Original Article

Technical skill differences in stroke propulsion between high level athletes in triathlon and top level swimmers

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ABSTRACT

Bottoni A, Lanotte N, Boatto P, Bifaretti S, Bonifazi M. Technical skill differences in stroke propulsion between high level athletes in triathlon and top level swimmers. *J. Hum. Sport Exerc.* Vol. 6, No. 2, pp. 351-362, 2011. In the latest decades the arm propulsion mechanism in human swimming has been an issue of great interest for researchers. The availability of new devices which can easily measure the stroke propulsion by means of a non invasive gauge allows the study of technical skills in real swimming, without artificial and distorting conditions like in a swimming flume or in tethered swimming. Performance in swimming is a crucial factor in another sport such as Olympic Triathlon, however we saw that the triathlon athletes presented shortfalls and differences with respect to expert swimmer, particularly in mean pressure and resultant momentum, but not maximum pressure. Each athlete showed a distinctive shape of the pressure curve, but triathletes present a greater variability in the pressure pattern than competitive swimmers, as is the case of novice vs. expert swimmers observed in previous studies. The possibility of pointing out some differences in stroke propulsion between top level swimmers and high level athletes in triathlon could give some useful indications for coaches in planning triathlon training. **Key words:** FRONT CRAWL SWIMMING, OLYMPIC TRIATHLON, DIFFERENTIAL PRESSURE, PERFORMANCE.

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INTRODUCTION

Stroke propulsion in swimming has been investigated since Counsilman (1971) gave his first contribution. In swimming, propulsion (Maglischo, 1989) is defined four basic hand propulsive movements: downsweep, insweep, upsweep and outsweep. The stroke is composed of a combination of these movements. The underwater motion of the arm in a freestyle stroke is also divided (Touissant et al., 2000) into a glide phase (from hand entry to the most frontal position of the finger), an insweep phase that lasts until the finger reaches the most medial position and the outsweep phase, which is the remainder of the stroke to hand exit.

Originally, force in swimming propulsion was usually divided into two components: a lift component normal to the hand motion and a drag one parallel to it. Once the assumption is made that the flow under steady condition under constant velocity, angle of attack and sweep back angle is comparable to the flow during swimming stroke, the propulsive force is composed by lift and drag forces generated by the hand. Schleihauf (1974, 1979) measured the lift and drag forces on hand models in various geometrical configurations of flow determining how lift and drag coefficients vary with angle of attack. Berger et al. (1995) using two models of a human hand-arm carried out similar measurements in flow and obtained results consistent with those by Schleihauf. The quasi-steady approach presents several limitations. Lauder et al. (2000) investigated the validity of hydrodynamic force estimation in swimming as calculated by the quasi-steady approach using a full-scale mechanical arm. The estimated shoulder torque was calculated using a quasi steady approach and compared to the direct measurement of shoulder torque from the mechanical arm, showing a considerable difference. Dickinson (1996,1999) using a dynamically scaled model of the fruit fly equipped with sensors and measuring directly the forces, observed three different mechanisms: delayed stall, rotational circulation, and wake capture that make the insect able to perform their aerodynamic task. Arellano et al. (2006) pointed out that sculling actions use the same mechanism. Swimmers can generate additional unsteady forces because the unsteadiness increments force through the same unsteady fluid-dynamic mechanisms that make the insect able to fly. Toussaint et al. (2002), who investigate using both tufts (10 tufts positioned below the elbow, 10 tufts halfway between the elbow and wrist, eight tufts at the wrist, and just above the knuckles) with video recording and pressure sensors (at the shoulder, elbow, wrist, back side of the hand and palm of the hand), wrote about a pressure gradient (pumping fluid along the arm toward the hand) induced by limb rotation both on leading and trailing edge of the arm. The resulting pressure across the hand, due to interaction of circumferential (arm rotation) and axial (arm translation) pressure gradient, would increase the propulsive force. Toussaint found stationary flow with Bernoulli and lift component during the glide phase (0.40s from the beginning), while the flow during the insweep (and to a lesser extent the outsweep) was highly unsteady and the direction of each tuft changed rapidly, especially during the transition from insweep to outsweep. Matsuuchi et al. (2008) using particle image velocimetry (PIV) in a swimming flume (flow speed was set at about 1.2 m/s, 50-μm-diameter nylon particles were used, the horizontal plane was set at a level so that the hand cuts the illuminated plane when it is just in the phase from in-sweep to out-sweep, about 55cm below the water surface) pointed out that during the stroke, in the transition from insweep to outsweep, a strong counterclockwise vortex is generated above the back side (the left side of the fingers) near the little and third fingers. The clockwise vortices were shed as a free vortex, which had been a bound vortex around a hand during the in-sweep motion. Another large scale vortex is also visible, rotating clockwise near the vortex of the minimum vorticity. These consist of a pair of vortices. Between the two counter-rotating areas, a strong induced flow gives strong momentum in the direction of the body displacement.

