BEYOND RACE ANALYSIS

Ross Sanders
Department of Physical Education Sport and Leisure Studies
The University of Edinburgh, Edinburgh, U.K.

Race analysis is now well entrenched as an important part of the application of science to swimming and is keenly sought by coaches and swimmers. At present, race analysis emphasizes stroke length and stroke frequency and component times such as mid-pool (free swimming) time, turn time, and start time. A new model for identifying important variables is presented. Many of these variables are not, as yet, determined routinely. The model comprises three 'global goals' – the minimization of resistive impulse, the maximization of propulsive impulse, and the development of techniques that restrain physiological cost. The section of the model dealing with maximising propulsive impulse is described. Problems involved in indirectly estimating forces produced by the arm and hand are briefly addressed. It is concluded that, at this time, accurate quantification of propulsive forces by indirect means is problematic. However, it is suggested that important 'critical features' such as the time of 'catch' and 'release' might by estimated with reasonable accuracy provided that the effect of acceleration is taken into account. Further investigation is required to establish the accuracy and reliability of estimating these times.

KEY WORDS: swimming, technique, race analysis, video analysis, propulsion, resistance, hydrodynamics.

INTRODUCTION: I am honored to have the opportunity afforded by Youlian Hong and his ISBS2000 Committee to commence this workshop devoted to the theme 'how can we improve analysis of swimming technique for feedback to swimmers and coaches?' The strong response to the invitation sent to leading international swimming researchers clearly indicates the importance of this theme. We have 14 papers submitted for this session by many of the world's foremost swimming researchers covering a range of issues within that general theme. My contribution deals with the idea that we, as swimming scientists seeking to provide scientific information that is useful for coaches and swimmers, can extend our service beyond race analysis. By saying this I am in no way down playing the importance of race analysis. The usefulness of measuring race parameters such as stroke length and stroke frequency, turn time, start time, free-swimming speed, and others, is shown clearly by the fervent interest by coaches and swimmers in obtaining these results. The development of systems that provide rapid feedback such as those developed and used by Bruce Mason (1998) and his Australian Institute of Sport colleagues; Raul Arellano (1992) and his team at Granada in Spain; and Rein Haljand (1997) in Estonia, to name a few prominent ones, have enabled coaches to identify areas requiring attention and to modify race strategies even between races at the same meeting. We are fortunate to have Bruce Mason and Jodi Cossor and Raul Arellano here at this workshop to enlighten us with the recent findings from those analyses with respect to able-bodied swimmers and Laurie Malone with respect to Paralympic swimmers.

A NEW MODEL FOR IDENTIFYING IMPORTANT VARIABLES: While the findings of these race analyses provide information about where swimmers need to improve, proffering advice as to how improvement can be made is often difficult. At the FINA Conference in 1999 (Sanders, 1999) I presented a model for identifying important variables in mid-pool swimming. This model differed from the traditional 'stroke length/stroke frequency' model. The rationale for doing so was that the new model may help identify other useful variables for assessing performance, and identifying strategies to improve.

The approach was based on established mechanical principles. Swimmers all attempt to optimise their performance by obeying these mechanical principles. The principles arise from the fact that the speed of a swimmer is the outcome of the net effect of forces in the desired direction of travel (propulsive forces) and forces opposing motion in the desired direction (resistive forces). Propulsive forces act for a period of time during a stroke cycle leading to a net propulsive impulse and, similarly, resistive forces lead to a net resistive impulse. When a swimmer's average speed for a stroke cycle remains constant across cycles it is because the net propulsive impulse is equivalent to the net resistive impulse. Of course, resistive impulse increases with increasing speed. Thus, performance is related to three global goals that govern technique. The swimmer's global goals are:

1. Maximise propulsive impulse.
2. Minimise the resistive impulse at any given speed. Reducing resistive impulse at any given speed means an increase in the speed attained when resistive impulse is as great as the propulsive impulse.
3. Maximise propulsive impulse and minimise resistive impulse using techniques that restrain physiological cost to that which can be sustained throughout the race.

