ABSTRACT

The amount of metabolic energy spent in transporting the body mass of the subject over a unit of distance has been defined as the energy cost of locomotion, or regarding to swimming, cost of swimming. The differences in the cost of swimming between the individuals seem to be influenced by two main factors, the hydrodynamic resistance and technical skill of the swimmer. The lower cost of swimming showed by females has been attributed to a smaller hydrodynamic resistance due to their smaller size, larger percentage fat and more streamlined position. However, the difference in cost of swimming between males and females disappears when correcting for body size. With regard to children, the higher energy cost of swimming when correcting for body size may be caused by the lower swimming technique showed by them. For individuals with the same anthropometric characteristics, the better swimming technique and larger size of propelling surface, associated with higher propelling efficiency, may decrease the energy cost of swimming. When comparing different types of strokes, the most economical stroke is crawl, followed by backstroke, irrespective the swimming velocity. Butterfly is the less economical at low velocities (<0.8 m·s⁻¹). However, above that velocity the breaststroke become the less economical stroke.

INTRODUCTION

Water resistance or drag is the main force to be won during locomotion in water. Since water density is approximately 800 times higher than the air’s (998.2 vs. 1.205 kg·m⁻³ at 20°C and 760 mmHg), it requires a high energy cost. Another important characteristic of locomotion in water is the large quantity of energy which is transferred to it during the movement’s performance. Contrary to the majority of activities on land where the impulse is performed against the ground which cannot be accelerated, during swimming the propulsion is performed against water, which can suffer acceleration. Therefore, the swimmer accelerates a certain water mass transferring an amount of kinetic energy in order to generate propulsive force. Such fact causes a certain part of the energy produced by the swimmer to be used in order to move water backwards instead of moving the swimmer forward. Consequently, the gross efficiency in swimming seems to vary from 3 to 10% depending on the velocity and the swimming style applied, while other sports on land vary between 20 and 40% [2]. Both factors make swimming an activity with a high energy cost of dislocation as well as very low maximum velocities [2].

The characteristics involving both the resistive and the propulsive forces previously described reinforce the large technical component present in swimming. Nonetheless, the main issue is not simply how to maximize the propulsive force and minimize resistance, but certainly how to perform it together with finite metabolic capacities. Therefore, the maximal performance in swimming is reached through the association between maximal metabolic power (aerobic and anaerobic) as well as the athlete’s locomotion economy (to maximize propulsion and to minimize resistance). Having these aspects as grounding, we will discuss in detail in this review the swimming energy cost and some of its determining factors.

MEASUREMENTS OF ENERGY COST

Different procedures have been used for the determination of the energy cost in swimming. The measurement of oxygen uptake (VO₂) during and immediately after exercise offers an indirect method for the estimation of the energy cost. The VO₂ is directly connected to the energy cost when the effort intensity is performed at a steady state or at intensities below the Lactate Threshold (LT) [2]. Several techniques have been developed in an attempt to estimate the VO₂ during swimming [4]. Initially, Montpetit et al. [3] introduced a technique consisting of the retro extrapolation of the VO₂ recovery curve in order to determine the VO₂ during swimming. In this protocol, the exhaled gas was continuously collected by the first 20 or 40 seconds after swimming [4]. Such procedures have the great advantage of allowing the athlete to perform swimming without restrictions presented by some evaluation instruments. Moreover, this method (retro extrapolation) has been valid (r = 0.99) and reproducible (r = 0.92) for the determination of the VO₂max [4]. Recently, continuous measurements of VO₂ have been taken during attached swimming [5], swimming flume [5] and free swimming [6]. The only procedure to quantify the swimmer’s economy or the swimming cost is determining the energy cost for the given activity. The amount of metabolic energy used in transporting one’s body mass by distance unit has been defined as energy cost of locomotion, or specifically for swimming, swimming cost (Sc, kJ·m⁻¹). The Sc has been usually measured through the ratio between the VO₂ and its corresponding progression velocity for velocities within the zone of aerobic intensities [2,6]. Besides that, the Sc has also been estimated in supramaximal velocities in which the anaerobic energy contribution is considered in the calculation of the exercise total energy balance [3,10]. Results of some studies which investigated the Sc have suggested that height (H) [11,12], body mass (M) [13], body surface area (BSA) [6-7], passive torque [9], floating [8], and differences in technique [13] may influence the Sc in swimming.

