, one should determine the error associated with that set-up before undertaking the test; something that hopefully constitutes good practice.

Refraction could restrict the experimental method that may be used to assess the accuracy of underwater filming owing to a limiting factor termed the critical angle ($\phi_c$). The critical angle defines the maximum angle at which incident rays will be refracted. Outside $\phi_c$ all incident rays will be totally reflected. In defining the experimental set-up, therefore, the critical angle becomes important when assessing the influence of object–glass–camera distances on accuracy.

Lauder and Dabnicki [29] and Lauder et al [30] used a scaled down underwater environment to investigate the effect of changes to the experimental set-up, on the accuracy of two-dimensional and three-dimensional reconstructions from underwater video analysis in order to provide an assessment of physical solutions to the accuracy problem. The experimental set-up used an overhead runway to control camera (Figure 4) and calibration object (Figure 5) positioning relative to the refractive surface. In a series of experiments the researchers sought to establish the influence of experimental set-up on the level and distribution of error in underwater three-dimensional kinematic data using a scaled-down environment and the influence of the frequency of the movement on accuracy and the criteria for filtering technique that should be adopted. The main objective was to provide practical solutions to improving the accuracy of underwater kinematic data collection.

It was found that, the position of the camera and the calibration object relative to the glass interface influenced the level of error, in the reconstruction of known lengths. The results provided evidence that there was a need for an augmented calibration procedure, in order to minimize the influence of unaccounted random errors, in underwater video analysis that uses underwater windows/housings. The research highlighted that the position of the object within a calibrated volume influences the accuracy of underwater data collection. Similarly it was
highlighted that there was an error associated with underwater filming due to turbulence. In research that used a controlled motorized rotating arm (Figure 6) with fixed rotation at different movement frequencies, it was noted that the variability in angular measurement of a dynamic movement was greatest at the fastest frequency of movement tested (1.25 Hz).

Figure 4: Experimental set-up used to evaluate error in underwater kinematic analysis [14].

Figure 5: Illustration of calibration frame used in underwater three-dimensional analysis.
Some work has also been done on data conditioning in underwater kinematic analysis. Smoothing and filtering techniques are commonly assessed by evaluating the %RMSE between the true signal and the calculated values [31]. This criterion can be employed to enable comparison of second derivative estimates across studies and can be calculated from a common formula [32].

\[
\text{%RMSE} = 100 \left( \frac{1}{n} \sum_{i=1}^{n} (X_{ci} - X_i)^2 \right) \left( \frac{1}{n} \sum_{i=1}^{n} (X_{ci})^2 \right) \]

where \( n \) is the number of data points, \( X_{ci} \) the \( i \) th value of the criterion signal and \( X_i \) is the \( i \) th value of the estimated signal.

In the evaluation of smoothing techniques in underwater analysis Lauder et al [30] used five separate methods to smooth and differentiate a raw data series of angular velocity using Peak Motus 32 Software (version 2000) and Biomechanics Toolbox [33]. Due to built-in limitations of the Peak Motus Software a cut-off frequency of 3.6 Hz [34] was not possible and consequently rounded to 4 Hz. The five separate methods were:

1) A 4 Hz cut off frequency that falls within the studied range by Yu et al [34].
2) Second order automatic Butterworth low-pass digital filter (Bwauto).
3) Fast Fourier transformation (FFT) with a cut-off frequency of 6 Hz [35].
4) Cubic spline (CS) with an automatic smoothing parameter determined by the software.
5) Quintic spline (QS) with the smoothing factor determined by minimizing %RMSE of the residuals between the calculated angular velocity and the criterion angular velocity [36].

The results (Figure 7) highlight the filter that responds best in an underwater environment. In front crawl swimming the underwater arm motion is a relatively slow, cyclic action yielding non-zero accelerations at the record boundaries. The mathematical underpinning of QSs is best suited to the type of action inherent in swimming [37] especially when large deviations in the level of random noise are apparent. This finding is not surprising as QS criteria are based on a weighted combination of weighted derivatives from nil to second order. As movement in swimming is inhibited by the water resistance it yields smooth acceleration curves allowing highly accurate first order derivatives.