To understand what constitutes good technique, and to identify where improvements can be made, we need to quantify propulsive and resistive forces and the times over which they occur. Of course, the need to quantify forces has been recognized for a long time. However, measurement of propulsive and resistive forces in an aquatic environment is far from easy. From this workshop we will gain a clearer perspective of how swimming scientists are finding ways to measure propulsion and resistance. The papers by Huub Toussaint and Sergei Kolmogorov will indicate the state of the art in this area.

A section of the whole model is shown in Figure 1. Here, the 'primary behavioral goal' of the 'primary mechanical principle' is extrapolated. Thus, our goal is to maximise the period of producing propulsive force relative to the period of the stroke cycle by applying the principle 'the change in motion depends on the magnitude of the net force and the time over which it acts'. This tells us that we have two basic options to achieve our goal. We can increase the magnitudes of the forces or we can increase the time over which they act. Because resistive forces predominate during the time between 'catch', that is, the time when the forces produced by the hand first become propulsive, and 'release', when the forces from the hand cease to be propulsive, three secondary behavioral goals emerge. These are 'maximise the time of the propulsive part of the pull'; commence the 'catch' soon after entry', and 'recover the hand quickly'. Observable 'critical features' (McPherson, 1990) follow naturally from these secondary behavioral goals. These are the variables that we would seek to measure as part of our technique analysis.

Thus, the critical features important to performance can be identified readily as a logical consequence of applying a principle. The new model provides analysts with an understanding of the effects of the critical features and an understanding of why they are 'critical'. The critical features correspond directly and clearly to the biomechanical principles. A change in a critical feature has a predictable effect on the variable/s embodied in the principle. However, the overall effect on performance may depend on the extent to which the change in technique affects variables embodied in other principles. There is no requirement for a critical feature to have only one effect on one variable.

Individual swimmers may optimise performance with varying emphasis on particular biomechanical principles. Further, the observable technique characteristics vary among swimmers due to differences in physical characteristics such as height, limb length, mass distribution, body morphology, density, hydrostatic lift, joint flexibility, and strength. Therefore, finding one's optimum technique is an individual task and requires application of mechanical principles with an emphasis appropriate to the individual. For example, some freestyle swimmers have a 'high elbow' recovery in which the hand is kept close to the axis of rotation (shoulder) while others have a 'straight' arm recovery characterised by an extended elbow. In the former, the principle of keeping mass close to the axis to reduce the torque required to recover the arm, increase the rate of rotation, and reduce unwanted counter-rotations is being applied. Given this well-established rationale that has translated to 'text book' technique and coaching practices, the swimming community has been somewhat surprised at the magnitude of success of swimmers like Janet Evans using the straight-arm technique. The 'straight arm' proponents have optimised performance by emphasising a different mechanical principle. They have found it more economical to keep the arm straight to make use of the existing rotational motion and minimise muscle actions associated with accelerating and decelerating body segments.

Recent use of the straight-arm technique by sprint swimmers such as Michael Klim has us searching for yet other explanations. To find those explanations we can apply more than one mechanical principle. Perhaps recovery can be just as fast with the straight-arm technique despite the great moment of inertia. Perhaps the circular path of the hand rather than the forward and backward motion allows a faster transition from entry to catch. Perhaps the resistive impulse, due to the arm and hand moving forward with respect to the water prior to the catch, is reduced. These questions have not been answered because we have not yet measured the right variables!

The moral is that there is no 'one' correct technique - different strokes for different folks! Over a period of more than a decade, Ulrik Persyn and Veronique Colman at the Catholic University in Leuven have applied the concept of modifying technique to suit the characteristics of the individual rather than applying a single 'copybook' technique to all swimmers. Their work on breaststroke technique indicates that the degree of 'wave action' that should be employed by breaststroke swimmers depends on characteristics such as flexibility (Colman and Persyn, 1990). This is an advanced and intelligent approach and warns coaches against changing techniques towards the wave action without considering the characteristics of individual swimmers. Thus, we look forward to Veronique's presentation later in these proceedings.