GENDER EFFECT

It has been acknowledged in the literature that female swimmers are more economical than male ones [2,4,14]. Nevertheless, the reasons for this difference are very controversial. In competitive swimmers, the Sc in the front crawl at 0.9 m·s⁻¹ is approximately 30% lower in women when compared with men [4]. For the backstroke, Klentrou and Montpetit [13] found a difference of 14% in the
The alterations that occur from childhood to adolescence are important since they are concerned with changes in the morphological and physiological characteristics as well as mechanical capacities[20]. Children tend to float with lower passive torque than adults, especially by the shorter distance between the mass center and the floating center, which are the points that interfere in the position the individual is when submerged in water[23,22]. It has also been suggested that the passive torque is the main determinant of the $\text{Sc}$ regardless the gender and swimmer’s skill[20,4,6,16]. Chatard et al.(6) analyzed the $\text{Sc}$ in 101 swimmers and divided them in three groups with different performance levels. Differences in the absolute value of the $\text{Sc}$ were not found among the three groups. However, the authors observed that the higher the performance level, the larger the swimmer’s dimension. Nevertheless, these results should not be only attributed to differences in body mass (higher rest metabolic rate), but as mentioned before, to its relationship with drag.

AGE EFFECT

The $\text{Sc}$ at a given velocity greatly varies from one swimmer to another. These variations especially depend on the swimmer’s technical skill[6,14,16,27]. Chatard et al.(6) analyzed the $\text{Sc}$ in 101 swimmers and divided them in three groups with different performance levels. Differences in the absolute value of the $\text{Sc}$ were not found among the three groups. However, the authors observed that the higher the performance level, the larger the swimmer’s dimension. Thus, the larger size of the best performance group made the analysis of the technical level effect over the $\text{Sc}$ difficult. Nevertheless, when the $\text{Sc}$ was expressed in relation to the $\text{BSA}$ the difference between groups occurred, demonstrating that more skilled swimmers have a lower $\text{ScBSA}^{-1}$ for the same velocity. Similar results were also found by Chatard et al.[12,12,16] in a group of 58 female swimmers. Since the $\text{Sc}$ increases with the $\text{BSA}$ for individuals of same technical skill, taller individuals are in disadvantage in long-distance bouts[6,7]. Thus, the best long-distance swimmers are shorter and lighter, as revised by Lavoie and Montpetit[28], while in velocity bouts taller swimmers with greater muscular mass may swim faster, especially due to their great quantities of energy in a short period of time[28].
Chatard *et al.* demonstrated in their study that in order to swim at a given velocity, long distance swimmers use an average of two leg kicks per arm-stroke cycle, while velocity swimmers used six leg kicks per arm-stroke cycle. Swimmers who used lower number of leg kicks per arm-stroke cycle (arm-stroke swimmers) have behaved more economically than the swimmers who used greater number of leg kicks per arm-stroke cycle (leg kick swimmers). Holmer and Hollander *et al.* have shown that leg kicks are 3 to 4 times less efficient than arm-strokes. Leg kicks require proportionally greater oxygen consumption than arm-strokes, as well as contributing little in propulsion. These results do not conclude that arm-stroke swimmers are faster than leg kick swimmers. Conversely, the leg kick swimmers may swim faster than the arm-stroke swimmers if they have a great aerobic and anaerobic power. However, it is worth mentioning that high aerobic power and high efficiency are not necessarily related.

**EFFECT OF THE DIFFERENT SWIMMING STYLES**

The Sc of the different swimming strokes is demonstrated in figure 1 and table 1. In the trial of going beyond the mere presentation of the different findings in the literature, figure 1 was designed from the data of several studies. Moreover, through linear and non-linear regressions it was possible to generate specific equations between the Sc and the velocity for each swimming stroke. For the front crawl and the backstroke the Sc demonstrated an exponential increase in relation to the swimming velocity. Nevertheless, for the breaststroke this increase was linear, and for the butterfly stroke the increase had a polynomial characteristic. As can be observed in table 1 and also demonstrated by Capelli *et al.*, the most economical stroke is the front crawl followed by the backstroke in any swimming velocity. The butterfly stroke is the least economical one at low velocities (< 0.8 m·s⁻¹). However, above this velocity the breaststroke becomes the least economical one. These data are different from those reported by Holmer who state that the butterfly stroke was the least economical in all analyzed velocities. Such difference may have been derived from variations in body dimension as well as performance level among the studies subjects besides the equations generated in the present review represent a ‘mean’ of the different studies.