The generation of turbulence in the underwater stroke can be related to the frequency of the movement. The internal friction of a fluid causes a resistance to the motion of an object moving through it, which is proportional to the gradient of the velocity. Increasing velocities influence the laminar boundary layer around

Figure 7: Comparison of the %RMSE between the true and estimated angular velocity are presented for both the clean and noisy data sets after filtration/smoothing.
the front of a moving object causing a transition of the laminar flow to a turbulent one \[38\]. Turbulence in underwater analysis severely distorts the image of the hand. The frequency of the movement therefore, becomes an important consideration when assessing error due to the relationship between the frequency of the movement and the creation of turbulence. Lauder and Dabnichki \[29\] Lauder \textit{et al} \[30\] demonstrated the problems associated with the reconstruction of kinematic data in underwater video analysis.

Why is it important to address refraction? Well, as technology has advanced, so have the kinematic techniques available to analyse technique. If these techniques are to be applied correctly, then the refraction problem must be addressed. More recently, Kwon \[39\], Kwon and Lindley \[40\] has addressed the issue of refraction through extensive studies that model refraction and which adopt a mathematical approach to the solution. With the development of kinematic analysis packages that have the functionality to use algorithms to correct for distortion due to refraction, the practical solutions described above appear redundant; however, the best possible image must still be available for use in the analysis of swimming technique. At present there exists no method of kinematic analysis that can reliably be used to assess technique in swimming that does not use the recorded image of the technique.

The use of the DLT algorithm in three-dimensional analysis of the swimming strokes is widespread e.g. \[41\]. Payton and Bartlett \[42\] conducted a study on the reliability of kinematic data from three-dimensional video of a swimmer’s stroke, which was used to estimate propulsive force. Propulsive forces are important determinants of swimming performance and the accuracy to which they can be estimated through digitizing procedures should be considered when addressing this issue. The results from this study indicated that inter-tester differences in locating the four points used to define hand orientation produced a mean error in pitch angle and sweepback angle of 1.8° and 2.1° respectively. The propagated error in the calculated resultant force was 8%.

Lauder \textit{et al} \[14\] expanded this work in a study which sought to establish the accuracy and reliability of current and newly proposed procedures for the reconstruction of hand velocity, sweepback angle and pitch angle from underwater three-dimensional video analysis. A full-scale mechanical arm capable of simulating a controlled and highly repeatable underwater phase of the front-crawl stroke was filmed and for a set of five trials. A seven-point model of the arm and hand was then digitized at 25 Hz. Hand velocity, sweepback angle and pitch angle were calculated using the procedures of Schleihauf \[43\], Berger \textit{et al} \[7\] and a newly proposed procedure (Lauder). Statistical comparisons were made between procedures to establish their relative accuracy and reliability throughout the stroke. The mean absolute error in measurement of hand velocity between points on the hand was very small (±0.04 and ±0.06 m s\(^{-1}\) in the x and z directions, respectively). The mean errors in sweepback angle and pitch angle were respectively: 9.3° and 7.6° (Berger), 10.1° and 8.1° (Schleihauf) and 10.7° and 7.0° (Lauder). Agreement between procedures showed the standard error between Schleihauf and Lauder to be the least (Schleihauf and Lauder, 0.4°; Berger and
Schleihauf, 1.3°; Berger and Lauder; 1.6°). The use of four points in the reconstruction of the orientation of the hand (Schleihauf and Lauder procedures) was shown to be less sensitive to errors in the digitizing procedure. The reconstruction procedure proposed in this study (Lauder) further reduced the sensitivity to digitizing error in the reconstruction of sweepback and pitch angles in swimming. It is important to remember that all kinematic variables discussed so far have an impact on the evaluation of technique in swimming.

Propagation of errors is an important consideration in any biomechanical analysis and due to the underwater environment, measures to reduce the error are essential if technique is to be adequately described. The lack of research in the literature suggests that swimming researchers have not been as concerned with the accuracy of their methods as have researchers of ‘dry land’ activities [31, 44]. The explanation for this could lie with the nature of the environment. Water makes the control of variables somewhat more difficult than air. This could explain why the problem has received very little attention in the literature. Similarly, advances in technology relating to kinematic analysis, such and on-line motion analysis systems, have not addressed the analysis of the underwater stroke. Such techniques and systems have exclusively been developed to address the analysis of techniques in the laboratory. If swimming kinematic analysis is to advance, new techniques of image analysis need to be developed beyond the relatively simple, yet time consuming, manual digitization process. Recent developments in shape recognition offer some hope to this, yet this technology is developing and it will be some while before it is commonly used in ‘dry-land’ analysis of sports activities, yet alone applied to the underwater environment.

