FROM TECHNICAL FOUNDATIONS TO INCREASED EFFICIENCY IN SWIMMING

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In this presentation a model of swimming performance based on work, energy, and efficiency is introduced. Examples are provided throughout to emphasise the importance of technique in relation to energy cost and efficiency.

KEY WORDS: swimming, efficiency, technique.

INTRODUCTION: From an energy perspective swimming performance depends on the ability to maximise kinetic energy possessed by virtue of whole body motion in the desired swimming direction. This 'output' is achieved within the physiological capacity of the swimmer to produce energy for muscular contraction 'input'. A swimmer seeks to maximise the energy output in terms of relative to the energy input, that is, the 'efficiency' to improve performance. The efficiency of the swimmer is given as:

$$\text{Efficiency} = KE_{wbsd}/Work_{ph} \quad (1)$$

Where KE_{wbsd} is the kinetic energy due to motion of the whole body in the swimming direction and $Work_{ph}$ is the physiological work. The efficiency depends on a number of processes in which work either contributes to the output or is lost (Figure 1).

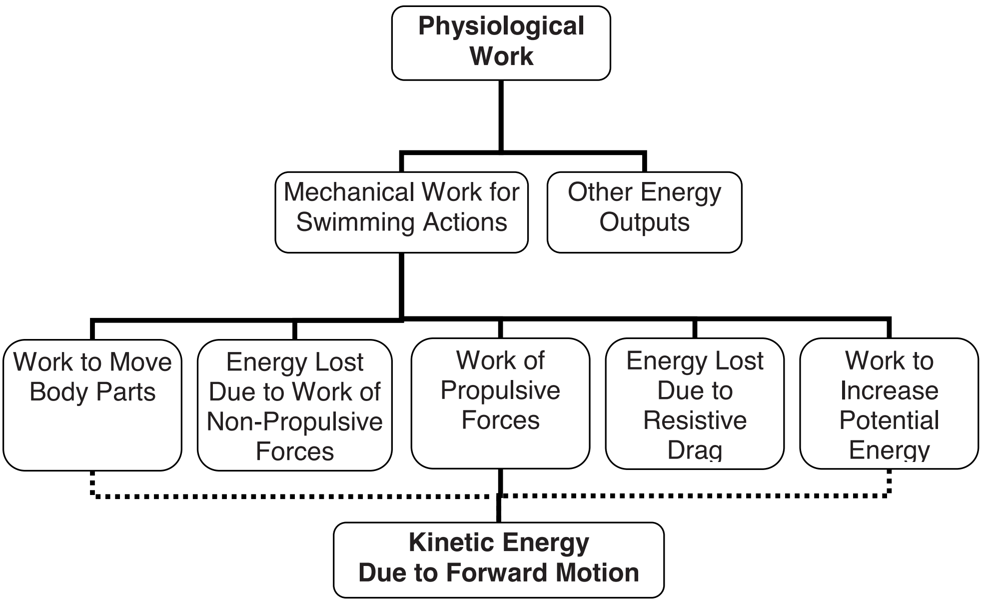

Figure 1: Model of energy and work variables in swimming.

Looking at each of the elements of the model:

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PHYSIOLOGICAL WORK: Improvements in performance can be gained without improvements in efficiency by increasing the physiological work capacity. Thus, enormous emphasis is accorded training in a manner that maximises capacity to deliver energy through metabolism in the muscles. The rate of energy supply, power, is maximised by astute training regimes to emphasise the contributions of aerobic, anaerobic, and ATP metabolic contributions appropriate for the event (Maglischo, 2003).
However, the magnitudes of all the other terms in the model are strongly dependent on technique. As a swimmer approaches their ultimate potential for work, their only recourse to improve performance is to increase efficiency by improving technique.