By considering the mechanical principles underlying performance we can identify meaningful critical features. We can develop a rationale for intervening or not intervening in a swimmer's technique. Before intervening, one needs to consider the 'whole picture' by considering all the principles impinging on performance and the characteristics of the individual. In the past, we have been guilty of 'latching on' to one principle or idea in isolation without considering the complex interaction of a number of principles. The new model offers the advantage that critical features can be considered with respect to several principles and the interactive effect of those principles taken into account before deciding whether an intervention is warranted.

MEASURING IMPORTANT VARIABLES: If we wish to quantify the contribution of the arm stroke to propulsion then we have a very difficult task. This is particularly the case if we wish to quantify forces of a swimmer without any mechanical imposition that may induce change in the natural swimming technique. Thus, we might resort to an indirect method whereby forces are estimated using lift and drag coefficients obtained from studies such as those of Schleihauf (1979; 1984), Berger et al (1995), and Sanders (1999) to known limb orientations and speeds obtained by digitizing landmarks of the limbs from video of the underwater motions. However, there is serious doubt as to whether forces quantified in this way are accurate enough to be meaningful. There are several sources of error:

1. **Digitising.** To estimate hand forces one has to digitize points on the hand to define its plane. The hand is invariably hard to digitize accurately because the hand is small, landmarks are close together, and even if the landmarks are marked with contrasting markers, these are often difficult to see due to the water disturbance and bubbles. Payton and Bartlett (1995) have indicated that the errors arising from these problems seriously affect the force estimates.
2. **Distortion and underwater video techniques.** To obtain good three-dimensional data for estimating hand or arm forces one requires multiple underwater camera views. This is often difficult to achieve. Even when facilities, and equipment allow this, there is often a problem of distortion and refraction, particularly when the view involves glass interfaces between air and water. In his paper coauthored by Steven Lindley, Young-Hoo Kwon will address some of these issues and how to minimize these errors.
3. **Errors in lift and drag coefficients.** Only a few sets of lift and drag coefficients have been published for a swimmer's hand (Schleihauf, 1979; 1984; Berger, 1995; Sanders, 1999). We would naturally expect some differences in the values obtained due to natural variation

in shape of swimmers hands. Added to this difficulty is the fact that the shape varies according to thumb adduction/abduction and finger spread. However, large differences in the magnitude of the coefficients among the data sets has resulted from differences in methods of quantifying them.

4. **Quasi-static assumption.** The method of quantifying hand/arm forces using the indirect approach relies on the assumption that there is steady flow and steady conditions yielding steady forces at given speeds and orientation of the hand or limb. In fact, the coefficients were generally determined under conditions of constant speed, constant direction of hand movement, and constant orientation of the hand. When quantifying the forces for each small sample period in swimming these conditions are assumed. However, it is well known that this is not the case. The formation and shedding of vortices produces some unsteadiness in forces even if speed and orientation is constant. We will learn more about the behavior of vortices and how they may add to propulsive and resistive forces in the presentation by Bodo Ungerechts.

An extended model for calculating hand forces. When the hand or limb accelerates there is also the effect of 'added mass'. An effective mass of water is accelerated, thereby yielding additional forces. Pai and Hay (1988) have shown that these additional forces may be considerable. In an attempt to account for accelerations In response to the findings of Pai and Hay I extended Schleihauf's model to include additional coefficients:

$$\boldsymbol{F}_{hand} = (C_X \rho A|\boldsymbol{v}|^2)/2 + (C_Y \rho A|\boldsymbol{v}|^2)/2 + (C_Z \rho A|\boldsymbol{v}|^2)/2 + D_X \rho A|\boldsymbol{a}_X| + D_Y \rho A|\boldsymbol{a}_X| + D_Z \rho A|\boldsymbol{a}_X|$$

