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Swimming Physiology

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Swimming takes place in a medium, that presents different gravitational and resistive forces, respiratory conditions and thermal stress compared to air. The energy cost of propulsion in swimming is high, but a considerable reduction occurs at a given velocity as result of regular swim training. In medley swimmers the energy cost is lowest for front crawl, followed by backstroke, butterfly and breaststroke. Cardiac output is probably not limiting for performance since swimmers easily achieve higher values during running. Maximal heart rate, however, is lowered by approx. 10 beats/min during swimming compared to running. Most likely active muscle mass is smaller and rate of power production lesser in swimming. Local factors, such as peripheral circulation, capillary density, perfusion pressure and metabolic capacity of active muscles, are important determinants of the power production capacity and emphasize the role of swim specific training movements. Improved swimming technique and efficiency are likely to explain much of the continuous progress in performance. Rational principles based on improved understanding of the biomechanics and physiology of swimming should be guidelines for swimmers and coaches in their efforts to explore the limits of human performance. (Ann. Physiol. Anthrop. 11(3): 269-276, 1992)

Key words: Biomechanics, Circulation, Energy expenditure, Respiration, Technique

Swimmers continue to break world records more frequent and with greater margins than in most other sports. This is in part a result of larger volumes of training work, but also of a better understanding of rational principles of training. The physical and physiological requirements of a sport are the fundamental determinants of the design of a training program.

Swimming as a form of exercise is unique in many respects. It takes place in water, that presents completely different gravitational and resistive forces compared to air. It is performed in a lying position, which alters gravitational effects on circulation. Breathing is restricted by stroke mechanics and the aquatic environment. Thermoregulatory demands do not compete with metabolic demands during heavy exercise in water at temperatures normally found during training and competition.

As a result of intensified research during the last two decades the science of swimming is better understood. Rational principles based on improved understanding of the biomechanics and physiology of swimming should serve as guidelines for swimmers and coaches in their efforts to develop the capacities of their adepts and explore the limits of human performance. Several reviews have been recently published on various scientific aspects of swimming (Cordain and Stager 1988; Costill, et al. 1992; Holmér 1980). Much of this new information may also be found in modern handbooks of swim training (Costill, et al. 1992; Maglischo 1982).

Research Methodology

The arrival on the market of swimming treadmills (Åstrand and Englesson 1972) started on era of intensified research on various aspects of human performance in aquatic environments. In principal, water is circulated in a closed loop system in a specially designed pool or "flume". The circulation is directed and controlled in such a way that one section of the flume, the test basin, receives an essentially laminar and constant flow of water. In this basin the swimmer swims "on the spot" (like running on a treadmill) at a speed controlled by the experimenter (water velocity).

The swimmer in the swimming flume may be equipped with more or less sophisticated transducers, easily connected to measuring instruments and recording devices at poolside. Continuous measurements of metabolic, cardiovascular and muscular parameters were made possible. The following review is a brief presentation of some of the research carried out in the swimming flume at the college of physical education in Stockholm, Sweden.

Propulsion in Swimming

The long prevailing theory of drag forces as the single and prominent source of propulsion has been abandoned, as a result of intensive research on the biomechanics of swimming (Counsilman 1971; Schleihauf Jr 1974; Schleihauf, et al. 1988; Toussaint 1988; Wood and Holt 1979). It is now generally recognized that propulsion is derived from the combined action of drag and lift forces. Lift forces are generated perpendicular to the traveling direction of the limb (hand or foot) and is function of angle and traveling velocity. The contribution of lift, originally, was used to explain the very curvilinear stroke pattern of elite swimmers (Counsilman 1971). It is readily understood that propulsion is the result of a complex and delicate interaction of the two forces acting perpendicular to each other in a three dimensional system. The challenge of today's coaches is the understanding of the underlying principles and their application to the individual swimmer's qualifications and capacities.