2.2 Other motion analysis techniques

Accelerometry provides one method of motion analysis that can be applied to swimming. As technology has become more miniaturized, opportunities to evaluate movement patterns through accelerometry have arisen. Ohgi et al [45] presented a miniaturized accelerometer contained within a waterproofed wrist watch. The device contained two monolithic bi-axial acceleration sensors (ADX250, Analog Devices Inc.), each sensor recording accelerations up to 50 G. Recording swimming strokes, the researchers were able to distinguish phases of motion within the swimming cycle (verified through video analysis). Although the technique was shown to give reliable profiles, its main application would be in monitoring of technique profiles for an individual swimmer and therefore having a direct coaching application, particularly as wireless advances could lead to a ‘real-time’ logging application.

2.3 Kinetic analysis

The accuracy of kinematic data is important not only for defining or characterizing technique but also as input data for the control of mechanical and
computer models. Kinematic data have been used in models, which attempt to assess the propulsive forces generated by the hand [46], forearm [7] and hand and forearm [8, 47] in swimming.

The measurement of hand forces has produced much interest in the assessment of swimming technique. Schleihauf [43] concluded that the hand was the 'single most important contributor to propulsion in the arm stroke'. Three major methods have been established for hand force estimation. The first direct method uses pressure sensors located on the hand to estimate hand forces directly [48]. This method was shown to be ineffective due to changing conditions of hand motion and orientation during the stroke. The second method, hydrodynamic analysis, is the combination of underwater three-dimensional film of the swimmer's technique and hydrodynamic lift and drag force coefficients for the hand obtained from laboratory experiments. The accuracy of the latter method is dependent on the accuracy of the kinematic data from the underwater three-dimensional video film and the accuracy of the drag and lift data obtained from hydrodynamic experiments using hand and arm models in static positions moving at constant velocities (quasi-static approach).

Hydrodynamic forces in swimming are dependent on two important effects associated with an immersed accelerating segment, namely vortex shedding and added-mass effects [49]. The testing protocols that have previously been used to obtain lift and drag coefficients ignore these effects, adopting the quasi-static approach. This has been shown to give different lift and drag profiles when compared to fluid conditions of unsteady flow, which are similar to those experienced in swimming [50]. Could it be then that the quasi-static assumption fails? Recently this problem has been addressed in insect flight [51] showing that extra lift from a leading edge vortex was sufficient to carry 2/3 of a Hawkmoth's weight, while the impulse from two ring vortices left in the wake of the movement was equivalent to 1.5 times the body weight of the insect. There has been limited research on flow visualization in swimming and a study reported by Toussaint et al [52] suggests that vortices may exist in swimming. Toussaint et al [52] showed that during the upsweep of the front crawl stroke a tip vortex, very similar to the three-dimensional leading-edge vortex described by Berg and Ellington [51] for insect flight, was exhibited along the leading edge of the hand (i.e. little finger side). It was concluded that more visualization studies are needed to substantiate their findings.

Both Schleihauf [43] and Berger et al [7] used a quasi-static approach to obtain hydrodynamic data for an immersed hand and immersed hand–forearm respectively for modelling hydrodynamic forces in front crawl swimming. Wood [53] applied a similar approach. However, lift and drag data were obtained from wind tunnel experiments. Recently, Sanders [35] used a quasi-static approach to determine velocity and acceleration coefficients for a swimmers hand, accelerating in the direction of flow. Using an approach similar to Schleihauf [43], he produced three-dimensional surfaces describing the magnitude of the coefficients as functions of pitch angle and sweepback angle, the acceleration coefficients reported, being in the order of 6% of the velocity coefficients. Sanders concluded that the
inclusion of acceleration coefficients was necessary for the accurate modelling of hand forces in swimming. Although the study begins to address the issue of unsteady flow conditions generated by an accelerating object, the reliability and the accuracy to which the kinematic parameters of velocity and acceleration can be measured, was not addressed. This must, therefore, raise questions as to the applicability of such coefficients to the accurate estimation of hand forces. These are the only studies that have published hydrodynamic force data for the hand–forearm. The relatively steady flow conditions created in these studies do not readily transfer to the flow conditions that are experienced in swimming. The hand in skilled front crawl swimming constantly changes its angle of attack and sweepback angle with respect to the water. It also accelerates, thus experiencing unsteady flow conditions. Similarly the movement of the forearm and upper arm could be expected to influence flow conditions. It would be expected, therefore, that the lift and drag profiles in swimming would be different from those obtained in the models of Schleihauf [43] and Berger et al [7]. These authors used force transducers positioned a distance away from the hand and arm model to measure the hydrodynamic force at the hand. This method would seem to measure a force proportional to rather than equal to the hydrodynamic force exerted by the hand on the water.