There are several methods to evaluate propulsion in swimming but measuring directly the pressure exerted by the hand has the potential to become a useful technique in stroke diagnostics (Takagi, 1999). The validity of a pressure differential method for estimating hydrodynamic force acting on the hand in swimming was shown measuring the pressure distribution on an entire hand model using a wind tunnel and 88 measuring points on the surface of the model (Takagi & Wilson, 1999). The results were compared to those derived from micro pressure sensors attached to both sides of the hand. The mean pressure difference can be estimated measuring pressure at a point proximal to the metacarpophalangeal II, III, IV and V joints. Takagi et al. (2002) using pressure sensors on the swimmer hand found a temporal pattern of forces similar to the results of Sevec (1982) and Loetz et al. (1988) and noticed that the novice swimmer produced peak force in the middle of a stroke with a greater variability than that of the competitive swimmer. A recent study of Takagi was conducted using a single subject in a swimming circulating water channel and in addition the swimmers hand was entirely covered by a surgical nylon glove. All these factors may interfere with the stroke action making the observed phenomena different from real swimming. In fact the difference between swimming in a water flume and in a swimming pool has already been observed (Hay et al., 1995; Wilson et al., 1998) and it is reasonable to think that covering the hand with a plastic glove may disturb the athlete sense for the water.

Although the measure of differential pressure is rather simple to perform it usually requires a swimming flume or tethered swimming conditions where the athlete is connected with gauges to the poolside. Devices and supports used can limit hand movements or even change its action, as well as reducing the active surface, thus interfering with the swimmer's technique. The availability of devices which can easily measure the free stroke propulsion by means of a non invasive gauge (Bottoni, 2010) allows the study of technical skills in real swimming, without artificial and distorting conditions. During the validation of the device used in the present study (Bottoni, 2010) and in previous studies (Toussaint, 2002) it was pointed out that the stroke pressure differential over the hand increases and it occurs because of a large reduction of pressure on the back side of the hand, rather than because of an increase in the pressure at the palm of the hand, which would be expected when the hand acts like a paddle. The strong reduction is probably connected with the rotational and unsteady effect that is crucial for explaining the propulsion in swimming as the flight of the insect observed recently by PIV (Matsuuchi et al., 2008).

Therefore the direct measurement of forces and pressure applied by the swimmer to the water could be the best way for coaches to evaluate the swimming propulsion, the mechanical power generated and the propulsive efficiency because it refers to real swimming and it can provide immediate feedback to swimmers and coach during the training control process.

The present study investigates whether the shape of the pressure signal can give information about the propulsive efficiency and how the shape takes into account several differences in swimming stroke technique. In particular it is reasonable to expect that expert swimmers and triathlon elite athletes show a different swimming technique due to a difference in the long term training and in physiological profile, which reflects their different performance requirements. The athletes in triathlon can present some shortfalls in swimming technique with respect to expert swimmers that could be partially pointed out in the present study.

MATERIAL AND METHODS

Ten male athletes (T) of the Italian triathlon U23 national team and ten male top level swimmers (S) in freestyle voluntarily took part into the study. The groups are homogeneous for age whereas members of S were taller (T: 177 ± 3.2 cm, S: 185.7 ± 4.1 cm, $p<0.001$) and heavier (T: 69.7 ± 3.1 kg, S: 76.7 ± 6.5 kg, $p<0.001$) compared to T. Triathlon athletes and Swimmers also had different performance in freestyle swimming. T is composed by athletes who compete in Olympic distance triathlon (best 1500m short course personal time: 1029 ± 25s) while S is composed by some of the top Italian swimming athletes who compete (front crawl swimming) in 200m (average best personal long course time of all athletes was 110.6 ± 1.9s), 400m (the average best personal long course time of five specialized athletes was 233.3 ± 6.1s) and 1500m (the average best personal long course time of four specialized athletes was 922 ± 23s).

