A Comparison of Video and Accelerometer Based Approaches Applied to Performance Monitoring in Swimming

by

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ABSTRACT

The aim of this paper is to present a comparison of video- and sensor-based studies of swimming performance. The video-based approach is reviewed and contrasted to the newer sensor-based technology, specifically accelerometers based upon Micro-Electro-Mechanical Systems (MEMS) technology. Results from previously published swim performance studies using both the video and sensor technologies are summarised and evaluated against the conventional theory that upper arm movements are of primary interest when quantifying free-style technique. The authors conclude that multiple sensor-based measurements of swimmers' acceleration profiles have the potential to offer significant advances in coaching technique over the traditional video based approach.

Key words: Biomechanics of Swimming, Front Crawl, Kinematics, Sensor Technology

INTRODUCTION

The principal aim of this paper is to describe how measurement of swimming performance, using miniature accelerometers offers advantages of greater accuracy and a broader range of performance measures compared to that afforded by the traditional video-based approach. In support of this objective, we review the methodology and results of several video and accelerometer based studies of swimming performance. Evidence that the accelerometer based approach has the potential to enable significant improvements in swim coaching technique is considered.

BACKGROUND

As Troup [1] recognises, capture of reliable performance data can provide greater insight into the dynamics of swimming and has the potential to enable swimmers to perform to their highest potential.

Historically, it has proven difficult to define an idealised stroke pattern and the swimming

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coach has had to couple generally accepted good practice with the characteristics of the individual athlete. Consequently, quantifiable approaches based upon sound scientific principles are essential. Traditionally, quantitative measurement of swimming performance has been achieved by analysis of video footage, whereas more recently miniature sensors in the form of accelerometers and gyroscopes have been fixed to the swimmer to record performance data such as stroke type and stroke rate [2].

VIDEO BASED ANALYSIS OF SWIMMING PERFORMANCE

Video based analysis of swimming performance allows calculation of stroke rate, stroke length and assessment of the general characteristics of a swimmer's style; for example, angles of arm joints or degrees of body roll. Video analysis uses either two or three cameras placed at various positions in and/or above the pool.

For quantitative scientific studies reflective markers are located at key positions on the swimmer, such as the wrist [3]. The coordinates are then manually digitised, but various computer software is also available that will track these points. Digitisation can produce errors as shown by Wilson [4], in three-dimensional kinematic analysis of swimming, acceptable reconstruction tolerance can be 1.61-2.35mm on the transverse axis; 2.99-4.64mm on the longitudinal; 2.59-2.83mm on the vertical axis [5]. The coordinates of these points of interest can then be extracted using the Direct Linear Transform (DLT) method. The DLT is an established algorithm that allows multiple images captured by asynchronous cameras to be extracted on a frame-by-frame basis [3]. This allows a composite 3D graph of position versus time to be constructed with minimum error [6]. DLT results can be displayed as shown in Figure 1.

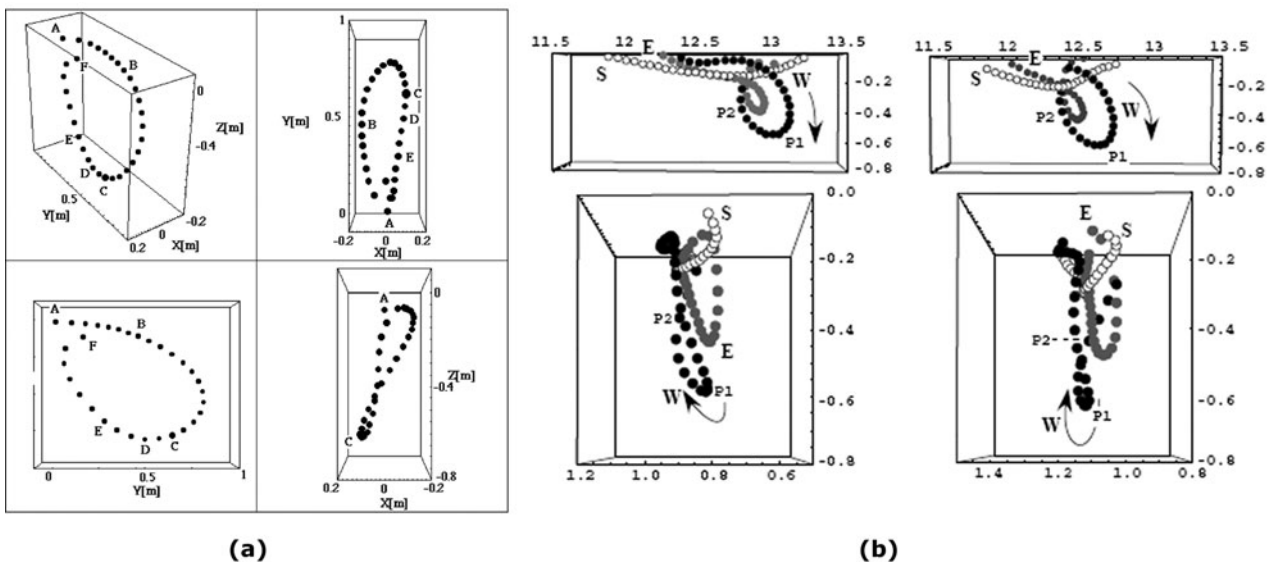(a)   (b)

Figure 1. (a) One Complete Cycle of the Hand Path Constructed from DLT data in 4 Perspectives (A-B Entry Stretch, B-C Down-sweep to Catch, C Catch, C-D In-sweep, D-E Upsweep, E-F Release and Exit). [7]
(b) Underwater Stoke Paths of Swimmer's Shoulder (S), Elbow (E) and Wrist (W) Joints [3] © 2002 IEEE

Ideally, cameras used for the DLT method should be synchronised to enable optimum reconstruction of image data [8]. However, such 'phase-locked' cameras are up to 20 times more expensive than standard camcorders [8]. Pourcelot et al. [8] describe a new low-cost method based on estimation of the time delay between standard video cameras. A cubic-spline interpolation method is then employed to minimise the error in determining the precise position of each moving point being tracked on the subject [8]. With this approach, one camera is used as a reference and the second or additional cameras can be synchronised to the reference camera without the need for expensive phase-locking circuitry.