Where: C_X C_Y C_Z are the coefficents for the component forces in the X, Y, and Z directions and are specific to the orientation of the hand with respect to its line of motion relative to the water (in the X direction); A is the surface area of the palmar side of the hand after projecting onto the hand plane; ρ is the density of the fluid; $|\boldsymbol{v}|$ is the magnitude of the hand velocity.
The terms $(C_X \rho A|\boldsymbol{v}|^2)/2$, $(C_Y \rho A|\boldsymbol{v}|^2)/2$, $(C_Z \rho A|\boldsymbol{v}|^2)/2$ are referred to as 'velocity' terms because their value is dependent on the velocity of the hand motion. The coefficients C_X C_Y C_Z are collectively referred to as the 'velocity' coefficents.
The terms $D_X \rho A$a, $(D_Y \rho A$a, $D_Z \rho A$a are referred to as 'acceleration' terms because their value is dependent on the acceleration of the hand in the direction of hand motion. The coefficients D_X D_Y D_Z are collectively referred to as the 'acceleration' coefficients.
While the new model does allow for acceleration in the direction of existing motion there remains the problem of the effects of direction changes. These changes are not only beyond the scope of existing models but may also invoke other effects that are difficult to account for. Huub Toussaint will discuss this problem further is his paper.

Applying the models. Given the problems of quantifying hand and arm forces in swimming using indirect means, it would seem that the potential application of existing hand and arm lift and drag coefficient data is limited. However, while we may not be able to quantify forces with confidence throughout the entire pull, it may be that some useful information, in which we do have confidence, can be gained from such analysis. From the principles based model described earlier we can see that the times of catch and release are important. This is because we are interested in ensuring that the swimmer applies propulsive forces for as long as possible compared to the time that resistive forces predominate. Quantification of these may yield interesting findings with respect to differences in timing and technique that are related to performance, the effect of fatigue on the time of propulsive force generation, and the development of skill in swimming.
But can the times of catch and release be quantified accurately given the problems described above? This has yet to be established. However, given that hand velocities are slow at these times, and accelerations are large, and provided that the hand is moving in a 'reasonably' consistent direction at these times, it is possible that the times of catch and release may be

estimated with acceptable accuracy using a model that includes acceleration coefficients, that is the model described above (Sanders, 1999).

We can see from this model that the timing of catch and release is important. This is because we are interested in ensuring that the swimmer applies propulsive forces for as long as possible compared to the time that resistive forces predominate. Although we cannot have much faith in our indirect measures of force produced throughout the stroke, we may be able to quantify with reasonable accuracy the time at which the hand catches and releases the water.

CONCLUSION: In this paper I have made a case for moving 'beyond race analysis'. A model was presented that offers an alternative approach to identifying variables that may provide important information in our quest to improve our understanding of swimming technique. In this paper, the new approach was applied to identify 'critical features' that are important to producing propulsion in mid-pool swimming. The model showed that the timing of the catch and release should be quantified. Difficulties of quantifying forces produced by the hand, required to identify the instants of catch and release, were recognised. It was suggested that, while the actual magnitude of hand forces may be prone to error, it is possible that the instants of catch and release can be determined with reasonable accuracy and reliability if accelerations are taken into account. This possibility will be investigated.

This paper has focused on propulsion produced from hand motion in mid-pool swimming. Subsequent papers address a range of other important issues. In addition to the presentations previously mentioned, we have a paper by Andreas Hohmann and colleagues that has important implications for scheduling training workloads to achieve peak performance for a race. A paper by Patrick Pelayo and his colleagues deals with the use of critical speed and critical stroke rate for monitoring endurance performance of swimmers. The paper presented by Antonio Martins-Silva deals with factors related to intracyclic velocity fluctuations, known to be related to skill and economy, of butterfly swimmers. Andrew Lyttle's paper includes new information on the important and understudied area of turns. A paper on starts by J. Paulo Vilas Boas completes a quite comprehensive coverage of topics. The outstanding program of acclaimed researchers indicates clearly the rapid advancement of analysis techniques within and beyond race analysis.