Recently, propulsive forces in swimming measured by the quasi-static approach have been compared to measures of active drag, measured by the MAD system [9, 54]. The main principle applied in these studies was that, at a constant swimming velocity, the mean propulsive force would be equal to the mean drag force acting on the body of the swimmer. The results from Berger et al [54] showed that the mean difference between the two measures was 5%, concluding that the kinematic approach could be used to estimate contributions of lift and drag forces to propulsive force [54]. The earlier study however [9], found that the kinematic approach was unable to estimate propelling efficiency. Berger et al [9] defined efficiency as the contribution of lift forces to propulsion; increased efficiency resulting from a greater contribution from lift forces to propulsion. The authors concluded that the generation of vortices in swimming may play an important role in propulsion.

To advance the knowledge in this area Lauder and Dabnichki [8] developed a direct approach to solving the problem. To obtain reliable data on propulsive forces in front crawl swimming, a mechanical model of the whole arm was developed that simulated the dynamic action of the arm in the front crawl stroke and measured the force profile throughout the stroke. The arm model was used to compare the quasi-static approach to the direct measurement of force. If the quasi-static theory was correct, then the torque profiles measured directly on the arm would be the same as the profiles calculated by the quasi-static approach.

The mechanical arm was shown to produce a controlled movement pattern, which was reliable and accurate to within ±1° for repeated trials and ±2.3° across different trials. The shoulder torque measurement was also shown to be reliable and accurate to within ±1.22 N m, over a range from 0 N m to 70 N m.
Differences in torque profiles for the quasi-static approach and the direct measurement of shoulder torque (Figure 8) indicated that the quasi-static approach might greatly underestimate the hydrodynamic forces acting on the arm during swimming. The results showed that the relative contribution of the hand to the propulsive force is dependent on the arm configuration. They cast some doubt on the widely shared assumption that the swimmers’ hand is always the main contributor to the propulsive force. Due to such an advance in the application of technology to the analysis of technique in swimming, the theoretical underpinnings of propulsive force estimation have been re-written.

Work has been taken further forward with the advances in computational ability. Very recently the use of Computational Fluid Dynamics (CFD) to model the propulsive forces generated by the hand and forearm has been introduced [55]. This approach offers some benefits in terms of the ability to run a number of simulations, which otherwise might be costly through experimental techniques. However, the problem of simulating unsteady flow conditions remains. Bixler and Riewald [55] replicated force coefficients for the hand and forearm that had been determined experimentally [7, 43], an important first step in the use of CFD techniques to solve the problem, but concede that simulation of unsteady flow conditions presents a greater challenge.

This challenge has been addressed in some part by Gardano and Dabnichki [47] in a paper that addresses the estimation of added mass effects due to acceleration of the arm in swimming. The authors adopted a Boundary Element Method to solve Laplace’s equation resulting in a much quicker way to solving hydrodynamic problems than CFD techniques. The results showed good agreement
between the calculated drag profiles and the direct drag profiles from Lauder and Dabnichki [8].

2.4 Swimming summary

In summary, motion analysis in swimming has been slow to implement the technologies that have become available to the single media researcher. There has been recent work validating and improving the application of kinematic techniques to the analysis of swimming technique, but this work has also led to the re-evaluation of the mechanisms of propulsion in swimming. Since Counsilman’s observation of an ‘s’ shaped pull pattern in 1971 through motion analysis and the subsequent theory applied to lift and drag force generation, it has been over 30 years until the technology has been applied to re-evaluate this problem. Work is on-going in this area as researchers establish the importance of added mass effects and the acceleration of the arm. The problem remains though; the barrier to research due to the environment in which the activity takes place.