While the DLT approach is successfully employed as an analytical tool in many sport disciplines, its application to assessment of swimming performance can be limited by the various difficulties associated with using a camera to obtain images in water. These include the parallax error at the water-air interface and turbulence affecting the view of anatomical points of interest [9].

Figure 2. Turbulence and Blurring Affecting Anatomical Viewing
(© Bournemouth University)

Several investigators have reported problems that result in occlusion of markers leading to a loss of continuity in the data required for successful application of the DLT algorithm [3, 7, 10, 11]. Figure 2 illustrates such problems with water turbulence and slow shutter speeds affecting image quality.

Kwon [12] also describes how refraction of light in water can cause errors in reconstruction of trajectory data when using the DLT algorithm. This problem is independent of the imaging approach as there is always a water - (glass) - air interface at some point in the optical path. Some improvement to image clarity might be obtained by employing a wide angle lens, but there is the additional problem of distortion due to short focal length when using this approach [13].

Despite the limitations of video based analysis, the technique has formed the basis on which our understanding of swimming performance has been built over the last three decades. For example, Ohgi [3] used the DLT method to track the shoulder, elbow and wrist. Anatomical sites such as the middle finger are frequently used to provide a standardised reference for comparison between different studies [7].

ACCELEROMETER-BASED ANALYSIS OF SWIMMING PERFORMANCE

An increasingly widely adopted alternative to video-based analysis employs small, electronic accelerometers located at various sites on the swimmers body. This approach typically supports measurement of linear tri-axial acceleration [2, 3, 7, 9, 14-16] or with an accompanying gyroscope [3] measurement of tri-axial angular velocity. The use of accelerometers in athletic performance monitoring has been validated by numerous studies covering a range of disciplines including: ambulatory measurements [17, 18]; physical activity [19-22]; gait analysis [23]; orientation and movement [10, 24-28]; and to improve athlete performance [29].

The application of accelerometer measurements to water-based monitoring requires hermetic sealing of the sensors, instrumentation and power supply and a reliable means of mounting the units on the swimmer. The recent availability of Micro-Electro-Mechanical-Systems (MEMS) based sensors simplifies the encapsulation of the system and ensures that the measurement system does not significantly affect swimming performance by increasing drag.

As well as overcoming the problems associated with video-based capture, the accelerometer approach supports higher sampling rates with more accurate measurements. However, there is potential for noise due to movement artefact which may require additional signal processing. DLT video analysis requires a minimum of two synchronised cameras, but tri-axial accelerometers and tri-axial gyroscopes have been used as a single combined device [3] in order to capture various performance data such as stroke rate and stroke type [2] and identification of stroke phases [9]. Using one device placed on the arm can produce limited results as it will only account for the actions of a single arm, but both arms are used in front crawl swimming. It may be assumed that both arms are identical, but in reality that is unlikely to be the case; for this reason, multiple devices should be considered.

The data obtained from accelerometer-based measurement systems depends to some extent on the method of operation. The general measurement principle is based upon a mass displacing a linear spring. As a force is applied to the device the spring stretches and the mass is displaced:

$$F = kx \qquad (1)$$

where F is the force measured in Newtons (N), k is the spring constant in Nm^{-1} and x is the spring extension in metres (m). Acceleration is the rate of change of the extension, given by:

$$a = \frac{F}{m} \qquad (2)$$

where F is the force acting on the body, m is the mass of the body in kilograms (kg), and a is the acceleration in ms^{-2} [24].

To understand the true acceleration of a body, the gravity vector must be removed. This can be done using 3D Pythagorean Theorem, with 1g being taken away from the result

leaving actual acceleration, where x, y, z are the values for acceleration at time t.

$$a_t = \left(\sqrt{x_t^2 + y_t^2 + z_t^2} \right) - g \tag{3}$$

Using acceleration, it is also possible to derive velocity and displacement from the recorded data through integration of the signal. This can produce incremental errors, however, as demonstrated by an Inertial Measurement Unit (IMU), a device typically used for boat navigation. An IMU comprises of an accelerometer, gyroscope and magnetometer (which typically measures the earth's magnetic field). In an IMU, the accelerometer and gyroscope are subject to baseline drift and require continuous compensation to ensure stability of heading and orientation. This can be achieved by using the relatively stable magnetometer signal as a reference. In principle, the same technique could be used to improve accelerometer-based assessment of swimming performance. However, the magnetic fields produced by water pumps under the pool are likely to introduce significant error in the magnetometer output data.

Gyroscopes are used to measure angular velocity about each axis of the body to which it is attached (rotation about the X axis is Roll (ωx), Y axis is Yaw (ωy), Z axis is Pitch (ωz)). MEMS gyroscopes typically measure angular velocity using the Coriolis effect. The magnitude of the Coriolis effect, in each axis, is proportional to the angular velocity and is realised by:

$$f_c = 2mv\omega \tag{4}$$

where f_c is the magnitude of the Coriolis effect, m is the mass in kg, v is the velocity of the mass in ms^{-1}, and ω is the angular velocity in ms^{-1} [10].

The direction of the accelerometer and gyroscope signals is dependent on the device orientation when placed on the swimmer. Previous studies have placed them in differing orientations, one such orientation setup is shown in the accelerometer results section later in this paper. However, at this time, it seems there is no standard orientation of such devices within the research community.

Using recent advances in 3D photolithographic techniques, mechanical sensors with integrated electronic circuitry have been realised that are capable of performing the preceding measurements over suitable ranges (Figure 3). These devices typically output an analogue signal that can then be processed and stored digitally using embedded microprocessors. This supports realisation of ultra-small sensors, which can be mounted on athletes. Furthermore, such devices can include smart technology; e.g., for auto-calibration and filtering to remove artefacts.

