FUNDAMENTAL HYDRODYNAMICS OF SWIMMING PROPULSION.

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INTRODUCTION

The study of human swimming propulsion is one of the most complex areas of interest in sport biomechanics. Over the past three decades research in swimming biomechanics has evolved from the observation subject's kinematics to a basic flow dynamics approach, following the line of the scientists working on this subject in experimental biology (1, 2).

The understanding of swimming propulsion based on steady-state flow mechanics left many questions unanswered, leading us to apply unsteady mechanisms of force production to resolve them. However, this approach needs to analyze the flow behaviour around the propulsive limbs to identify the phenomena, a difficult task in a swimming pool.

Vortices, circulation, vorticity, delayed stall, stroke reversal, wake, Strouhal number, CFD, PIV and so on are some terms and concepts that have recently been included in the vocabulary of swimming biomechanics and have opened up new ways of research.

METHODS

A compilation of flow visualization methods applied in human swimming research will be presented including: natural or spontaneous bubbles, tuft method, shadowgram, injected dye, reflective small particles, injected bubbles and bubble wall. Simultaneously, some researchers are using Computer Fluid Dynamics to simulate the water and hand and forearm interactions. To quantify the information gathered thanks to the flow visualization methods it is necessary to apply a tool called Particle Image Velocimetry, which gives a velocity vector map of the flow around the propulsive element. This useful tool has been extensively used by biologists to study the wake of the propulsive movements of water animals, but very few studies have been developed in human swimming.

Our work has been oriented during the recent years to applying different flow visualization methods during simple and complex propulsive movements, developing new tools to visualize the wake generated by the human propulsive limbs. Vortices are generated in different magnitude and position after the hand or feet, depending on limb velocity, angle of attack and change of direction of the propulsive path and compared with some water animals.

A clear Karman vortex street was observed after the underwater undulatory swimming of top performers combined with a more efficient Strouhal number. Complex wake structures were observed after simple sculling movements where the lift force is the primary source of propulsion, suggesting the use of stroke reversal to combine the forces generated in both directions. The application of the methods referred to above in normal stroke mechanics seems less clear and more complex. The 3D pulling swimming path increases the difficulty of obtaining clear water wakes around or behind the hand and only incidental vortices are found after very restricted conditions, in spite of the clear wakes generated by the hands in laboratory tests.

CONCLUSIONS

The analysis of vortices generated and 3D analysis of the pulling path seems the most adequate method to develop a new understanding of swimming propulsion in the near future.

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THE USE OF CRITICAL VELOCITY IN SWIMMING? A PLACE FOR CRITICAL STROKE RATE?

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For any swimmer, a hyperbolic relationship links velocity (v) to time to exhaustion (t) (Figure 1). The asymptote of the relationship is called Critical Velocity (CV) and this particular v could be maintained, at least in theory, indefinitely. Stroke rate (SR), changes in a similar manner with time (Figure 1), the asymptote of this relationship being called Critical Stroke Rate (CSR; 2). This comes from the original work of Monod and Scherrer (1), authors of the original Critical Power concept (CP).

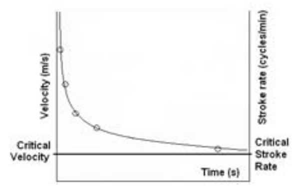

Figure 1: Velocity-time and stroke rate-time relationships

Numerous studies have been conducted on the CP and CV parameters in order to test their reliability, better understand their physiological meanings (3) and validate their use for training. Whilst most of the studies have been conducted in laboratories, mainly on ergometers, some studies have been undertaken in swimming. While being aware of the several assumptions underlying the application of the CP concept in swimming (4), coaches should appreciate the ease in using the CV model to predict performance, set training loads, discriminate effects of training, and establish energetic potentials of swimmers.

Alongside the CV/CP concept, a SR concept has been proposed, CSR being the SR spontaneously chosen by swimmers at CV (2). Knowing the CV and CSR of a swimmer would enable valuable technical work performed around CV.

Further research is required investigating these concepts. However, current available knowledge suggests there is merit in using the parameter for training.

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STATE OF THE ART ON SWIMMING PHYSIOLOGY AND COACHING PRACTICE: BRIDGING THE GAP BETWEEN THEORY AND PRACTICE.