Swimming movements are quite different from walking and running movements. The specificity of swim training, therefore, is quite obvious. Extensive time has to be spent on learning and training the types of movements engaged in swimming. Propulsive and recovery phases of strokes must be adapted to conditions and capacities of each individual and be based on rational hydromechanical principles.

Water Resistance

The swimmer applies force to the water to accelerate his body and overcome the resistance of the water against propulsion. Numerous investigators have shown the dependence of resistance on body size, body cross-sectional area, body form, position in water etc. in prone, horizontal position (see e.g. (Clarys 1979)). In general females experience less resistance at a given velocity, not only due to their smaller body size, but also because of their body build (shorter legs) and composition (higher percentage body fat) resulting in a higher and more horizontal position in the water.

During actual swimming resistive forces become more complex (active drag). During recovery phases of the stroke cycle, body limbs, in particular, may considerably increase the cross-sectional area (legs in breaststroke). Various techniques have been applied to the study of active drag. Pendergast et al. (1974) and Holmér (1974b) used an indirect method and reported active drag values 2-3 times higher passive drag values for the various strokes. Other investigators using calculations based on videotape recordings (Schleihauf Jr 1979) or force measuring apparatus (Toussaint 1988) found little or no difference between the two. The accurate determination of the various forces exerted by and on the swimmer should be the subject of more investigations.

Energy Cost of Swimming

If the velocity within a stroke cycle is assumed to be constant, the following expression can be applied to the energy balance of the swimmer:

$$v = E \cdot \frac{e}{D}$$

where E is the overall energy production rate, e is the mechanical efficiency, and D is the water resistance to overcome. This simple expression is a good basis for the analysis of swimming performance. Consider the following

$$v_{max} = E_{max} \cdot \frac{e}{D}$$

where v_{max} is the maximal attainable velocity and E_{max} is maximal total energy production rate of the swimmer.

It is readily seen, that v_{max} can increase (the ultimate goal of swim training) by increasing E_{max}, or by increasing the ratio e/D. The first is achieved by training of the capacity of the cardiovascular system to deliver oxygen and the muscle tissues to take up and utilize it. The second is achieved by improving the neuromuscular function of active muscles by proper swimming technique and by minimizing resistive forces. Most swim training today is devoted to improving E_{max}, through training of aerobic and anaerobic capacity. It is much more difficult to improve e/D, because of the lack of knowledge by many coaches and the lack of simple and objective evaluation methods.

The potential for improvement of performance is likely to be as high or even higher for the technical components compared to the physiological capacities. Much more attention should be paid to this in the swim training program.

Energy expenditure rate increases exponentially with velocity. This is mainly due to the exponential increase in drag. At very high velocities a decrease in efficiency may contribute to a sharp increase in energy expenditure (Pendergast, et al. 1978).

The energy cost of swimming depends of many factors, such as water resistance, swimming technique and style. Figure 1 shows the oxygen uptake of three swimmers representing different levels of skill. The energy cost of the unskilled swimmer is almost twice as high at a given velocity as for the elite swimmer. In addition the elite is able to sustain a higher level of oxygen uptake and swim at a much higher velocity.