RESULTS OBTAINED USING VIDEO BASED ANALYSIS OF FRONT CRAWL SWIMMING

Counsilman [30] found that a significant number of top swimmers employed an 'inverted question mark' stroke as part of their natural front-crawl technique (see Figure 4a.). Further studies led to the proposal of a fundamental relationship between forward motion and the action of pushing against 'still' water, by curving the path of the hand during the stroke creating a 'sculling' motion [31] (see Figure 4a). The sculling technique allowed an increase in the volume of water displaced and hence greater forward propulsion. The finding was confirmed in subsequent studies by Toussaint and Beek [32] and Maglischo [33]. Maglischo [33] added further detail to the standard motion diagram by including details of the stroke
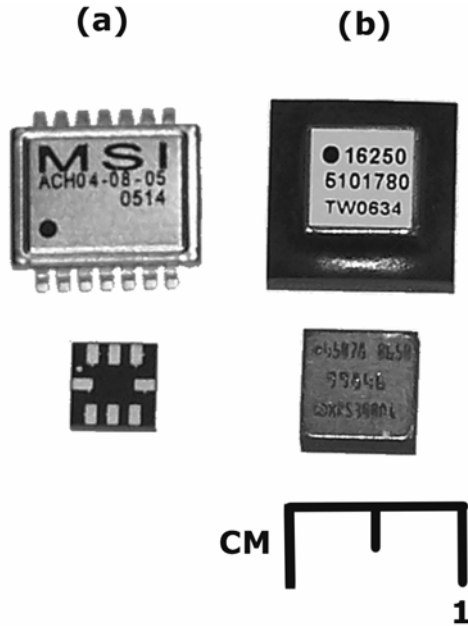
Figure 3. (a) Tri-Axial Accelerometer Integrated Circuits (b) Single Axis Gyroscopes (©Bournemouth University)

1-2 Entry and stretch
2-3 Downsweep to catch
3   Catch
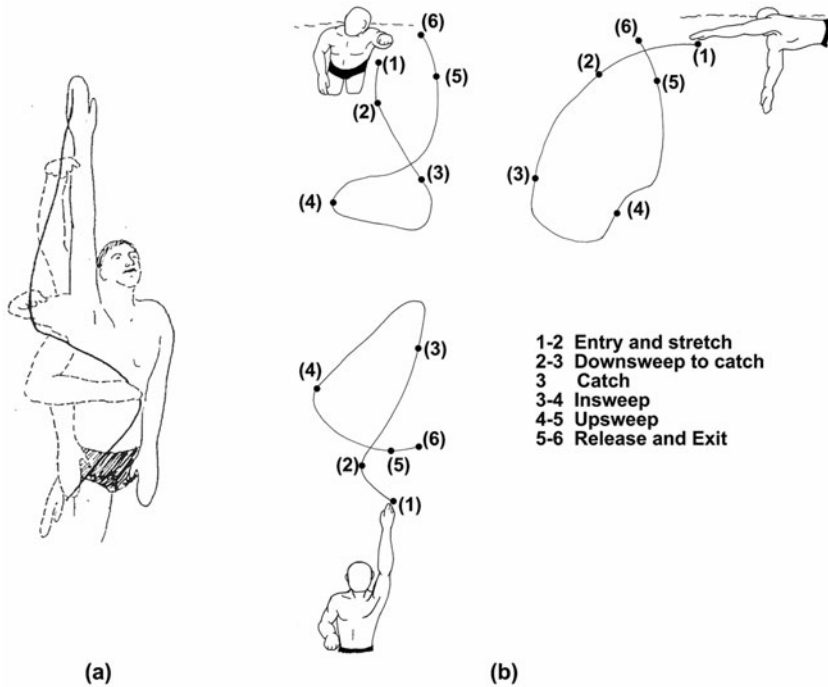3-4 Insweep
4-5 Upsweep
5-6 Release and Exit

Figure 4. (a) Pulling Pattern Relative to Body: Bottom View [31] (Courtesy of Brent T. Rutemiller) (b) Sculling Motion in Front Crawl Swimming Based on Examples Produced by Counsilman, Maglischo and Toussaint [31-33] (Drawn by Megan Henesy; ©Bournemouth University)

phases (Figure 4b). Consequently, sculling has come to be regarded as a highly desirable feature in front crawl swimming [34].

Building on work by Scheuchenzuber [35], who developed a hand pressure pattern for the phases of the stroke (which assumed hand pressure increases proportional to acceleration), Counsilman [31] added the diagram of the swimmer to position data to enhance visualisation of the swimmer's motion (Figure 5). The analysis afforded by this approach led to the introduction of a "soft catch" at the start of the stroke followed by a gradual acceleration of the hand throughout the pull phase.
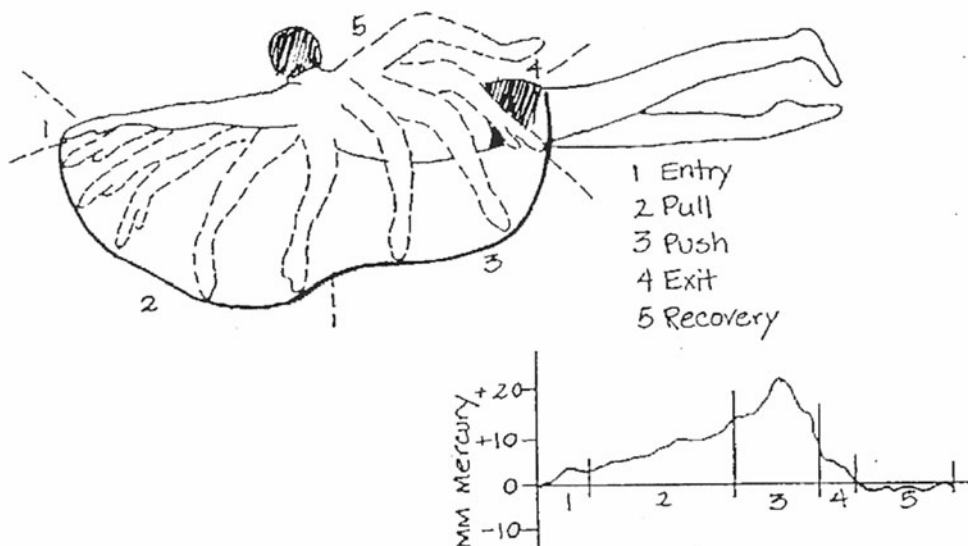

Figure 5. Hand Pressure Differential of a World Class Swimmer [31] (Courtesy of Brent T. Rutemiller)

The use of cameras demonstrated for the first time that the modified sculling technique resulted in an increasing palmar surface pressure throughout the arm cycle, which, coupled with the momentum from the previous stroke, allowed maximum forward velocity to be achieved at 80% of the effort required in the standard sculling technique.

