Intrinsic factors of the locomotion energy cost during swimming*

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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.

Keywords: Cost of swimming. Gender. Children. Swimming strokes.

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^{-1} at 20^{o}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(1), 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 ($\dot{V}O_2$) during and immediately after exercise offers an indirect method for the estimation of the energy cost. The $\dot{V}O_2$ is directly connected with 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 $\dot{V}O_2$ during swimming(3-4). Initially, Montpetit *et al.*(3) introduced a technique consisting of the retro extrapolation of the $\dot{V}O_2$ recovery curve in order to determine the $\dot{V}O_2$ during swimming. In this protocol, the exhaled gas was continuously collected by the first 20 or 40 seconds after swimming(3-4). 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 $\dot{V}O_{2max}$(4). Recently, continuous measurements of $\dot{V}O_2$ have been taken during attached swimming(4), swimming flume(5) and free swimming(1,6).

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})(2). The *Sc* has been usually measured through the ratio between the $\dot{V}O_2$ and its corresponding progression velocity for velocities within the zone of aerobic intensities(2,6-8). 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(9-10). Results of some studies which investigated the *Sc* have suggested that height (H)(11-12), body mass (*M*)(11), body surface area (*BSA*)(6-7), passive torque(9), floating(6), 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(14). For the backstroke, Klentrou and Montpetit(15) found a difference of 14% in the

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Sc between men and women in all analyzed velocities. In the study by Pendergast *et al.*(14), the differences remained even when the *Sc* was adjusted by the *BSA*. However, some studies have shown that these differences between genders disappear when the *Sc* is adjusted by the *M* and *BSA*(6-7,16). This difference in the *Sc* which occurs between men and women may be explained by the different body density and anthropometrical characteristics. Actually, when a body is horizontally immersed in water, the torso tends to float while the lower limbs tend to sink. Such situation generates a torque (rotational force), given by the product of the feet weight immersed in water by the distance of the feet to the center of the volume of the lungs(9). Women in average have larger storages of body fat when compared with men. Fat is less dense than water, while muscles and bones are denser; therefore, women are characterized by a torque lower than men's. Thus, women may need less energy to keep the body in the horizontal position, once a more horizontal position may significantly reduce drag.

During a constant swimming velocity, a considerable fraction of the energy cost is used to surpass drag(2). When the energy cost was related with the necessary power to surpass drag, no difference was found between men and women(17). In other words, men do not spend additional energy to float. The 30% in the difference of energy cost shown by Pendergast *et al.*(14) may be explained by the lower resistance found in women when compared with men at the velocity of 1 $m \cdot s^{-1}$ in the front crawl(18). The same group of authors also demonstrated a high correlation between body mass and drag ($r = 0{,}83$). A lower drag value has been also related to differences in the frontal area(19). Such evidence follows the observations made by Montpetit *et al.*(16), according to whom the differences in the energy cost between men and women disappear when corrected for the body dimension. Moreover, Montpetit *et al.*(16) demonstrated that *M* can represent 40% of the variability present in the *Sc* between men and women, values close to the 31% found by Chatard *et al.*(6) for a heterogeneous group of male swimmers. Values even more extreme were demonstrated by Kjendlie *et al.*(11) when adults with mean *M* equivalent to the double of the one presented by children were compared in the same group. In this study, *M* can represent 74% of the variability present in the *Sc*. These aspects demonstrate that the energy cost to swim a wide variation of velocities is clearly affected by the swimmer's size. Nonetheless, these results should not be only attributed to differences in the body mass (higher rest metabolic rate), but as mentioned before, to its relationship with drag.

AGE EFFECT

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(9,21). It has also been suggested that the passive torque is the main determinant of the *Sc* regardless the gender and swimmer's skill(22). It probably occurs due to its strong relationship with the active drag(21), especially in velocities above 1,2 $m\ s^{-1}$(9). However, it is worth mentioning that the hands and feet movements during swimming cause an active torque which is probably different from the passive torque measured with the swimmer still(23). Therefore, even if children have a passive torque smaller than adults, it does not necessarily mean that they also have a smaller active torque.