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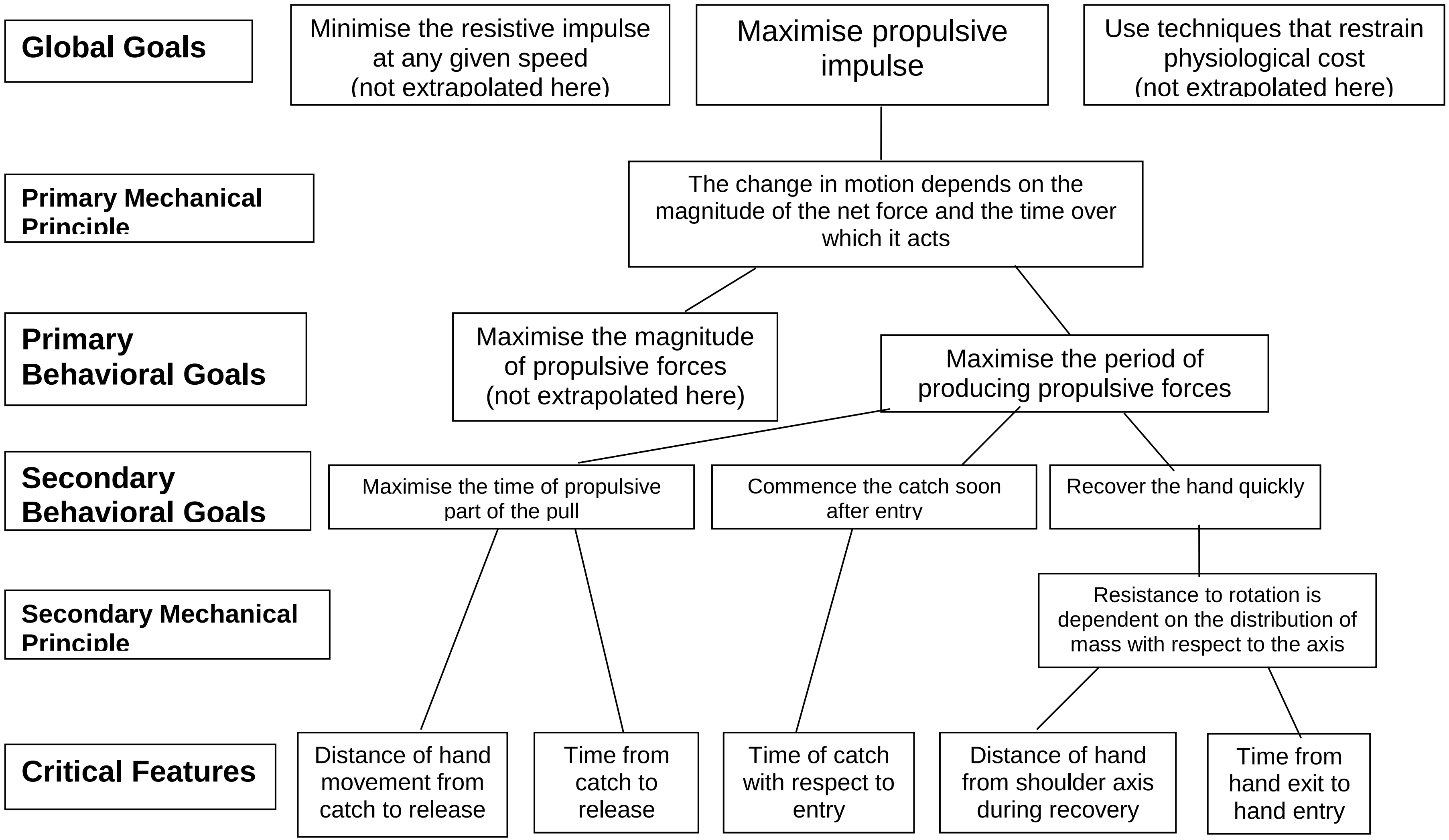

Figure 1 - An example of the alternative model extrapolated for a selected biomechanical principle and behavioral goal.