The high values of Sc at low velocities in the butterfly stroke (polynomial characteristic), may have been caused by the greater energetic cost in order to act against the body’s tendency to sink during the body waving movement, which in the slower velocities is not being opposed by a suitable sustaining force in this kind of symmetric arm-stroke. As velocity increases, an increase in the

*Figure 1 - Relationship between swimming cost (Sc) and velocity in the different swimming styles. Each point in the figure represents the mean value of the Sc obtained in a study or the mean of different studies which analyzed the Sc for the same velocity. References of the front crawl, backstroke, butterfly, and breaststroke.*

<table>
<thead>
<tr>
<th>Velocity (m·s⁻¹)</th>
<th>Breaststroke (kJ·m⁻¹)</th>
<th>Butterfly (kJ·m⁻¹)</th>
<th>Backstroke (kJ·m⁻¹)</th>
<th>Crawl (kJ·m⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.8</td>
<td>1.08</td>
<td>1.00</td>
<td>0.69</td>
<td>0.70</td>
</tr>
<tr>
<td>0.9</td>
<td>0.89</td>
<td>0.99</td>
<td>0.76</td>
<td>0.74</td>
</tr>
<tr>
<td>1.0</td>
<td>1.29</td>
<td>0.95</td>
<td>0.84</td>
<td>0.79</td>
</tr>
<tr>
<td>1.1</td>
<td>1.39</td>
<td>0.99</td>
<td>0.93</td>
<td>0.84</td>
</tr>
<tr>
<td>1.2</td>
<td>1.50</td>
<td>1.06</td>
<td>1.03</td>
<td>0.91</td>
</tr>
<tr>
<td>1.3</td>
<td>1.60</td>
<td>1.16</td>
<td>1.13</td>
<td>0.98</td>
</tr>
<tr>
<td>1.4</td>
<td>1.71</td>
<td>1.30</td>
<td>1.25</td>
<td>1.07</td>
</tr>
<tr>
<td>1.5</td>
<td>1.81</td>
<td>1.48</td>
<td>1.38</td>
<td>1.18</td>
</tr>
<tr>
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<td>1.52</td>
<td>1.30</td>
</tr>
<tr>
<td>1.7</td>
<td>2.02</td>
<td>1.95</td>
<td>1.68</td>
<td>1.45</td>
</tr>
</tbody>
</table>
sustaining force is observed, as well as the relative contribution of the several energy forces dissipation may be altered, leading to a temporary decrease of Sc[43]. In the breaststroke, another symmetric swimming stroke, the great intracrystal variation in the velocity occurs when the athlete tries to compensate the disacceleration present during the non-propulsive phase of the cycle. Therefore, the energy required in order to accelerate the body is increased and probably constitutes a large fraction of the total Sc. It is also possible that with velocity increase, the higher frequency of arm-strokes and leg kicks, consequently lower intracrystal variation in velocity (smaller disacceleration, lower energy cost) decreases the exponential increase of the energy cost due to the drag exponential increase. These factors could explain the linear increase and the high Sc at velocities demonstrated during the breaststroke. It is also important to highlight that the breaststroke is the one which reaches the lowest maximal velocities of all strokes.

**EFFECTS OF THE TECHNICAL SKILL LEVEL**

It has been demonstrated that the swimming technique influences drag, and therefore the swimming energy cost[12,26]. Some studies have observed alterations in the anthropometrical characteristics of swimmers and the performance improvement in the last decades. From 1964 to 1992, data demonstrated that Olympic swimmers increased their height without corresponding increase in weight[40,42]. Although some anthropometrical variables could not determine a better performance, the arms, hands, legs and feet size influence the arm-stroke length (Asl) and the arm-stroke frequency (Asf) which one swimmer combines to reach a given velocity[43]. Craig et al.[44] analyzed Olympic swimmers in 1984 and observed that the alterations in the Asl and Asf were associated with better times than in 1976. The highest velocities were reached with higher Asl and with lower or equal Asf.

According to several authors[26,30,44] Asl is an index that reflects the propulsive efficiency (Pe, capacity of changing mechanical work in dislocation), thus, the higher the Asl the higher the Pe and vice-versa. Several studies have demonstrated that the increase in velocity (from 1 to 1.7-1.8 m·s⁻¹) is mainly obtained through the Asl, while the Asf remains almost unchanged (v = Asl·Asf)[44,45]. Therefore, the alterations in the Sc observed in these velocities are not attributed to alterations in the Pe. Specifically, they reflect a drag increase, which increases along with velocity. Above these velocities, additional increases of the Asf are followed by a decrease in the Asl[44]. In this case an increase in the Sc is due to an association between the Pe decrease and drag increase. Moreover, the increase in the Sc may also result from the contraction of non-propulsive muscles as well as an increase in the legs use[6].