Over the last decade, the basic detail included in swimming motion analysis diagrams has been extended by various researchers. Cappaert [36] concluded that elbow angle during the insweep phase is the most important factor governing performance and demonstrated a typical mean value of 106° based on a study of nine swimming athletes. Payton et al. [37] conducted a similar study with a smaller sample group of five swimmers and obtained a typical mean value of 105° for elbow angle during the insweep phase (Figure 6c).

The addition of elbow and shoulder angle information has proven useful in furthering understanding of common swimming strain injuries. In particular, "swimmer's shoulder" (rotator cuff tendonitis) affects 66% of swimmers according to Pink and Tibone [38], and 40-70% of swimmers according to Yanai et al. [39]. Some 70% of complaints were caused during the catch phase of the stroke and 18% during recovery [38]. The basic cause of this ailment is widely recognised as being the relative position of the elbow and hand to the shoulder during the catch phase.

A high proportion of swimmers achieve a quick catch by moving the arm outside the line of the body, with the hand directly in line with the flexed elbow (see Figure 7a). Using the elbow in this manner allows the swimmer to accelerate sooner in the stroke and minimises the deceleration from the previous phase [33]. It also has the advantage of decreasing pushing drag (the counter force produced when pushing in any direction other than backwards) and additional propulsion can be gathered as the arm is positioned to push directly backwards against the water [33].
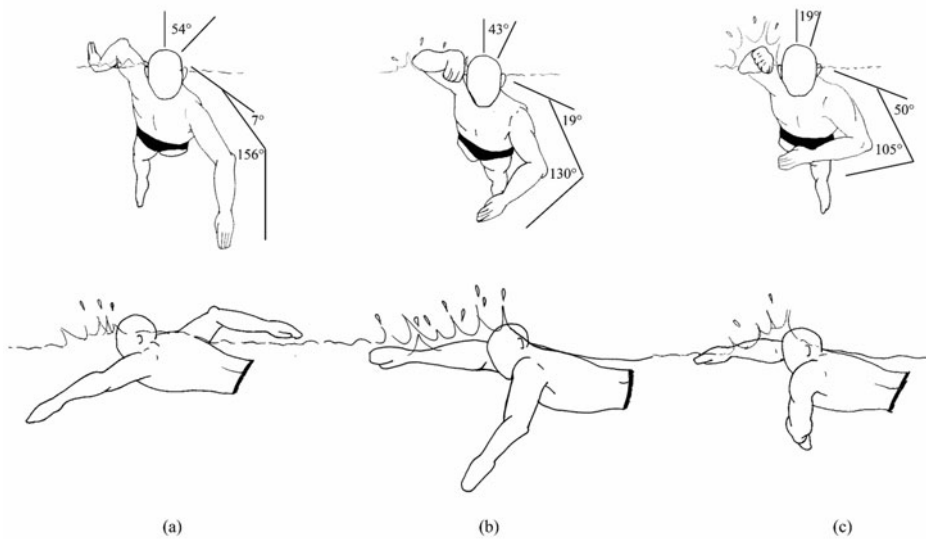
Figure 6. Angles Based on Payton's [37] Findings: (a) Start of Insweep, (b) Mid-Insweep, (c) End of Insweep
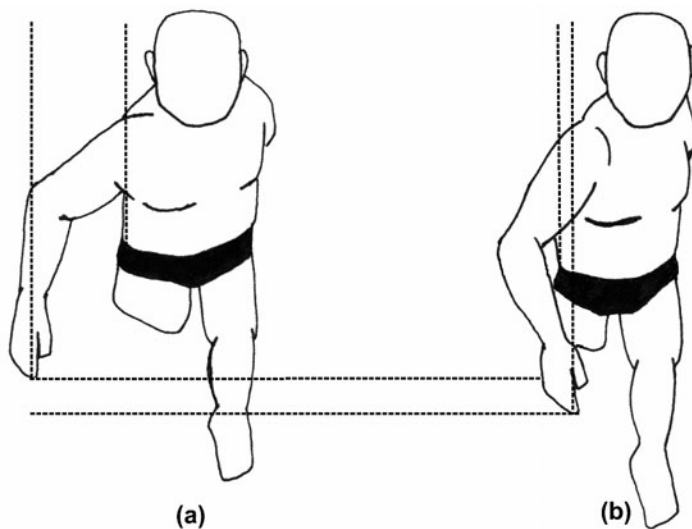(Drawn by Megan Henesy, © Bournemouth University)

Figure 7. Variations of Catch Technique. The Catch: (a) Outside the Body line. (b) Inside Body Line, Deeper in the Water
(Drawn by Megan Henesy, © Bournemouth University)

The disadvantage of this method is that the humerus rubs across the supraspinatus tendon, both bicep tendons and the corcoacromial ligament potentially causing tendonitis; this mechanism originally being proposed by Kennedy et al. [40]. A second disadvantage is that this propulsive phase is outside the line of the body. An alternative method would be to use a greater degree of body roll allowing a deeper catch (Figure 7b). This still results in the hand being just outside of the shoulder, but the elbow is lower in the water; this method is less likely to produce tendonitis and also allows the insweep to be within the confines of the body. The disadvantage of this method is that the arm has to travel deeper in the water; this takes longer and results in a decrease of forward velocity [33]. The Egyptian team coach, Dodson [41], stated that the angle of the elbow to the water should be in the region of 45° on exit in order to prevent shoulder injury, but no evidence was presented to support this view.

It is important to appreciate that the findings discussed in the preceding section relate to direct assessment of a swimmers anatomical performance. Video camera analysis has allowed researchers to discover the consistent behaviour between top level swimmers and have aided with the development of what is now considered to be a standard swimming model. Alternative studies have focused on the effect of drag on the swimmer; for example, Toussaint's MAD System [42].

RESULTS OBTAINED USING ACCELEROMETER BASED ANALYSIS OF FRONT CRAWL SWIMMING

Data obtained from accelerometer based measurements can be processed to extract a range of useful information, including the velocity of the swimmer [16], the angles of the joints [36], and body roll [34, 43, 44].

By attaching an accelerometer to a swimmer's lower back, Holmér [16] pioneered analysis of acceleration in swimming. In a study of experienced swimmers previously classified as good and elite swimmers, whole body velocity was measured in a flume and acceleration determined using an analogue integration method. The elite group showed consistently higher velocities which was interpreted as an indication of better stroke economy. While the findings of this study are of interest and demonstrate the potential of an accelerometer-based approach, the use of a flume is likely to produce significantly different results to pool-based studies. With a swimmer being situated in a flume, it is unclear how natural acceleration can be achieved as the swimmer's position is effectively stationary with water passing over them. This setup is likely to affect normal stroke dynamics and stroke rate as the swimmer attempts to keep up with the flow of water.