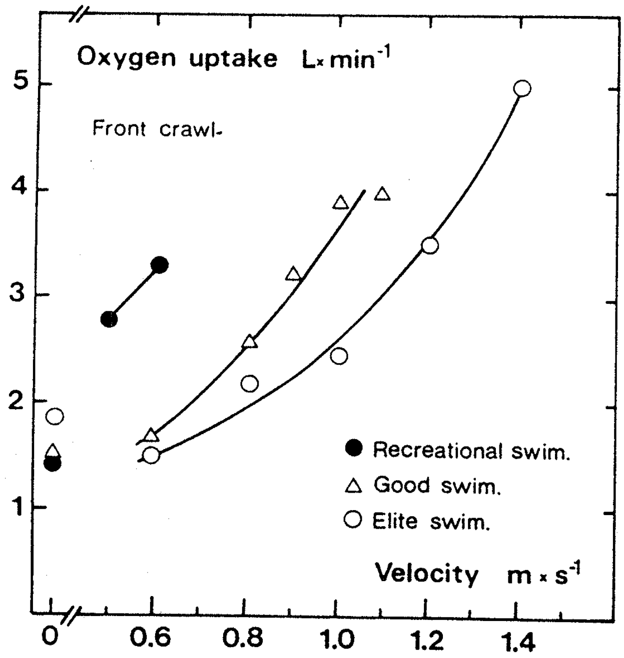

Fig. 1 Oxygen uptake of three male swimmers of various capability swimming front crawl. Also depicted is the oxygen uptake during water treading.

Breaststroke and butterfly are more expensive at a given velocity than the more continuous front crawl and backstroke. Figure 2 shows the average energy cost for trained swimmers in the different swim strokes.

The energy cost of running a leg kick is high in most strokes (Holmér 1974a). The value of leg kicking, therefore, must be evaluated in terms of its net contribution to propulsion. In breaststroke and butterfly, evidently, play an important role during the recovery phase of arms. In continuous strokes like front crawl and backstroke the picture is more complex. In long distance events ($\geq$400 m) the role of leg kicking may be reduced to stabilizing a prone body position and create reactive forces to rotating elements of the arm stroke.

The maximal aerobic power of male and female elite swimmers are given in Figure 3. The average

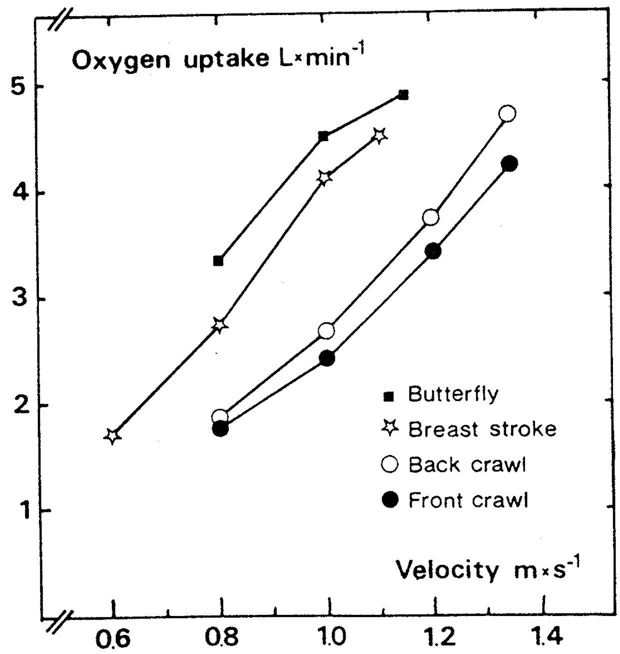

Fig. 2 Mean values for oxygen uptake during swimming different strokes by proficient swimmers.

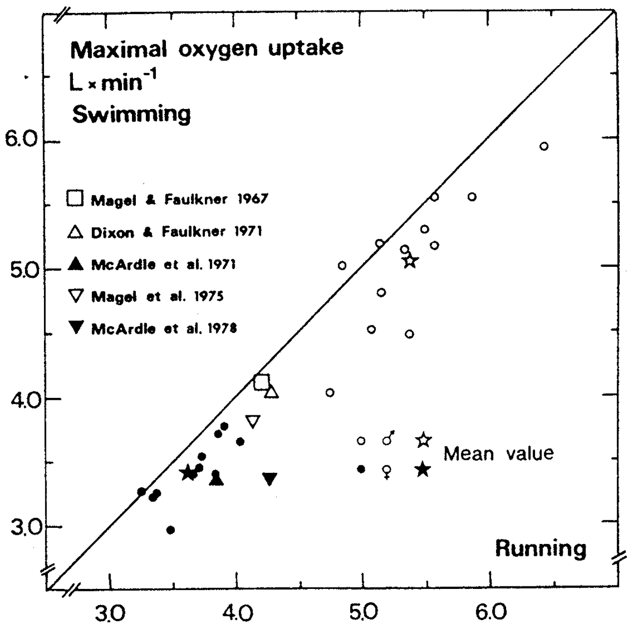

Fig. 3 Maximal values for oxygen uptake during swimming and running by elite swimmers. Mean values for male and female group are denoted, and compared with mean values reported in other studies.