Since Asl is an index which reflects the Pe, the deterioration of the arm-stroke presented by individuals in fatigue, could lead to a progressive increase in the Sc. Recently Zamparo et al.[8] demonstrated that after a 2 km test the Sc and the Asf were increased, the Asl decreased, and that such facts could be related with the fatigue development. Actually, Craig et al.[44] observed that for 200 m or longer bouts, the Asl tends to decrease with fatigue development. According to the authors, the better performance swimmers could compensate the decrease in the Asl keeping or increasing the Asf with the purpose to keep velocity steady. Chronically analyzing (i.e. training effect), several authors have demonstrated that the increase in the Asl leads to a decrease in the Sc for a given velocity. For instance, Termin and Pendergast[46] demonstrated that the performance improvement with training (100 and 200 yards) correlated with 20% of reduction in the Sc and with the 16% of increase in the Asl. Similar results were obtained by Wakayoshi et al.[47] in which the swimmers who could reach a higher Asl for a given velocity also reduced the Sc.

An interesting work was conducted by Toussaint[13] in order to evaluate the technical skill in the Pe. Two groups of highly-trained endurance athletes, swimmers and triathletes, were compared at equal energy cost levels, which represented a metabolic power of 1000 W or a VO₂ of ~2.86 L.min⁻¹. The results demonstrated that with the same metabolic power level (VO₂) the triathletes swam at a velocity of 0.95 m·s⁻¹, while the swimmers swam at 1.17 m·s⁻¹, being 23% faster. Such difference cannot be explained by the gross efficiency, Asf and work by arm-stroke, once no differences between these variables were found in the swimmers and triathletes respectively. However, there was a difference in the Asl (2.46 vs. 1.84 m), and in the Sc (0.85 vs 1.05 kJ·m⁻¹) between swimmers and triathletes respectively. The longest Asl and the shortest Sc presented by the swimmers were due to a difference in the Pe: 44% for the triathletes and 61% for the swimmers. In other words, the swimmers used 61% of the work by arm-stroke to win the drag, while only 39% were converted in kinetic energy to the water during the arm-stroke. Therefore, the swimmers had longer Asl than the triathletes, who on the other hand, ‘wasted’ 56% of the available energy per arm-stroke in moving water. These data emphasize the importance of the technique in improving the Pe as well as being an important determinant for performance.

In order to test whether the increase of the propulsion surface would increase the Pe, Toussaint et al.[48] and Ogita and Tabata[5] analyzed the Sc and Pe to swim the same velocity with and without palmaris. In the same velocity, the use of palmaris decreased the Sc in 6% and increased the Pe in 8%. Likewise, Chatard et al.[6] demonstrated that the arm and hands length joined directly influences the Sc. For a given height, the longer the arms the shorter the Sc; a variation of 4 cm corresponded to a gain of 12% in the Sc[6-7]. Such evidence agrees with the data demonstrated by Grimston and Hay[43] in which the high level swimmers had a broader surface of hands and arms compared with lower level swimmers.

More recently, it has been demonstrated that the utilization of fins may reduce in 10% the Sc during the front crawl. Such reduction was mainly due to a decrease of the total mechanical work. Consequently, values 20% higher in the Pe were found with the utilization of fins[50]. It is interesting to mention that the use of fins in the front crawl both induces a reduction in the leg kicking frequency as well as a decrease in the Asf. This is an indication that the fins not only improve the Pe of lower limbs but also influence somehow in the Pe of arms. Actually, the Pe increase in the front crawl with the use of fins was doubled when compared with the increase demonstrated with the utilization of palmaris[5,30,48]. The effect of the legs action in increasing the total propulsive forces has been previously suggested by other authors as well. Deschott et al.[49] demonstrated that leg kickings (during complete swimming) allowed an increase of 10% in the maximal velocity in a 25 m sprint (compared with arms only), as well as directly influenced the kinematics of arm-strokes, modifying the wrist trajectory and increasing the Asl.

**CONCLUSIONS**

Among the main factors which interfere in the swimming cost are gender; age; level of technical skill and swimming style. Women present a lower Sc; however, such difference disappears when corrected by the body dimension. The highest Sc presented by children seems to be related to lower technical skill and by morphological and physiological characteristics as well as mechanical capacities which are not totally developed yet. For individuals with similar anthropometrical characteristics, better technical skill and better propulsion surface seem to contribute to reduction in the Sc. Concerning the different swimming styles, the most economical is the front crawl followed by the backstroke in any swimming velocity. The butterfly stroke is the least economical at low velocities (< 0.8 m·s⁻¹). However, above this velocity, the breaststroke becomes the least economical one. The understanding of the interaction of these factors may help in the evaluation and training prescription processes in this sports modality.
REFERENCES