In swimmers with similar performance, studies have demonstrated that 11-12 year-old children(11,20) present *Sc* absolute values lower than the ones reported in adolescents (14 years old) and adults(6,11). Moreover, the absolute values of *Sc* were similar between adolescents and adults(6). These findings suggest that the absolute values of the *Sc* seem to increase only between 12 and 14 years, once no differences in the *Sc* were observed from 14 to 21 years(6,11). When the *Sc* is expressed in relation to the *BSA* the results revert, with the children and adolescents having the same *Sc* value and both presenting values higher than adults (≥ 17 years)(6,20,24). Nonetheless, when the *Sc* is expressed in relation to height (*H*), no difference is found between children and adults(24). In addition, only *M* and the distance between the center of mass and the center of floating still correlate with the *Sc* when the effect of the swimmer's dimension is removed (i.e. ScH^{-1})(11). In other words, even when differences in the ScH^{-1} between adults and children do not appear, when analyzed as a single group, individuals of heavier *M* present higher ScH^{-1}. Since *M* and torque have shown a high correlation with drag, heavier individuals and with higher torque present higher values of drag(9,19). Therefore, Kjendlie *et al.*(11) suggest that opposite effects between the best technique demonstrated by adults (e.g. longer arm-stroke; larger surface area for propulsion) as well as children's smaller drag (e.g. lighter *M* and lighter torque) may explain the similarity in the ScH^{-1} between children and adults.

A longitudinal study conducted during 2,5 years in the growth period in swimmers (mean initial age of 12,9 years), found that the magnitude of the total drag activity did not significantly alter despite the increase of 16% in the transversal section area(25). These data partly reinforce the idea that growth (greater height) significantly reduces the wave drag, even with increase in the pressure and friction drag due to a greater *BSA*(26). Moreover, an increase in technical skill may have also decreased the total drag. Therefore, further research is still needed in order to determine if the difference in drag between children and adults is derived from differences in body dimension or difference in the swimming technique, once older individuals in many cases have better technique.

Poujade *et al.*(20), found out that the *Sc* was not correlated with different variables such as floating and anthropometrical ones in children (*H, M* and *BSA)*. These results contrast with similar studies performed with adults in which *M* and *H* were correlated with the *Sc*(12,16). In addition, in the study by Chatard *et al.*(12) the swimmers who presented better floatation had a lower *Sc*. It is important to highlight that the passive torque was not measured in the study by Poujade *et al.*(20), and as previously mentioned, this is one of the parameters with great influence in the *Sc*. Therefore, for a population specifically consisted of children, technical skill, maturation, energy metabolism and passive torque seem to be the main determinant of *Sc.*

PERFORMANCE LEVEL AND SPECIALTY EFFECT

The *Sc* at a given velocity greatly varies from one swimmer to another. These variations especially depend on the swimmer's technical skill(4,6,14,16,27). Chatard *et al.*(6) analyzed the *Sc* in 101 swimmers and divided them in three groups with different performance levels. Differences in the absolute value of the *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 *Sc* difficult. Nevertheless, when the *Sc* was expressed in relation to the *BSA* ($ScBSA^{-1}$) the difference between groups occurred, demonstrating that more skilled swimmers have a lower $ScBSA^{-1}$ for the same velocity. Similar results were also found by Chatard *et al.*(7) in a group of 58 female swimmers. Since the *Sc* increases with the *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(6).