Davey [2] also used an accelerometer located on the lower back and monitored acceleration in the pool including push off from the wall. The results of the study indicated that accelerometer data could be used to correctly identify stroke type with an accuracy of over 95%. Furthermore, in a study of 164 swimmers, Davey [2] was able to identify automatically when a swimmer pushed off the pool wall, signifying the start/stop of a lap. This result is important, as the accuracy of timing was shown to be significantly better on average than manually recorded lap times. This is important as quantifying improvements of a few tenths of a second may be necessary when assessing performance variations in elite swimmers.

Ohgi et al. [3, 7, 15] and Ichikawa et al. [9, 14] have used one accelerometer on each wrist and achieved similar results to Davey [2], yet recorded superior results showing stroke phases (Figure 9b), stroke count, and perhaps more importantly quantified hand pitch (Figure 8). Ohgi [7] placed an accelerometer and gyroscope device on the wrist of the swimmer. The axes of the device were aligned with a human body in the standard anatomical position; the x-axis aligning with the frontal plane, y-axis aligning with the transverse plane, and z-axis aligning with the sagittal plane.
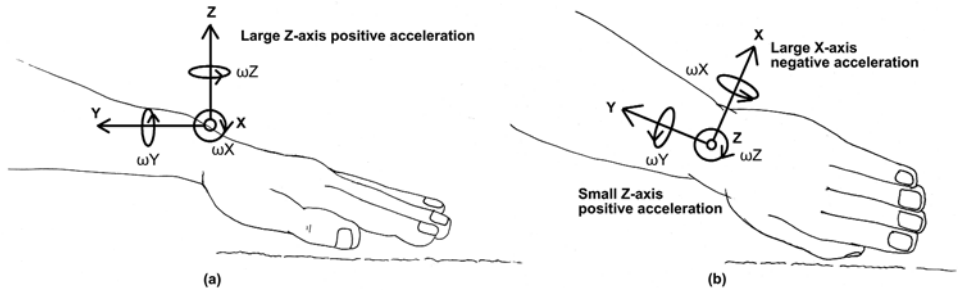
Figure 8. Hand Pitch at Entry to the Water: (a) Flat Palm Entry, (b) Pitched Hand Entry. (Drawn by Megan Henesy, © Bournemouth University) Notations: ωX, ωY, ωZ are rotational velocities from Gyroscope.

Hand pitch is an important parameter that allows a swimmer to achieve significant gains in stroke performance. Maglischo [33] states that the hand should enter the water at an inward facing angle. This can be achieved with medial rotation, as shown in Fig. 8a; this results in the production of a hydrofoil effect. Ohgi et al. [7], with the use of accelerometers, were able to determine that if the swimmer had small Z-axis positive acceleration and large X negative acceleration (Figure 8b) the swimmer had a pitched entry. Conversely, if the swimmer had large Z acceleration then the swimmer had a flat palm entry. This offers a distinct advantage over cinematography, where turbulence may result in occlusion of the hand.

Ohgi [3] was later able to verify this with the use of gyroscopes, allowing angular velocity data to be measured. Similar to the accelerometers, if the gyroscope has a high angular velocity about the x-axis and the z-axis signal is close to zero then it can be assumed that there is little or no forearm flexion with respect to the elbow and consequently no angle of attack (Figure 8a). This system was also used as a measure of fatigue in accompaniment with blood lactate and heart rate sampling.

Despite these advances, the information provided by accelerometer-based systems remains less than that afforded by cameras – particularly in terms of the usefulness of the output data. Even if a multiple sensor-based system is employed, the problem remains of interpreting and presenting the data in a form suitable for consideration by the coach and swimmer. Consider, for example, the DLT data in Figure 9a extracted from video by Ohgi et al. [7] (which shows a close correlation with the theoretical sculling patterns of Figure 4b) to the representation of acceleration which still appears in its original waveform, Figure 9b. The acceleration waveform (Figure 9b) cannot be as directly interpreted in a meaningful way, whereas the DLT reconstruction is more intuitive and informative.

The DLT algorithm also has the advantage of allowing prediction of shoulder angles and elbow and arm position relative to the horizontal. An alternative approach, employing a biomechanical model was described by Hay et al. [34]; however, this still requires an initial DLT analysis to take place. Ichikawa et al. [14] demonstrated that the same angles could be attained through acceleration data. The results were found to be more accurate during larger accelerations (catch, insweep), whereas during phases with less acceleration (entry and stretch), angles were harder to measure due to the lack of acceleration. According to Ichikawa et al. [14], this can still be used as a real-time feedback system, which cinematography does not permit at present.