3 Technology in kayaking research

3.1 Introduction

The origins of the kayak date back more than 4000 years [56]. Now a range of disciplines undertaken by paddlers is evident and include white water, slalom and flat-water. Again due to the nature of the environment, there is little technology applied to the analysis of slalom and white water kayaking, with scientific analysis usually taking the form of simple timing of phases of activity based on strokes and entry/exit from gates. The flat-water event however has received some scientific attention and will form the focus of this section.

Flat water kayaking involves many different events ranging from a 200 m sprint to a 26 mile marathon. In all events the paddler must simultaneously balance the boat while applying force to the paddle in order to propel themselves and the boat forward. Technology has been able to assist in the understanding of what makes this process efficient in two ways; through a kinematic analysis or through a kinetic analysis (in some cases, both approaches have been applied). Technological advances have allowed research to develop in the areas of kayaking technique [57–59], paddle design [58] and on-water force analysis [60].

3.2 Analysis by film

Kayak technique has been greatly influenced by the change in paddle design from a flat blade to a wing blade. The technique has had to adapt to incorporate the principles of the new blade. Kerwin et al [58], Sanders and Kendal [61] and Sanders and Baker [62] all identified that the blade is moved laterally away from the centre line of the boat after entering the water, as opposed to the flat blade being pulled parallel but opposite to the direction of travel.
Average boat velocity is a key determinant of success in kayaking. Kendal and Sanders [63] found that the average velocity ranged between 4.63 and 5.38 m s\(^{-1}\). With high-speed cameras (100 Hz) it was possible to also identify that the two sides of the body did not elicit the same velocity profiles, indicating that the forces produced by the kayaker may be asymmetrical. Asymmetry in the kayak stroke has also been highlighted by Lovell and Lauder [64] in a study investigating the relationship between the incidence of injury and stroke asymmetry. Asymmetry in this instance was measured using an instrumented kayak ergometer.

An early study by Plagenhoef [57] was one of the first attempts to quantify technique. Using cine film, Plagenhoef [57] collected footage from a side-on view at film speeds from 64 to 100 frames per second. From the footage the joint centres and the absolute motion of the paddle was measured, using the cockpit and kayak lengths to establish scale. Plagenhoef [57] identified that during performance an increase in stroke rate was not the influential aspect of improving velocity and that instead it was a smooth rhythmical stroke that allowed the greatest force to be applied through the blade on to the water, resulting in a higher constant velocity.

Sanders and Kendal [61] investigated the differences in technique between elite and novice paddlers using the wing paddle. Using three-dimensional footage at 100 Hz, the trajectories of the joint centres from the hip and above and the motion of the paddle were measured. The results showed that the most important factor in determining average boat velocity and ability level was the stroke rate. They also showed that the determining factor between elite and novice paddlers was that the elite paddlers exhibited a much shorter glide and pull time than the novice paddlers. By applying a two-dimensional kinematic analysis to the stroke cycle in sprint kayaking, it was possible to show how elite paddlers produce a faster stroke rate by reducing the pull and glide phases of the stroke. Such work has also been supported by Kerwin et al [58] who, using a three-dimensional on-water analysis, identified that an increased paddle rate resulted in increased average boat velocity.

Technology in sprint kayak research has primarily been used as a tool to be incorporated into the coaching of race tactics [65] and kayaking technique [60]. Lauder et al [65] presented a simple approach to the analysis of key events in kayaking. The simplest form of notational analysis is the recording of the sequence, position and frequency of events. An ‘event’ is simply any object or happening of interest. Computer systems can be used to gain such information and since digital video technology and multimedia applications are now a reasonably mature technology, it is possible to develop a bespoke application to log and analyse simple notational data. For Sports Scientists, such an application is particularly useful outside the laboratory environment where speed of delivery and accuracy are two very important factors in the feedback process. In sprint kayaking (and rowing), stroke frequency and stoke length are important factors that coaches use to analyse and monitor performance. There exist simple measures of each; however there is a need, particularly at a top level, for quick and accurate measures of these factors.
The highest quality video images are obtained from equipment that conforms to the component signal standard. Such equipment is very costly and it is prohibitive to many. The availability of VHS, S-VHS and Mini DV digital video formats is widespread and cost continues to fall. Domestic video equipment provides the user with position information by using the frame interval signal on the tape to index an internal counter. This value, as it is a simple counter, resets whenever the tape is removed and is not considered a viable option for recording time. Many video recording devices, for example the Panasonic 7350 (IA-232 TC Interface), use one of the audio signal tracks to write a time code signal to the videotape. This signal is permanent, or absolute, and so can be used to find video sequences even if the tape is removed from the VCR. In a digital package the software uses the frame as the unit of time (i.e. 0.04 second increments at 25 Hz and 0.02 second increments at 50 Hz). This approach is important due to the ease of downloading digital.