MECHANICAL WORK FOR SWIMMING ACTIONS AND OTHER ENERGY OUTPUTS: Not all of the energy provided by metabolic processes in the muscles is used to create motions of the body parts relevant to swimming. Energy is used by muscles that maintain posture. Energy is used by muscles working as antagonists and in stabilising the joints during the actions. Energy is also used by agonists and antagonists of joints when there is no useful contribution to be made to the swimming actions. For example, a skilled swimmer will allow the muscles to relax when they are not required to generate force related to the swimming motions. This is evident in the relaxed recovery of the arms of a skilled swimmer compared to the very 'stiff' and effortful recoveries of less skilled swimmers. The latter tend to over-control the recovery and entry, activating muscles inappropriately and wasting energy. The same may apply with the activation of postural muscles that contribute nothing to the swimming motion. Relaxing muscles when not required to generate force may be learned with practice but may also need to be encouraged by coaches and consciously implemented by swimmers. Even swimmers at a high level may be wasting energy by not relaxing muscles that aren't required to propel the swimmer or maintain a streamlined posture. Perhaps some swimmers waste energy in important events because they 'tighten up' thereby expending energy that could have been used to assist their performance. We actually do not know much about the extent to which these energy losses may occur.
However, muscle activity can be measured by electromyography (EMG) and there is great scope to learn more about how skilled swimmers activate and relax muscles in swimming to improve their swimming efficiency. Obtaining EMG data from swimmers has been problematic in the past but recent developments in technology using wireless EMG systems (for example, Kine ehf, Iceland: www.kine.is) that can be used in water have offered the opportunity to conduct studies to address these important questions.

WORK TO MOVE BODY PARTS: The muscles contract and convert the energy previously stored as chemical energy to kinetic energy of translation and rotation of the body parts, some potential energy if the body part is raised, and perhaps some elastic energy in elastic elements of the muscle and tendon complex. Putting the body parts into motion requires energy but does not contribute to propulsion unless that energy is used to push water backwards. For example, the hands may be oriented so that they slip through the water rather than move water backwards to propel the body forward. We see many examples of energy being spent to move body parts without the motion contributing to swimming speed – the head being thrown about, arms spinning like a windmill, legs thrashing.

WORK OF PROPULSIVE FORCES: However, doing work to move the limbs affords the opportunity to do work against the water to generate external forces. The extent to which forces are generated, and the extent to which the forces are in the desired direction, depends on the technique. Skilled swimmers have learnt to optimise the forces generated from their actions by maximising the mass of water pushed in a backward direction (Toussaint et al., 2005). This is achieved by strategies such as maximising the surface area of the limbs pushing against the water, generating and shedding vortices (Ungerechts, Persyn, & Colman, 1999), using well timed actions and changes in direction, and orienting the limbs, hands and feet in particular, so that the reaction forces generated are in the forward direction despite the motion not being directly backwards.

ENERGY LOST DUE TO WORK OF NON-PROPULSIVE FORCES: When the moving body parts push water in component directions other than backwards, that is, laterally or vertically, energy is lost to the water without benefit in terms of increasing the kinetic energy of motion in the desired direction of swimming. Techniques in front crawl characterised by 'digging', 'straight arm pull', and 'dropped elbow pull' are inefficient because much energy is used to push the water in directions other than backwards. This does not mean that all actions must be in the backward direction, but actions that are not backwards should result in water being accelerated backwards. The hands and feet should be oriented to push water backwards in the breaststroke actions even though the actions are not backwards. However, some actions are beneficial even though much of the reaction force may be in directions that do not contribute to forward motion. An example is the outward sweep of the hands in breaststroke and butterfly. This action helps to elevate the body to breathe and to generate an undulating rhythm that may lead to propulsion through the actions of other body parts.