value for Swedish males were 5.1 l/min and for females 3.4 l/min. The higher values for the Swedish swimmers in comparison with swimmers of other countries may reflect the great emphasis on aerobic training given by Swedish coaches. Apparently, they don't swim that much faster than their competitors, which justifies the suggestion above on more emphasis on technique and propulsion efficiency.

Physiological Adjustments

Although it is of fundamental importance for performance to optimize stroke mechanics, it is equally important to consider the physiological limitations to metabolic power production and muscular work. In the following sections these problems will be dealt with in more details.

As seen in Figure 3 elite swimmers were not able to attain the same high values of oxygen uptake during maximal swimming as in running, the difference being 8-10 % (Holmér, et al. 1974a). The cause of this difference should be found in limitations in respiratory, central circulatory or peripheral/muscular capacities for oxygen transport and utilization.

Pulmonary ventilation is controlled by stroke rate and the constraints imposed by water and body position. As expected maximal ventilation rate is

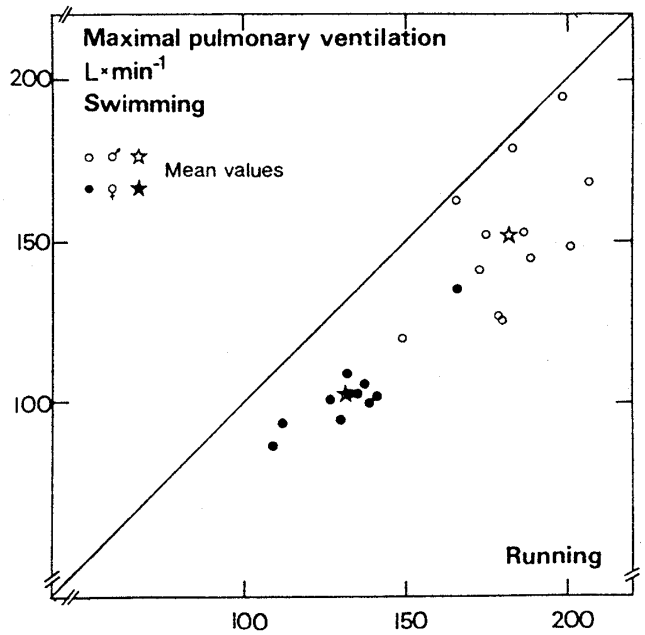

Fig. 4 Maximal pulmonary ventilation during swimming and running by elite swimmers.

lower than for running (Figure 4). On the other hand ventilation per liter oxygen consumed indicates normal ventilation rather than hyperventilation, which is often seen during maximal running.

The restrictions on breathing would indicate difficulties with oxygen saturation of blood in the alveoli, suggesting pulmonary diffusion being limiting for maximal oxygen uptake. However, arterial blood samples taken during maximal swimming show similar values for arterial oxygen saturation and oxygen pressure, as for maximal running with unrestricted breathing (Holmér, et al. 1974b).

Figure 5 shows the cardiovascular adjustments to swimming at incremental velocities up to maximal. It is readily seen that cardiac output at a given oxygen uptake is about the same in swimming as in running, maximal value, however, being significantly lower in swimming. A tendency could be observed that stroke volume attained higher value and heart rate lower value at a given sub maximal oxygen uptake. This has also been observed in tethered swimming compared to running (Magel 1971).

At maximal level heart rate is about 10-15 beats/min lower in swimming than in running (Figure 6). One good explanation for this could be the better diastolic filling with supine body position, negligible gravitational effects and limited thermoregulatory adjustments. On the other hand mean arterial pressure tended to be higher in maximal swimming compared to running, indicating a higher peripheral resistance of the vascular bed (Holmér, et al. 1974b).