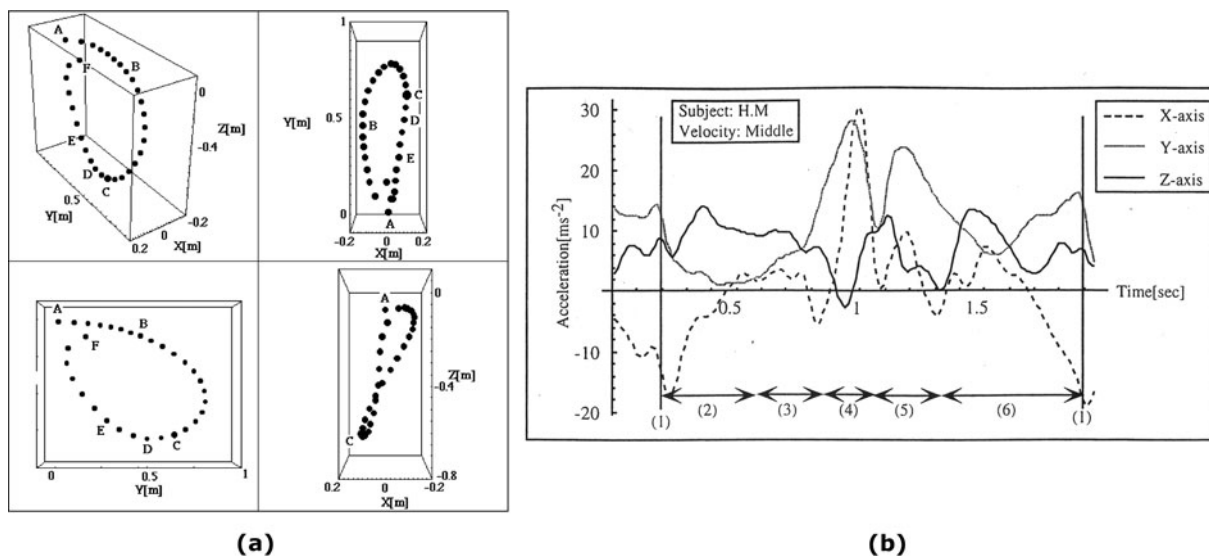**(a)**   **(b)**

Figure 9. (a) One Complete Cycle of the Hand Path Constructed from DLT Data in 4 Perspectives, (A-B Entry Stretch, B-C Downsweep to catch, C Catch, C-D Insweep, D-E Upsweep, E-F Release and Exit) [7] (Courtesy of Dr. Yuji Ohgi) (b) Acceleration of One Stroke and Each Phase: (1) Entry, (2) Stretching Arm, (3) Downsweep, (4) Insweep, (5) Upsweep, (6) Recovery [9] (Courtesy of Dr. Yuji Ohgi)

Payton et al. [37] state that the models produced by Hay et al. [34] and Payton et al. [44] were oversimplified by assuming that the shoulder, elbow and wrist remained perpendicular to the sagittal plane. This indicates that there needs to be a modification to the model, but this would not alter the elbow angles found by Ichikawa et al. [9].

Ichikawa et al. [9] also determined the acceleration characteristics (Figure 10a) of the swimmer. In comparison with a replicated graph of a 3-time Olympic Gold medallist, Rowdy Gaines' arm acceleration (Figure 10b) as recognised by Counsilman and Wasilak [45], there are some similarities. Due to differing scales, it is hard to fully compare the two graphs; but it can be clearly seen that Figure 10b has a much higher acceleration during the upsweep (d-e) phase of the stroke. This trend is continued in the velocity graphs shown in Figure10c and Figure 10d.

Maglischo [33, cited 46] states that the gradual acceleration as defined by Counsilman and Wasilak [45] is not as simple as their interpretation suggests due to phases where there are pulses of acceleration. This is considered to be a consequence of the major arm direction changes during the stroke (Figure 3b). Counsilman and Wasilak [45] discuss how acceleration graphs are "of little instructional value in helping the swimmer understand the concept of hand speed" and velocity graphs as shown in Figure 10 are easier and more meaningful to the swimmer. It should be noted that velocity graphs can be obtained through integration of acceleration data and hence obtaining this additional information does not require significant change to the sensing technology.

Maglischo [33] (Figure 10c) shows Tom Jager decreases velocity during the entry to catch phases (a-c) which differs to one produced by Counsilman and Wasilak [45] (Figure 10d) of Rowdy Gaines, which shows increasing velocity during those same phases.
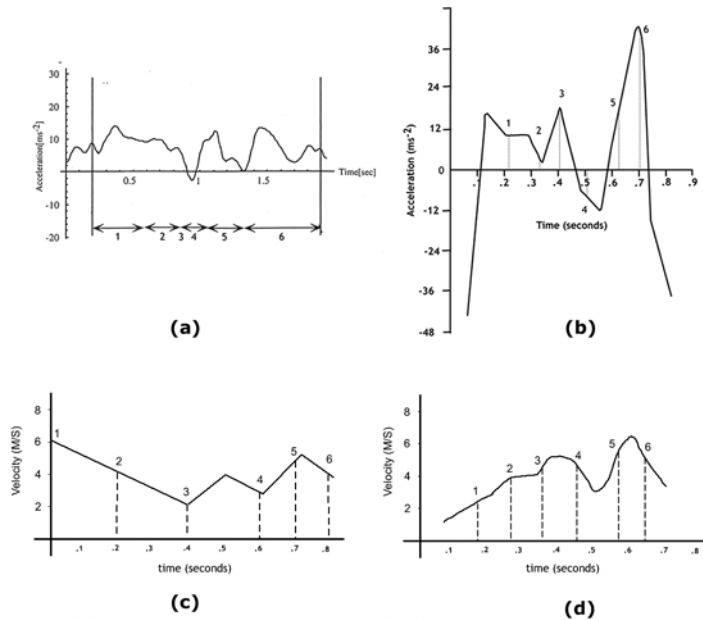
Figure 10: (a) Acceleration of One Stroke and Each Phase: Image Modified to Show Z axis only Due to Arm Orientation [9]. (Courtesy of Dr. Yuji Ohgi.)

(b) Reproduction Graph showing Acceleration, Relative to the Body, of Olympian Rowdy Gaines Based on Work by Counsilman and Wasilak [45].

(c) Reproduction Graph Showing Hand Velocity of Olympian Tom Jager, Based on Graph Produced by Maglischo [33].

(d) Reproduction Graph Showing Velocity, Relative to the Hand, of Olympian Rowdy Gaines Based on Work by Counsilman and Wasilak [45].

(1) Entry, (2) Stretching Arm, (3) Downsweep, (3-4) Catch, (4) Insweep, (5) Upsweep, (6) Recovery

This difference between the two Olympic champions (Figures 10c and 10d) show that it is not only hard to find the ideal stroking pattern for a swimmer [32], but it is also difficult to find an acceleration/velocity model within that stroking pattern for the swimmer.

CONCLUSION

This article has focused on a comparison between video- and accelerometer-based assessment of swimming performance which is currently a prominent focus of research within the field. However, there are many other approaches to assessing swimming performance as noted by Bixler [47-50] who introduced Computational Fluid Dynamics (CFD) to swimming research. His work identified other types of drag that have not been acknowledged or investigated previously and may be important in analysis of video and accelerometer data. Other investigators have also emphasised the importance of stroke length on performance [51, 52] and this has been verified by Chollet et al. [51] who have demonstrated a consistent ability of skilled swimmers to maintain stroke length over the course of a race.