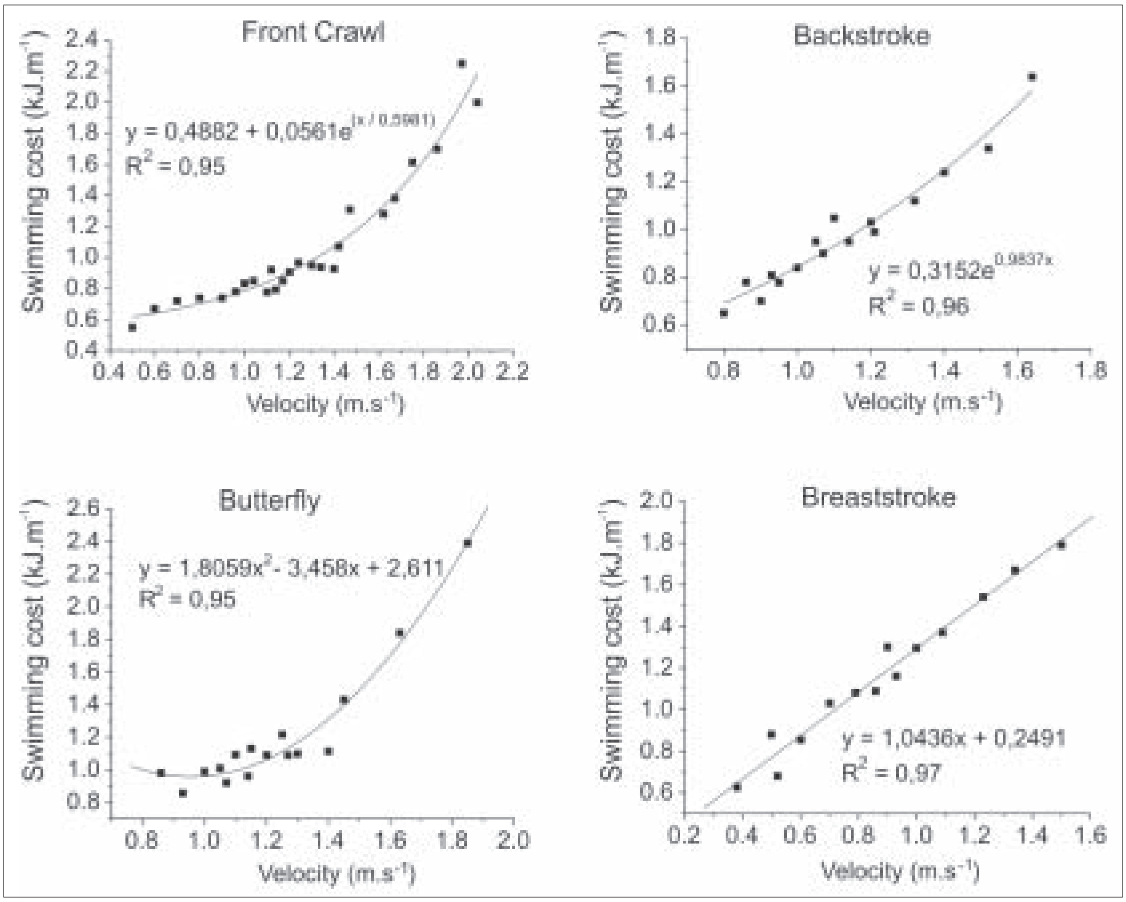

***Figure 1** – Relationship between swimming cost (Sc) and velocity in the different swimming styles. Each point in the figure represents the mean value of the* Sc *obtained in a study or the mean of different studies which analyzed the* Sc *for the same velocity. References of the front crawl(2,4,6,8-11,13,22,30-34); backstroke(10,15,33,35), butterfly(10,36,37) and breaststroke(10,33,38,39).*

Chatard *et al.*(6) 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)(6-7). Holmer(27) and Hollander *et al.*(29) 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(6).

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.*(10), 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 $m\cdot s^{-1}$). However, above this velocity the breaststroke becomes the least economical one. These data are different from those reported by Holmer(33) 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.

TABLE 1
Values of the swimming cost ($kJ\cdot m^{-1}$) in the different styles calculated from the equations described in figure 1

Velocity ($m\cdot s^{-1}$)	Breaststroke ($kJ\cdot m^{-1}$)	Butterfly ($kJ\cdot m^{-1}$)	Backstroke ($kJ\cdot m^{-1}$)	Crawl ($kJ\cdot m^{-1}$)
0,8	1,08	1,00	0,69	0,70
0,9	1,18	0,96	0,76	0,74
1,0	1,29	0,95	0,84	0,79
1,1	1,39	0,99	0,93	0,84
1,2	1,50	1,06	1,03	0,91
1,3	1,60	1,16	1,13	0,98
1,4	1,71	1,30	1,25	1,07
1,5	1,81	1,48	1,38	1,18
1,6	1,91	1,70	1,52	1,30
1,7	2,02	1,95	1,68	1,45

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 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*(10). In the breaststroke, another symmetric swimming stroke, the great intracyclic 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 intracyclic 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(13,26). 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 *Asf*, while the *Asl* remains almost unchanged ($v = Asl{\cdot}Asf$)(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 $\dot{V}O_2$ of ~2,86 L.min^{-1}. The results demonstrated that with the same metabolic power level ($\dot{V}O_2$) 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 palmers. In the same velocity, the use of palmers 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(30). 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 palmers(5,30,48). The effect of the legs action in increasing the total propulsive forces has been previously suggested by other authors as well. Deschodt *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.

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