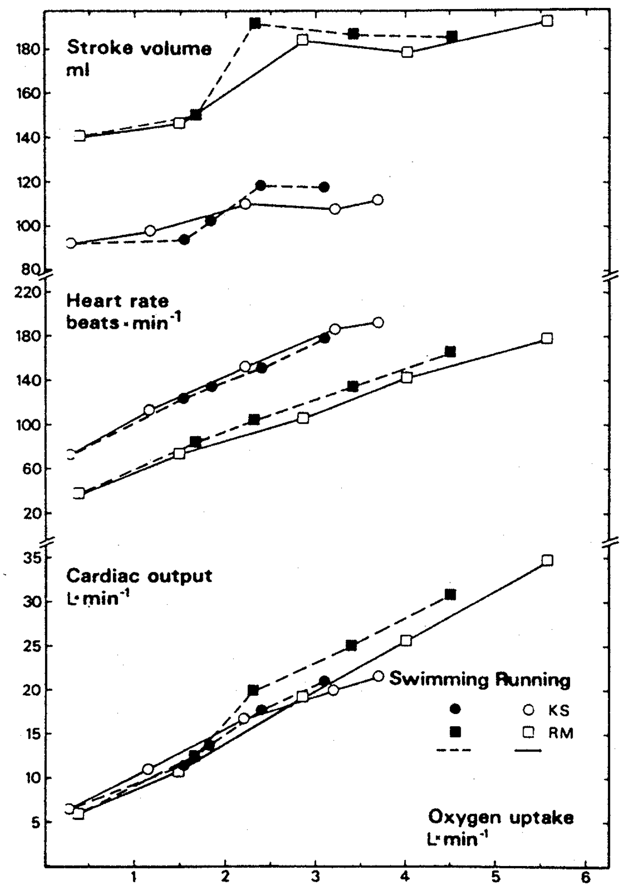

Fig. 5 Circulatory responses to swimming breaststroke in two subjects of different capability.

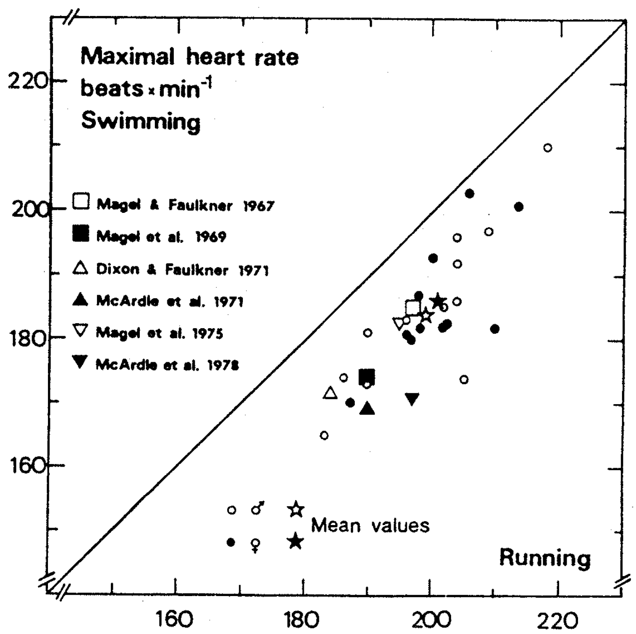

Fig. 6 Maximal heart rate during swimming and running by elite swimmers. Values are compared with reported data from other studies.

One obvious explanation for the lower maximal power output of elite swimmers in swimming compared to running is lower cardiac output. This may be caused by the smaller size of the active muscle mass, as swimming is predominantly arm work. Also, perfusion pressure may be lower with gravitational forces almost eliminated. The elevated mean arterial pressure in some swimmers might indicate, that the work of the heart is the same and maximal in both forms of exercise, thus representing an upper limit of performance. Further studies are required to elucidate the details of these cardiovascular responses.