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INTRODUCTION
The description of the art of swimming dates back to 5000 y BC by Egyptian hieroglyphs and paintings. Kahein papyrus 3000 y BC mentioned medical findings related to protection against Schistosomiasis while swimming (Clarys, 1996). The modern history of Swimming Physiology dates back to early 1900's where we recall pioneering work of e.g. Du Bois-Reymond (1905) and Liljenstrand & Stenström (1919) in cardiovascular and metabolic aspects of swimming as well as Hill (1923) who explored the basic relationships between the maximal performance and maximal oxygen consumption describing also the role of lactic acid in the muscle after exercise. Holmer & Åstrand laid the basics for physiological testing of swimmers in 1970's. Since then the literature has accumulated rapidly. The aim of the present paper was to survey the state of the art on swimming physiology as related to coaching practice in order to help bridging the gap between theory and practice.

METHODS
Systematic literature searches were performed through the years 1990 – 2006 utilising EBSCOhost Research Databases and SportDiscus. Ovid Medline was used to scan materials for randomized controlled trials (RCT). The searches were done in three steps using both key words and thesaurus decodes. In the first phase, "Swimming" without any limitations was fed to the system and again with animals excluded, second, "Swimming and Physiology" was used and third, subdivisions were connected to the precedents.

RESULTS
When the time line was kept unlimited a total of 22.192 hits by key words (16.362 by thesaurus decode) were observed with Swimming. When animal experiments were excluded 21.882 (16.067) hits were found. During the 1990 – 2006 there were 9.778 (7.092) papers in English including 2.212 (1.451) in advanced and 688 (507) in intermediate category. When Swimming and Physiology (no animals) were connected 1.975 hits were found, out of which 833 (557 advanced, 110 intermediate) appeared during 1990 – 2006. When the subdivisions were added to the searches the number of papers remained at reasonably low levels to enable content analysis. RCT was found in 61 papers, none with population based sampling. Materials concerning data to be utilised by practitioners in sports coaching and fitness training were well represented in all subdivisions.

DISCUSSION
The major finding was that all subdivisions of swimming physiology included studies that could be considered valid for sports coaching and fitness training. Previous findings of Keskinen (1991) reported 539 items (peer reviewed, books chapters and books) on Swimming Physiology through the years 1893 – 1990. Clarys (1996) reported that by the mid 1990's there were 685 peer reviewed papers on Swimming out of which 18 % were on Swimming Physiology. When these data are connected to the present one, an expansion of scientific approaches in swimming literature can be observed.

CONCLUSIONS
The body of knowledge for the improvement of sports coaching and fitness training in Swimming is large and well represented in all subdivisions of Swimming Physiology.

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ENERGETICS IN COMPETITIVE SWIMMING AND ITS APPLICATION FOR TRAINING.

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INTRODUCTION
Competitive swimming events consist of different distances from 50m to 1500m. The exercise intensity and the relative importance of aerobic and anaerobic energy processes vary depending on the exercise time (and thus swimming distance). Therefore, determining time dependent metabolic profile would provide important information for developing effective training program.

TIME DEPENDENT METABOLIC PROFILE
To determine the time dependent metabolic profile of arm stroke (A), leg kick (K) as well as whole body (S) swimming, the accumulated O2 uptake (AOU) and the accumulated O2 deficit (AOD) were determined at six different water flow rates in a swimming flume, which were estimated to cause exhaustion in 15 s, 30 s, 1 min, 2-3 min, 4-5 min, and 8-10 min, with each stroke. As the results, the AOU increased linearly with exercise time in all strokes, and the increased rate of AOU in A and K corresponded to 70, and 80% in S, respectively. The AOD in A and S significantly increased until 2-3min of exercise time, while the AOD in K more rapidly increased and the AOD

at 30 s was not significantly different from those at 1 min and 2-3 min. The relative importance of anaerobic energy process in three strokes decreased from 78-85% for 15 s to 50 % for 1 min, 30% for 2-3 min, 5% for 8-10 min duration, and it was greater in K than those in A and S until 30 s duration. These findings suggest that the coach should design specific training programs to improve the metabolic capacity for each stroke, and those results concerning time dependent metabolic profile in A, K, and S, gives helpful information to plan training successfully.

ENERGETICS IN SUPRAMAXIMAL SWIMMING UNDER HYPOXIC CONDITIONS

The changes in aerobic and anaerobic energy release in supramaximal swimming lasting 2-3 min were determined under different levels of hypobaric hypoxic condition (a normal condition; 999hPa, 800 m; 912hPa, 1600 m; 836hPa, and 2400 m above sea level; 751hPa). All measurements were done in a chamber where the atmospheric pressure could be regulated. The water flow rate of the supramaximal swimming decreased with decrease in atmospheric pressure. However, when these water flow rates were expressed as percentage of VO_2max determined in each condition, no significant differences were observed among conditions. Mean oxygen uptake determined every 30 s also decreased with effective altitude. Conversely, no significant differences were observed in mean AOD determined every 30 s. Consequently, mean maximal AOD were not significantly different among conditions, either. These results suggest that during supramaximal swimming, rate of aerobic energy release diminished with increase in hypobaric hypoxia, while not only AOD but also rate of anaerobic energy release throughout the exercise were unaffected despite the decreased O_2 demand caused by diminished exercise intensity due to hypobaric hypoxia.