All the athletes wore two mini-paddles (KZ by APLab), whose size and shape do not interfere with the hand's movement and sensibility in the water. The paddles measure the pressure field around the hands and store the data in an Electronic Control Unit contained in a little box. The sensor measures the pressure difference between palm and back of the hand. This approximates the pressure field. Hydrostatic pressure is the same on both sides and therefore is not measured. The acquired data are transmitted via a wireless connection. The box has neutral buoyancy and the whole system does not interfere with the action of the athletes, who can swim freely (Figure 1).

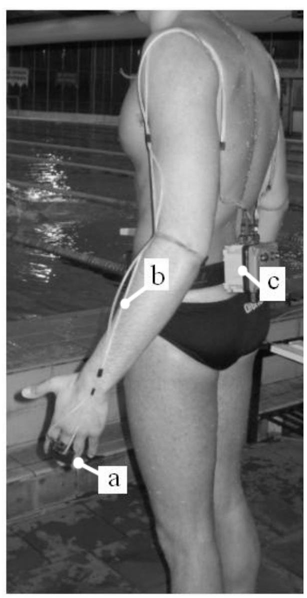

Figure 1. *The differential pressure signal measured by the paddle (a) through silicon tube (b) in processed and transmitted by the waterproof ECU box (c). The system does not interfere with the action of the athlete who can swim freely.*

The device presents a 8% (current value) of accuracy. The sampling frequency was set to 50Hz. For higher frequency it shows a low pass filter behaviour due to air flowing through an elastic tube. The tubes are made of silicon and have a 2mm internal diameter. The tube length was selected according to the height of the athlete and in order to not interfere with their swimming strokes. The variation of the tube was within 15% of maximum length and the response of the system wasn't changed. In two cases the tubes were accidentally over stretched but the variation of the signal was directly observed on the signal response and the test was repeated. The paddle graduation curve was obtained in controlled lab conditions by means of a more accurate pressure system generator. At the beginning of the test session the calibration of the system was carried out simply by means of water static pressure putting the paddle into the water at different depths from 0 to 1m with step of 0.1m and two different zero pressure lines were obtained for the right-left paddle. The calibration was repeated every three tests and at each stage any variation of environment pressure or temperature was noted.

The device is able to measure, store and handle autonomously and simultaneously the signals from both the right and left arm. The right arm and left arm signals were considered independently in this study. The athletes wore the paddles and after some free swimming to get acquainted with the instrument performed 25m in front crawl swimming at their best 1500m pace. Six central strokes were considered and superimposed for the analysis. During the six central strokes the athletes swam without breathing to avoid influencing the measure with other elements. Analyses considered the mean value of maximal differential pressure (Pmax), the mean value of average differential pressure (Pav), the pressure ratio (Pav/Pmax), the mean value of stroke period (SP) and the mean value of momentum per m^2 (M). The momentum per surface unit is calculated as the time integral of the differential pressure. In addition, pressures were normalized wrt stroke period and the same variables above mentioned were considered for each stroke phase in order to extract (during the glide phase) the mean value of maximal differential pressure (GP_{Pmax}), the mean value of average differential pressure GP_{Pav}, the mean value of stroke period GP_{SP} and the mean value of momentum per m^2 (GP_M). Similar definitions applied to the other stroke phases taken into account: the insweep phase (IS_{Pmax}, IS_{Pav}, IS_{SP}, IS_M) and outsweep phase (OS_{Pmax}, OS_{Pav}, OS_{SP}, OS_M). In order to point out the variability of the propulsive action, the mean value of standard deviation of momentum per m² exerted throughout the stroke (MV) for the six consecutive strokes was also considered. Statistical analysis was performed by the Mann-Whitney U test.