ENERGY LOST DUE TO RESISTIVE DRAG: Much of the energy generated by the swimmer is lost to the water due to resistive drag (Vorontsov & Rumyantsev, 2000). Resistive drag comprises wave drag, surface drag (skin friction), and pressure drag (form drag). Wave drag is due to the swimmer moving at or near the interface of air and water. The waves that emanate from the moving body represent energy that has been absorbed from the swimmer (Vennell, Pease, D. & Wilson, 2005). A swimmer's technique can influence the magnitude of wave drag. For example, vertical forces that create 'bouncing' of the body increase the magnitude of wave drag. Surface drag is due to the friction between the water molecules and the surface of the swimmer's body parts as they move forwards through the water. Swimmers seek small reductions in surface drag by shaving down and by wearing swimming costumes with textures that minimise surface drag (Roberts, Kamel, Hedrick, McLean, & Sharp, 2003). Pressure drag is due to pressure differences between the front and rear surfaces of the swimmer's body parts. It depends on the body shape and alignment of the body and limbs (Benjanuvatra, Blanksby & Elliott, 2001). A swimmer's technique influences pressure drag (Clarys, 1979 ; Berger, Hollander & De Groot, 1997). A swimmer tries to 'streamline' as much as possible to reduce the areas of high and low pressure. Good technique contributes to being able to maintain good postures that minimise cross sectional area to the flow and pockets of low pressure. Alignment is often disrupted, particularly among unskilled swimmers, by unwanted torques due to the limb and body actions. For example, swinging the arm wide in the recovery in front crawl causes the legs to splay outwards thereby increasing the cross sectional area striking the oncoming flow. Balancing the torques due to the arm actions in backstroke is important to avoid the body and legs swaying out of alignment. A 'catch up' technique in front crawl helps to keep the legs elevated so that the pressure drag is minimised.

Uneven contributions by right and left sides create asymmetries that may increase resistive drag due to body sway or limbs swinging out of alignment to compensate for unbalanced torques. Uneven contributions and differences between right and left sides in front crawl is often associated with continually favouring one side to breathe. The head, in particular, can lose its alignment. Body roll and associated rhythm of the stroke is often upset by rolling more to one side than another. These asymmetries can lead to alignment that is not optimal for streamlining and compensatory limb motions that increase resistive drag. This emphasises the need to teach bilateral breathing early in the development of swimmers.

WORK TO INCREASE POTENTIAL ENERGY: Potential energy is gained when body parts are raised above the water surface and are therefore the gravity force is not offset by the buoyancy force. Raising body parts out of the water requires work equivalent to the energy gained. The arms are raised during the arm recovery in backstroke and front crawl. The head and upper body are raised in butterfly. In breaststroke more work is required to raise the upper body in the undulating style than the flat style.

TRANSFER OF ENERGY: As discussed above, body parts may possess energy as kinetic energy of translation, kinetic energy of rotation, and gravitational potential energy. The work

of internal forces and torques across joints may transfer this energy to other sites, such as the feet or hands, where the energy can do work against the water to produce propulsive force. There is evidence that this occurs in butterfly swimming (Sanders, Cappaert & Devlin, 1995). The action of raising the upper body to breathe generates potential and rotational kinetic energy of the upper body that is transferred to the lower body and culminates in a propulsive kick. The timing of the segments gaining and losing energy indicated that some of the energy contributing to the kicking action does not need to be generated by the muscles of the lower limbs normally involved in kicking. The re-use of energy in this way contributes to efficiency in butterfly swimming and explains why skilled swimmers such as Michael Phelps can swim 200m butterfly in a time that is only 8 seconds slower than 200m front crawl despite the work done to raise the upper body and despite having only one arm pull per cycle. By contrast, a swimmer who has not yet developed the correct coordination and 'rhythm' in butterfly swimming is quickly exhausted.
Wavelike sequences of coordination are also evident in front crawl with six beat kick (Sanders & Psycharakis, 2009). Skilled front crawl swimmers generate torsional waves that travel at moderate speeds from hips to feet due to sequencing of hip, knee, and foot roll about the longitudinal axis of the body. While it is established that the torsional wave is characteristic of elite front crawl swimmers using the six beat kick, the benefit of the travelling body wave with regard to energy saving is less clear at this time than in butterfly swimming.

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