However, the importance of acceleration and in particular acceleration through different phases of the stroke, as emphasised by Counsilman [31, 45], is still a principal focus of research. Pure acceleration of a swimmer's body segment, in the authors' opinion, does not determine the performance of a swimmer; acceleration needs to be used in context with the section of the stroke. Acceleration data can be used to show important information; angles such as entry using the mathematical model defined by Payton [37], velocity to calculate the proficiency of a swimmer [16], hand pitch [7], stroke identification [2] and acceleration over the phases [9]. However, when teaching a swimmer, as discussed by Counsilman and Wasilak [45], velocity is easier to interpret and replicate. Furthermore, it should be noted that the use of accelerometer-based measurements to inform adjustment of swimming technique is currently limited by issues of accuracy. The significance of this issue is being progressively reduced through advances in the underlying technology and improved methods of data analysis. The increased utilisation of accelerometers, particularly in ambulatory monitoring is driving this refinement and will be beneficial in monitoring swim performance. The aim of our group is to demonstrate new uses for MEMS accelerometers and gyroscopes and exemplify the value of acceleration in the area of technique analysis in swimming. Our intention is to extend the results of previous studies by exploiting recent developments in measurement technology.

ACKNOWLEDGEMENTS

REFERENCES
1. Troup, J.P., Preface, in: Troup, J.P., Hollander, A.P., Strasse, D., Trappe, S.W., Cappaert, J.M. and Trappe, T.A., eds., *Symposium on Biomechanics and Medicine in Swimming VII,* E & FN Spon, London, 1994, ix.

2. Davey, N.P., *Acquisition and Analysis of Aquatic Stroke Data from an Accelerometer Based System*, Masters of Philosophy Dissertation, Griffith University, 2004.

3. Ohgi, Y., Microcomputer-Based Acceleration Sensor Device for Sports Biomechanics – Stroke Evaluation by Using Swimmer's Wrist Acceleration, *IEEE Sensors*, 2002a, 699- 704.

4. Wilson, D.J., Smith, B.K.,Gibson, J.K.,Choe, B.K.,Gaba, B.C. and Voelz, J.T., Accuracy of Digitization Using Automated and Manual Methods, *Physical Therapy*, 1999, 79(6), 558.

5. Gourgoulis, V., Aggeloussis, N., Kasimatis, P., Vezos, N., Boli, A. and Mavromatis, G., Reconstruction Accuracy in Underwater Three-Dimensional Kinematic Analysis, *Journal of Science and Medicine in Sport*, 2008, 11(2), 90-5.

6. Marzan, G.T. and Karara, H.M., A Computer Program for Direct Linear Transformation Solution of the Collinearity Condition, and Some Applications of It, *Proceedings of the Symposium on Close-Range Photogrammetric Systems*, 1975, 420-76.

7. Ohgi, Y., Yasumura, M., Ichikawa, H. and Miyaji, C., Analysis of Stroke Technique Using Acceleration Sensor Ic in Freestyle Swimming, *Engineering of Sport*, 2002, 7, 503-511.

8. Pourcelot, P., Audigie, F., Degueurce, C., Geiger, D. and Denoix, J.M., A Method to Synchronise Cameras Using the Direct Linear Transformation Technique, *Journal of Biomechanics*, 2000, 33(12), 1751-1754.

9. Ichikawa, H., Ohgi, Y. and Miyaji, C., Analysis of Stroke of the Freestyle Swimming Using Accelerometer, *Symposium on Biomechanics and Medicine in Swimming VIII*, Jyväskylä, Finland, 1998, 159-164.

10. Luinge, H. J., *Inertial Sensing of Human Movement*, PhD Thesis, University of Twente, 2002.

11. Seifert, L., Chollet, D. and Allard, P., Arm Coordination Symmetry and Breathing Effect in Front Crawl, *Human Movement Science*, 2005, 24(2), 234-256.

12.   Kwon, Y.H., A Camera Calibration Algorithm for the Underwater Motion Analysis, *Scientfic Proceedings of the XVII International Symposium on Biomechanics in Sports*, Edith Cowan University, Perth, Australia, 1999, 257-260.

13.   Drenk, V., Hildebrand, F., Kindler, M. and Kliche, D., A 3D Video Technique for Analysis of Swimming in a Flume, in: Sanders, R.H. and Gibson, B.J., eds., *International Symposium on Biomechanics in Sports,* School of Biomedical and Sports Science, Edith Cowan University, Perth, Western Australia, 1999,

14.   Ichikawa, H., Ohgi, Y., Miyaji, C. and Nomura, T., Application of a Mathematical Model of Arm Motion in Front Crawl Swimming to Kinematical Analysis Using an Accelerometer, *Engineering in Sport 4,* 2002, 644-50.

15.   Ohgi, Y., Ichikawa, H., and Miyaji, C., Characteristics of the Forearm Acceleration in Swimming, *Symposium on Biomechanics and Medicine in Swimming VIII*, Jyväskylä, Finland, 1998, 77-82.

16.   Holmér, I., Analysis of Acceleration as a Measure of Swimming Proficiency, in: Terauds, J. and Bedingfield, E.W., eds., *Swimming III*, University Park Press, Baltimore, MD, 1978, 118-124.

17.   Bussmann, J.B.J., Martens, W.L.J., Tulen, J.H.M., Schasfroort, F.C., van den Berg-Emons, H.J.G. and Stam, H.J., Measuring Daily Behaviour Using Ambulatory Accelerometry: The Activity Monitor, *Behaviour Research Methods, Instruments and Computers*, 2001, 33(3), 349-356.

18.   Bussmann, J.B.J., Tulen, J.H.M., Herel, E.V. and Stam, H.J., Quantification of Physical Activities by Means of Ambulatory Accelerometry: A Validation Study, *Psychophysiology*, 1998, 35(5), 488-496.

19.   Bao, L. and Intille, S.S., Activity Recognition from User-Annotated Acceleration Data, in: Ferscha, A. and Mattern, F., eds., *Lecture Notes in Computer Science*, Springer-Verlag, Berlin, Germany, 2004, 1-17.

20.   Lee, S.H., Park, H.D., Hong, S.Y., Lee, K.J. and Kim, Y.H., A Study on the Activity Classification Using a Triaxial Accelerometer, *25th Annual International Conference of the IEEE EMBS*, Mexico, 2003.

21.   Ravi, N., Dandekar, M., Mysore, P. and Littman, M.L., Activity Recognition from Accelerometer Data, *Proceedings of the National Conference on Artificial Intelligence*, 2005.