Training for Improved Performance

Performance in swimming is the result of a complex interaction of physical, biomechanical and physiological factors, as well as psychological factors. It is a clear, but often forgotten, fact that most swimmers compete in events lasting less than 2 minutes. Nevertheless, their training program comprises thousands of meters swum to increase maximal oxygen uptake. As already mentioned above, too much emphasis, at least in Sweden, is probably placed on aerobic training at the expense of other important components.

It has been claimed, but not proven, that swimming with controlled frequency breathing improves the anaerobic power. This type of suppressed breathing, however, does not produce metabolic acidosis but respiratory alkalosis (Craig Jr 1979; Holmér and Gullstrand 1980). Hence, it would not affect maximal power output. On the other hand there may very well be a biomechanical effect reducing drag (Holmér and Gullstrand 1980). From this point of view such a training program might be justified, the major effect be an improved tolerance to hypercapnea.

Training for improved aerobic capacity is rather straight forward and must be a basis of the program, but must be balanced against anaerobic training, muscular power training and technique training. The specificity of swim training is well documented (Gergley, et al. 1984; Holmér and Åstrand 1972). Figure 7 shows the variation in maximal oxygen uptake of a world class swimmer during his most successful years. It is readily seen that the maximal aerobic power related to swimming and, in particular, to arm swimming was sensitive to variations in swim training intensity, whereas the maximal aerobic capacity during running remained constant. Research on anaerobic training and the value of lactate tests for assessment of training intensity and dose has been extensive, valuable and useful. With the advent of versatile video cameras and specific computer programs the technique component could possibly regain some of the importance it should have in a modern swim training program. A comprehensive review of the

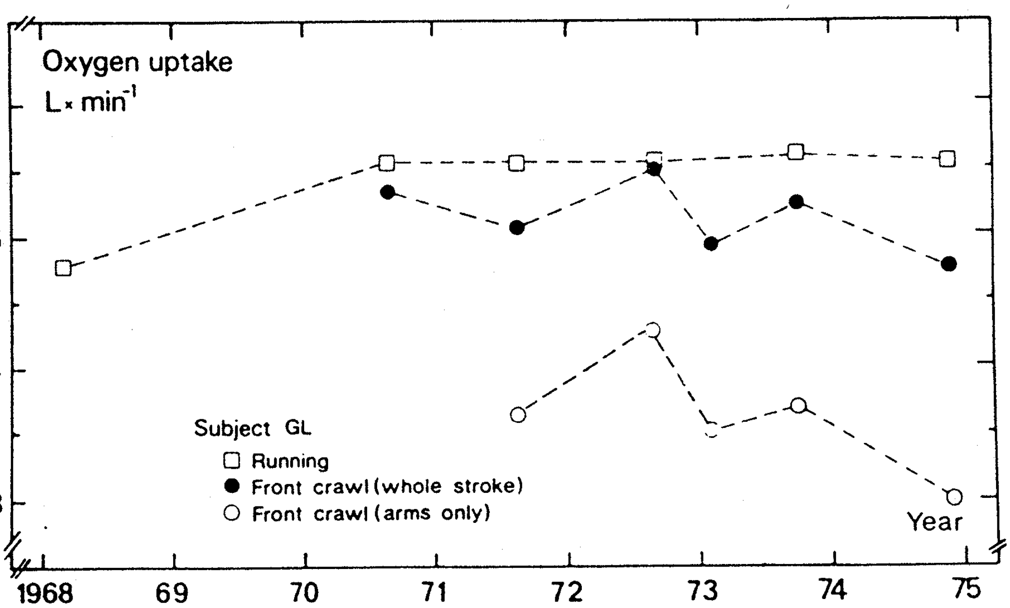

Fig. 7 Oxygen uptake during maximal effort in different types of exercise in a world-class swimmer over a period of eight years.

scientific basis for swimming and its application to training can be found in (Costill, et al. 1992).

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