The basic package developed was an integrated system, comprising various software and hardware components. The desktop VHS/S-VHS package incorporated the interfacing of a Panasonic AG-7350 through an RS232 serial port, technology that is available to most sport science laboratories. A video desktop was accomplished using a capture board utilizing the Microsoft Windows Multimedia Application Programming Interface (MMAPI). The interface allowed the full control of the VCR thus enabling a hands-free approach in identifying and recording clips.

The digital package used by the British Canoe Union Sprint Kayak Squad utilizes the IEEE 1394 interface built into the Sony range of VAIO notebook PCs and a MiniDV camcorder. Replay of video (AVI) files was achieved digitally via a custom Multimedia player designed in house. This system allowed the de-interlacing of 25 Hz video frames into separate 50 Hz fields.

The desktop VHS/S-VHS notation package had a three-tier approach. It allowed the user to identify and mark clips of interest (ten), name events (25 per clip) of interest and record the occurrence of these events (2 billion for each event) at the speed of playback desired (Figure 9). The programme then allowed the user to plot the frequency data or export the data for further analysis (Excel). Figure 10 illustrates the screen for the graphical output within the package while Figure 11 illustrates is a screen shot of the desktop package itself. The desktop package also allowed clips to be captured and stored to the hard drive for feedback purposes and for clips to be captured for two-dimensional digitization.

The digital package, used by the BCU, offered a more specific application. This package allowed any number clips to be stored (to hard drive) and accessed for analysis. There was only one event option in this package, which gave a direct measure of stroke frequency. The recording of an event was achieved by clicking anywhere on the image, this making it easy to analyse and record specific events.

Figure 12 illustrates the screen for the DV package. The graph of stroke frequency was reconstructed on the screen as the analysis progressed. Once the
Figure 9: Control screens for notational analysis package.

Figure 10: Example of screen window for frequency graphs.
Figure 11: Screen shot of desktop package.

Figure 12: Screen shot of DV package.
analysis was complete, there was the option to change the number of samples over which stroke frequency was calculated. The data was then linked to the video clip analysed and to an athlete profile. The latter option allowed profiles of different races to be compared. Although a simple approach, many sports utilize bespoke analysis packages to gain valuable information relating to performance. As technology has progressed, so has the ability to provide real-time data relating to the event. Such advances have no-doubt contributed to a better understanding of performance by the athletes and coaches.

From a coaching perspective and in an attempt to look at the differences between male and female paddlers Baker et al [59] analysed ten national level paddlers (six male, four female) using a three-dimensional kinematic analysis at 50 Hz. Baker et al [59] analysed left and right sides looking at intra-stroke velocities, timing and displacement measures, two and three dimensional measures of the entry and exit angles, and trunk rotation (represented by shoulder rotation). The findings indicated that there was a significant difference between males and females in velocity and intra-stroke velocity resulting in a significant difference in distance covered during stroke and glide. No difference in spatial parameters however highlighted that male and female techniques were similar and therefore there was no need to coach males and females differently.

With any kinematic analysis in kayaking, perhaps the most important factor to be considered is the accuracy and reliability of the kinematic reconstruction. For two-dimensional analysis it is possible to use the kayak itself as the calibration length. It is necessary to follow two-dimensional set-up procedures [37] in order to maximize the accuracy of the two-dimensional kinematic data, but such analyses have been conducted successfully [62]. Three-dimensional analysis provides a different problem as there is a need for a calibration object in the field of view. Kerwin et al [58] used fixed cameras and calibration markers in the field of view, but not in the line of the kayaking action. They reported limited results, however showed their reconstruction technique to be accurate in reconstructing upper body three-dimensional profiles. Hay and Kaya [66] used a fixed camera on a motor boat that ran alongside the kayaker to elicit kinematic data. While this allows a number of strokes to be analysed, the data is limited to two-dimensional parameters. For a three-dimensional analysis a calibration frame is required. Figure 13 illustrates a floating calibration frame (5 m × 2.5 m × 1.8 m), which allows a complete stroke to be captured within the volume. The calibration frame illustrated can be positioned on the water in the area where the action will occur, a key requirement of a three-dimensional calibration set-up.