22.   Morris, J.R., Accelerometry – A Technique for the Measurement of Human Body Movements, *Journal of Biomechanics*, 1973, 6(6), 729-736.

23.   Levine, J.A., Baukol, P.A. and Westerterp, K.R., Validation of the Tracmor Triaxial Accelerometer System for Walking, *Medicine and Science in Sports and Exercise*, 2001, 33(9), 1593-1597.

24.   Roetenberg, D., *Inertial and Magnetic Sensing of Human Motion*, PhD Thesis, University of Twente, Netherlands, 2006.

25.   Luinge, H.J. and Veltink, P.H., Measuring Orientation of Human Body Segments Using Miniature Gyroscopes and Accelerometers, *Medical & Biology Engineering & Computing*, 2005, 43(2), 273-282.

26.   Luinge, H.J., Veltink, P.H. and Baten, C.T.M, Ambulatory Measurement of Arm Orientation, *Journal of Biomechanics*, 2007, 40(1), 78-85.

27.   Lynch, A., Majeed, B., O'Flynn, B., Barton, J., Murphy, F., Delaney, K. and O'Muthuna, S.C., A Wireless Inertial Movement System (WIMS) for Interactive Dance Environment, *Journal of Physics*, 2005, 15, 95-100.

28.   Roetenberg, D., Slycke, P., Ventevogel, A. and Veltink, P.H., A Portable Magnetic Position and Orientation Tracker, *Sensors & Actuators, A: Physical*, 15 April 2007, 135(2), 426-432.

29.   Anderson, R., Harrison, A.J. and Lyons, G.M., Accelerometer Based Kinematic Biofeedback to Improve Athletic Performance, in: Ujihashi, S. and Haake, S., eds., *Engineering in Sport 4*, 2002, 803-809.

30.   Counsilman, J.E., *Competitive Swimming Manual for Coaches and Swimmers*, Pelham Books, London, 1977.

31.   Counsilman, J.E., Hand Speed and Acceleration, *Swimming Technique*, 1981, 18(1), 22-26.

32.   Toussaint, H.M. and Beek, P.J., Biomechanics of Competitive Front Crawl Swimming, *Sports Medicine*, 1992, 13(1), 8-24.

33.   Maglischo, E.W., *Swimming Faster*, Human Kinetics, Champaign, IL, 2003.

34.   Hay, J.G., Liu, Q. and Andrews, J.G., Body Roll and Handpath in Freestyle Swimming: A Computer Simulation Study, *Journal of Applied Biomechanics*, 1993, 9, 227-237.

35. Scheuchenzuber, R.J., *Kinetic and Kinematic Tethered Swimming of the Front Crawl Arm Stroke*, PhD Thesis, Indiana University, 1974.

36. Cappaert, J.M., Biomechanics of Swimming Analysed by Three-Dimensional Techniques, in: Keskinen, K., Komi, P. and Hollander, A.P., eds., *Symposium on Biomechanics and Medicine in Swimming VII*, Jyväskylä, Finland, 1999, 141-145.

37. Payton, C.J., Baltzopoulous, V. and Bartlett, R., Contributions of Rotations of the Trunk and Upper Extremity to Hand Velocity During Front Crawl Swimming, *Journal of Applied Biomechanics*, 2002, 18, 243-256.

38. Pink, M.M. and Tibone, J.E., The Painful Shoulder in the Swimming Athlete, *Orthopedic Clinics of North America*, 2000, 31(2), 247-261.

39. Yanai, T., Hay, J.G. and Miller, G.F., Shoulder Impingement in Front-Crawl Swimming: I. A Method to Identify Impingement, *Medicine and Science in Sports and Exercise,* 2000, 32(1), 21-29.

40. Kennedy, J.C., Hawkins, R. and Krissoff, W.B., Orthopedic Manifestations of Swimming, *American Journal of Sports Medicine*, 1978, 6(6), 309-322.

41. Dodson A., Kiss Shoulder Pain Goodbye: Proper Technique – The Key to Preventing and Relieving Shoulder Pain, Http://www.coachesinfo.com, Accessed, 2006.

42. Toussaint, H.M., Van Den Berg, C. and Beek, W.J., Pumped-up Propulsion During Front Crawl Swimming, *Medicine and Science in Sports Exercises*, 2002, 34(2), 314-319.

43. Liu, Q., Hay, J.G. and Andrews, J.G., Body Roll and Handpath in Freestyle Swimming: An Experimental Study, *Journal of Applied Biomechanics*, 1993, 9, 238-253.

44. Payton, C.J., Hay, J.G. and Mullineaux, D.R., The Effect of Body Roll on Hand Speed and Hand Path in Front Crawl Swimming: – A Simulation Study, *Journal of Applied Biomechanics*, 1997, 13(3), 300-315.

45. Counsilman, J.E. and Wasilak, J., The Importance of Hand Speed and Hand Acceleration, in: Ousley, R.M., ed., *ASCA World Clinic Yearbook*, American Swimming Coaches Association, Fort Lauderdale, FL, 1982, 41-55.

46. Schleihauf, R.E., Biomechanics, in: Johnston, T., Woolger, J., Scheider, D (eds). *ASCA World Clinic Yearbook*. American Swimming Coaches Association, Fort Lauderdale, FL, 1986b, 88-93.

47. Bixler, B.S. and Riewald, S., Analysis of a Swimmer's Hand and Arm in Steady Flow Conditions Using Computational Fluid Dynamics, *Journal of Biomechanics*, 2002, 35(5), 713-717.

48. Bixler, B.S., The Fastskin 2, *Fluent CFD Summit Conference*, Dearborn, Michigan, 2004.

49. Bixler, B.S., The Mechanics of Swimming, in: Stager J.M.C. and Tanner, D.A., eds., *Swimming*, Blackwell Publishing, Oxford, 2005, 59-101.

50. Bixler, B.S. and Schloder, M., Computational Fluid Dynamics: An Analytical Tool for the 21st Century Swimming Scientist, *Journal of Swimming Research*, 1996, 11(1), 4-22.

51. Chollet D., Pelayo P., Delaplace C., Tourny C. and Sidney M., Stroking Characteristic Variations in the 100-m Freestyle for Male Swimmers of Differing Skill, *Perceptual and Motor Skills*, 85(1), 167-77.