ALTITUDE TRAINING – AEROBIC OR ANAEROBIC?

Training at altitude has been primarily performed for the purpose of improving O_2 transport system, i.e. maximal aerobic power (VO_2max). On the other hand, several studies recently reported that maximal accumulated O_2 deficit (MAOD) and buffering capacity increased after altitude training, and a new possibility that the altitude training may also improve effectively anaerobic energy releasing system was suggested. Therefore, to examine the effects of altitude training on metabolic capacity, two groups (normal group; N and hypoxic group; H) had high-intensity-training 2 times/day, 5 days/week, for 3 weeks under a normal or hypobaric hypoxic condition. Before and after the training period, VO_2max and MAOD were determined. After the training, VO_2max significantly increased in both N and H, and no significant difference was observed in the increase ratio of VO_2max between N (12%) and H (12%). MAOD also significantly increased in both groups, however, the increase ratio of MAOD was significantly higher in H (29%) than N (14%) ($P<0.05$). These results suggest that the high-intensity training could contribute to induce a large improvement of metabolic capacity in both conditions but that the hypoxic training would be favorable for the improvement of the ability to supply anaerobic energy such as MAOD rather than VO_2max.

CONCLUSION

We conclude that metabolic capacity can be improved more effectively if you understand time dependent metabolic profile and you can tax an appropriate training stimulus to the aimed energy system.

BIOPHYSICS IN SWIMMING.

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INTRODUCTION

Swimming performance is judged by the time to cover specific distances (50m to 1500m) or velocity ($v = d/t$). The velocity can be quantitatively analyzed: 1) as a function of the stroke rate (SR) and the distance the body travels per stroke (d/S) that are determined by biomechanics (1) and 2) the energy cost to swim at that velocity (Cs) and the time dependent maximal metabolic power (2). These two factors have to balance and together they explain performance; and they can be affected by training to improve performance (3).

DEVELOPMENT OF THE TOPIC

Craig in 1979 showed that there are specific characteristics of the relationship between v, SR and d/S for each competitive stroke and that these characteristics related these to swimming performance. Termin has demonstrated that the SR-v relationship can be "shifted" (increased 16% d/S_{max} and 8% SR_{max} at v_{max}) by biomechanical training, independent of strength training, and these changes result in improved performance. The biomechanical factors influence drag and efficiency, that are interrelated, and they in-turn determine the metabolic requirements. Drag forces can be evaluated during actual swimming or while being towed. It is comprised of friction, pressure, and wave retarding forces, and at competitive v of 2.2 m/s are ~ 55, 24 and 23% respectively. Drag reduction can be achieved by training and to a lesser extent by special swim suits. Efficiency and the work/time determine the Cs. They are influenced by drag (Wd), water accelerated away from the swimmer (Wk) and acceleration and deceleration of the limbs (Wint), which in-turn are influenced by SR-v relationships (4). The Cs and v determine the metabolic power required to swim at that velocity (3). The total power increases as expressed by $E_{tot} = kv^{1.83}$, is highly variable among swimmers, and decreases with training (3). $E_{tot} = E_{an} + kV_{O2max}\, t_p - kV_{O2max}\, \tau\, (1- e^{-(tp/\tau)})$, where E_{an} = anaerobic (rate of blood lactate increase), V_{O2max} = maximal oxygen consumption, k = O_2 equivalent, τ = time constant for V_{O2max}, t_p = performance time (3). At competitive velocities Cs was least in front crawl and greater in backcrawl, butterfly and breaststroke, respectively, at competitive velocities and are associated with the SR-v curves. For most strokes in longer distance races (v = 1.6 m/s) the division of aerobic (E_{ae}), anaerobic lactic acid (E_{anla}) and anaerobic alactic acid (E_{analac}) sources are 37.8, 43.0, and 19.3%; while for shorter distances (v = 2.0 m/s) they are 19.4, 54.2, and 26.4%, respectively (2). V_{O2max} in over-distance trained (moderate v) swimmers is low and not very variable, while high velocity training increases it 48%, along with 35% in E_{anla}, and resulted in a 27% increase in v_{max}.

CONCLUSION.

The biophysics of swimming can be quantified as v_{max} = SR x d/s and Cs x (Eae + Eanla + Eanala) (Etot). These biomechanical and metabolic factors are greatly variable and each component is changed by training, even in elite swimmers.