RESULTS

The swimmers have a bigger body structure and better performance in front crawl swimming but contrary to what could be expected, swimmers didn't exert a greater maximum pressure during the stroke. The results didn't indicate significant differences in Pmax for groups T and S (S:$55.6\pm12.1\cdot10^2$Pa, T:$54.8\pm9.8\cdot10^2$Pa, $p>0.5$) as shown in Figure 2a. Anyway the strokes considered were the six central stroke during 25m and they refer to a uniform swimming speed. During the six central strokes swimmers exerted a higher average pressure (Pav) compared to T (S:$28.7\pm4.5\cdot10^2$Pa, T:$20\pm3.1\cdot10^2$Pa, $p<0.001$) as shown in Figure 2b. This value is also an expression of general momentum exerted per surface unit by the athlete. Despite the fact that Pav is an average value of six mean differential pressures (one for each stroke), this value isn't influenced by the shape variability of the stroke because those variations doesn't result in the stroke mean pressure. Consequently swimmers showed also a higher mean value of pressure ratio (Figure 2c). Figure 2d indicates that the expert swimmers showed a higher number of strokes per unit of time and therefore a lower stroke period (SP) compared to triathletes (S:1398±137ms, T:1579±147ms, $p<0.01$). S also showed a much lower value of MV (S:8.4 ± 2.1kg·m·s^{-1}·m^{-2}, T:17.1 ± 6.4kg·m·s^{-1}·m^{-2}, $p<0.001$) as shown in Figure 3.

Regarding the stroke phases T showed a greater length of the glide phase than S (Figure 4) even if this value is calculated on the basis of the delay of the insweep pattern with respect to the beginning of the stroke. Several triathletes presented a very short, in some cases even an absence of the insweep phase, and as a consequence had a longer glide phase time. The value of GPSP shows a strong variability (T: 588±80ms, S:364±99ms, $p<0.005$). The glide phase of triathlon athletes is also characterized by a lower mean value of the average differential pressure (Figure 5) than the value measured on swimmers GP_{Pav} (S: 16±3.5·10^2 Pa, T:7.9±3.6·10^2Pa, $p<0.001$) so that, despite T showing a much longer glide phase than S, the momentum of triathlon athletes during the glide phase isn't higher than that of swimmers. Even during the insweep phase, S showed a higher value of IS_{Pav} (S:46.5±7.8·10^2Pa, T:30.3±7·10^2Pa, $p<0.001$). S also had a better value of GP_M (S:6.3±2.1·10^2 kg·m·s^{-1}·m^{-2}, T: 5.1 ±2.6·10^2 kg·m· s^{-1}·m^{-2}, $p<0.05$) and IS_M (S:13±1.3·10^2 kg·m· s^{-1}·m^{-2}, T:9.9±3.9·10^2 kg·m· s^{-1}·m^{-2}, $p<0.05$) as shown in Figure 6.