On-water kinematic analysis of techniques presents similar problems for the research as underwater kinematic analysis. The environment presents the researcher with problems of camera location and calibration techniques. Often, specialist equipment set-ups are required, particularly if three-dimensional analysis is to be undertaken. These problems can and have been overcome, but there are very few researchers working in this area, not through lack of interest, but more so through the barrier due to water.
3.3 Kinetic analysis techniques

Asymmetry is clearly an important aspect of many water-based activities where a cyclic action is most efficient for performance. Perhaps the most direct way to analyse asymmetry is by the measurement of forces. In kayaking, the active force is delivered by the working muscles to the paddle. Efficient technique is dependent on the skill of the performer to return the propulsive force from the paddle to the boat. It is for this reason that the link between the paddle and the boat is an essential factor of performance. The force applied to the kayak has not yet been reported in the literature. Technology such as pressure mats and instrumented footplates could in theory measure this. Paddle forces however have been recorded, with instrumented paddles being used in research and applied practice.

Logan et al [67] investigated the force production characteristics during on-water paddling and simple land based resistance training exercises. Complete stroke profiles of eight paddlers completing trials over 100 and 1000 m were compared to force characteristics produced during a series of resistance training exercises. Although similar force traces were shown to exist, Logan et al [67] concluded that further analysis was required of more specific resistance exercises in order to test the strength capabilities of flat-water sprint kayakers.

Aitken and Neal [60] also investigated the forces produced during on water performance through the use of Wheatstone bridges within the shaft of the...
paddle. These were placed at each end of the paddle between the point of force
application of the hand and the blade of the paddle (Figure 14) as a tool for meas-
uring performance. Calibration was by static loading of the paddle using weights
between 50 N and 300 N. Subjects’ own paddles were used and each was cali-
brated separately. The calibrated paddles were used to record force profi les from
sub-elite paddlers during a 500 m sprint race.

The instrumented paddles were used to report mean peak force, impulse,
time-to-peak force and wet time of the paddle for both the right and left blades.
Peak forces were in the region of 210 N for left and right sides and the data was
shown to be reliable. It was reported that the instrumented paddle was a useful
tool for analyzing the force characteristics and for coaching of kayak paddlers.
Unfortunately such technology for on-water analysis is not real-time, so the ret-
rospective nature of the feedback is somewhat limited. With developments in
video goggles, such as those used by the Australian Institute of Sport in rowing, it
may not be long before kinetic information is relayed to the performer along with
video images of their technique.

3.4 Using electromyography as feedback in kayaking

Electromyography is a method of analysis where technological advances have
allowed researchers to gain a clearer insight into technique in kayaking. Tokuhara
et al [68] attempted to identify the effects of using electromyographic feedback
on kayak arm pull movement. Fourteen male paddlers were used all with 2 to
3 years paddling experience, grouped into a control group (n = 7) and a feedback
group (n = 7). Each subject undertook pre testing and posting testing consisting
of a seated arm pull which included trunk rotation and leg extension in an attempt
to imitate paddling technique and a standing arm pull, during which the activa-
tion of the posterior aspect of the deltoid, the long head of the biceps brachii, the
brachialis and the lateral head of the triceps brachii were measured. The arm

Figure 14: Arrangement of Wheatstone bridges to measure paddle forces (gauges
1 and 3 measure elongation and gauges 2 and 4 measure compression).
pulls were all carried out through an isometric contraction in conjunction with a dynamometer for force measurement. All subjects were required to train 20 days over the 6 weeks following pre testing during which the standing and seated isometric arm pulls were carried out twice in addition to the subjects’ usual training regime, with the feedback group being given continuous information of their performance throughout the training.

4 Summary

Clearly the barrier due to water presents researchers with an immovable obstruction in their quest for knowledge in water-based sports. Advances in technology do allow research to move forward in this area, but progress has been slow. There have been many challenges that have been overcome, however it is clear that there is more work to be done to explain the mechanisms that underpin movement through the medium of water and the effects that this has on the movement of the water itself and any efficiencies that might be gained from it [69].

References


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