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

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INTRODUCTION

Methods of analysing motion have advanced greatly in recent years due to improvement in technology as well as application of scientific approaches. However, analysis of swimming continues to be very challenging compared to many other sport activities due to the fact that swimming is performed at the interface of two media. This paper provides an overview of some of the methods currently used to provide feedback for swimmers and coaches as well as to address scientific questions to understand more about how swimming performance is optimised. The presentation includes methods of collecting data, analysing data, and presenting results for different levels of analysis including qualitative analysis and simple quantitative analysis for immediate feedback, two-dimensional (2D) and three-dimensional (3D) quantitative analysis of kinematics, and deriving forces from the whole body centre of mass. Examples of specific applications and implications are described.

QUALITATIVE ANALYSIS AND SIMPLE QUANTITATIVE ANALYSIS FOR IMMEDIATE FEEDBACK

Various programs provide immediate feedback to swimmers and coaches. The program at the Centre for Aquatics Research and Education (CARE) features outstanding under-water and above-water video equipment controlled from poolside. The data are replayed as digital 'avi' movies in slow and stopped motion on large plasma screens. Other centres, for example, the Centre for Aquatics Research at the University of Granada, and Katholieke Universiteit Leuven, have developed sophisticated automated reporting systems. Several portable systems for quantifying fractional race times and distances of all swimmers in a competition have been developed, for example, the 'Australian' system by Mason and Cossor at the Australian Institute of Sport.

TWO-DIMENSIONAL (2D) AND THREE-DIMENSIONAL (3D) QUANTITATIVE ANALYSIS FOR RESEARCH

Staff and postgraduate students at CARE regularly conduct 2D and 3D data collection and analysis. 2D approaches include the quantification of passive drag and added mass from digitised video data of subjects performing inclined glides, and quantification of movement rhythms and inter-joint coordination in various modes of swimming. 3D approaches are being used to quantify body roll and fine changes in temporal and spatial movement patterns across conditions such as swim speeds, stages of a simulated race, and preferred race distance.

DERIVING FORCES FROM THE WHOLE BODY CENTRE OF MASS

Researchers at CARE have developed a PC version of Jensen's 'elliptical zone' digitising program to yield accurate body segment parameter data. This enables the centre of mass of a swimmer to be calculated accurately so that derived net forces provide an indication of the interplay between propulsion and resistance. This is leading to an improved understanding of how propulsive and resistive forces are produced and how swimming technique can be optimised.

TECHNOLOGY APPLIED TO OPTIMISE TRAINING FOR IMPROVEMENT OF FRONT-CRAWL SWIMMING PERFORMANCE.

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Peak performances in sport require the full deployment of all powers an athlete possesses. The development of those powers require years of hard training. It may be argued that training-time will be especially efficient when devoted to the enhancement of those performance factors that are weak links in the individual performance chain. Developments of measurement technology (with special reference to the MAD-system) have aided the sport scientist in identifying several factors as determinants of performance. These include drag, propulsion technique, and mechanical power (2). The development of this knowledge provides the modern coach with some guide-lines how to design training programmes. However, it may be argued that training-time will be especially efficient when devoted to the enhancement of those performance factors that are weak links in the *individual* performance chain. This implies that on an *individual* level it is necessary to identify in what phase of the process the performance system first becomes insufficient. Those factors when improved would immediately contribute to overall performance and, consequently, training time allotted to these factors would be well spent.
In the training process it is rather challenging for coaches to determine which training load is sufficient to induce the

required adaptation without risk of overtraining. More insight in the individual relation between training dose and adaptation response is necessary to optimise this training process.
Training dose and changes in performance capacity can be modelled (1). In this model performance is a systems output varying over time according to the systems input; the training dose or training impulse (TRIMP), quantified from exercise intensity and volume. The subject is represented by a system with a daily amount of training as input and performance capacity as output.
It is possible to use heart rate recordings as indicator for the training dose while simple time trials can be used to monitor the development of the performance capacity (see Figure 1). A sketch will be given how technological developments leading to instrumented swimming wear could be put to use to optimise the training process.

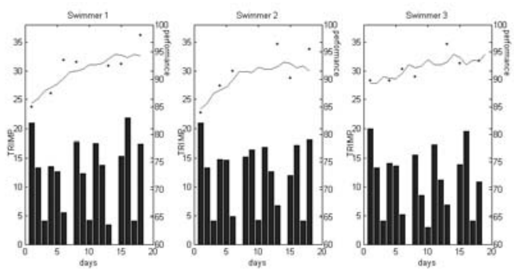

Figure 1: Bars represent TRIMPs; line represents predicted performance; dots represent criterion performance.

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