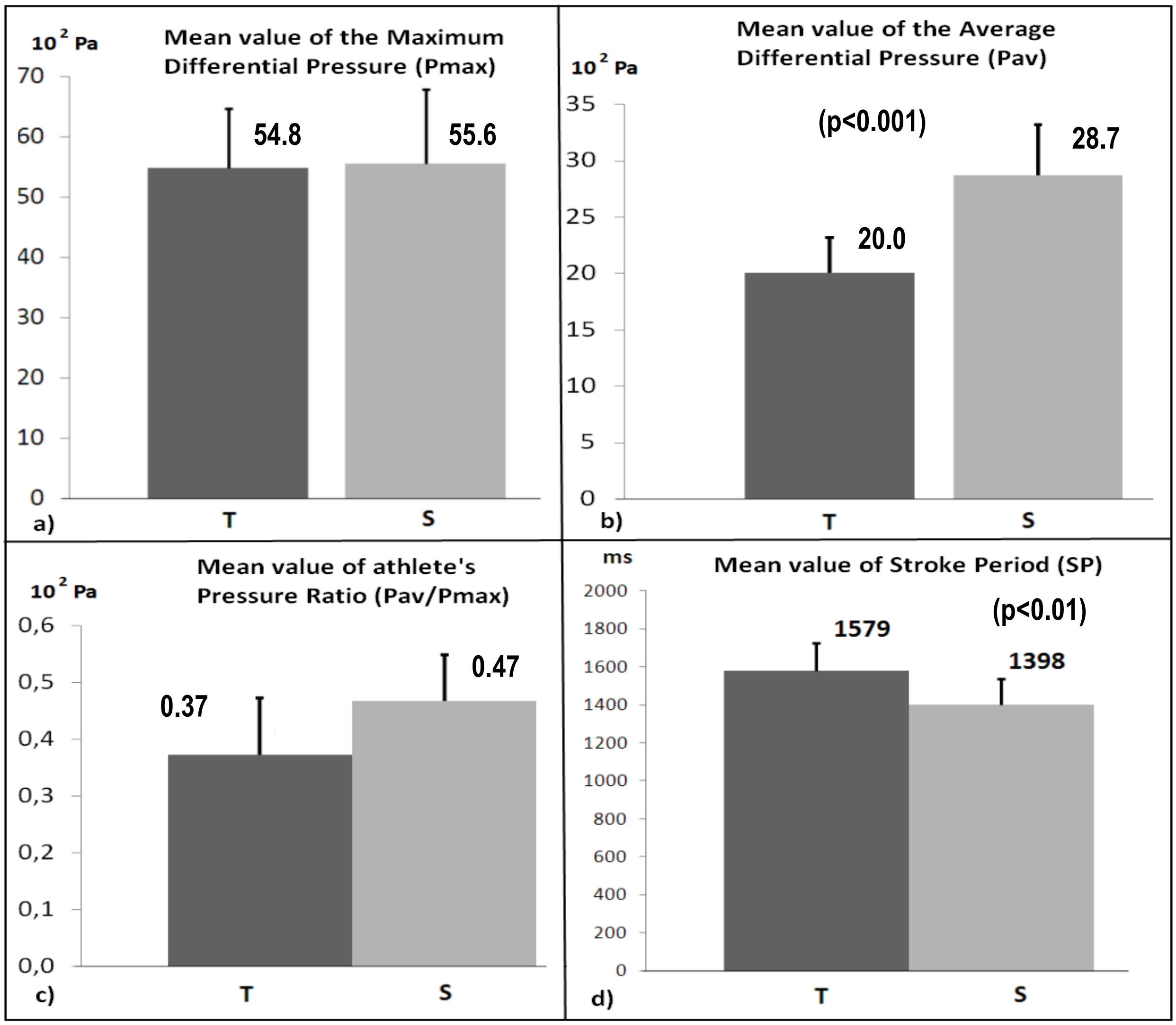

Figure 2. *Mean values exerted by the athletes during the six consecutive strokes. Maximum differential pressure (a), average differential pressure (b), pressure ratio (c) and stroke period (d).*

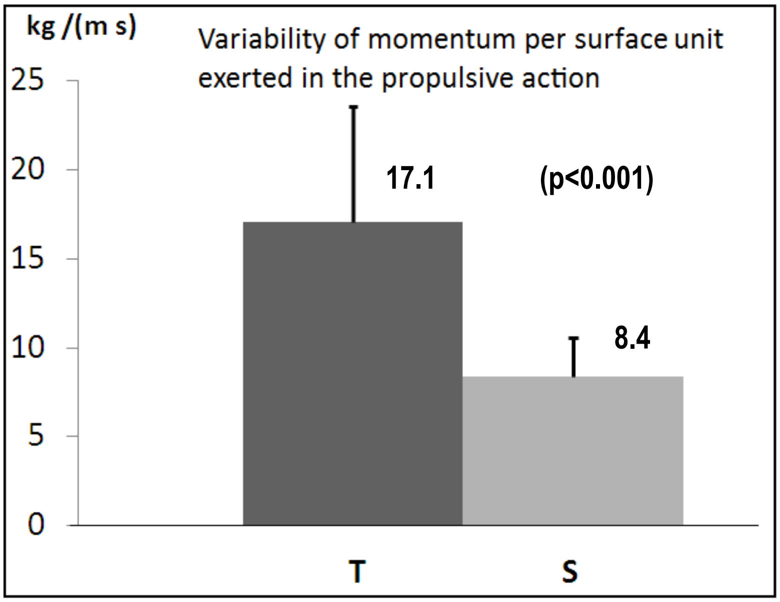

Figure 3. *Average values of the propulsive action variability, expressed by standard deviation of momentum per surface unit exerted throughout the stroke (MV) by T and S.*

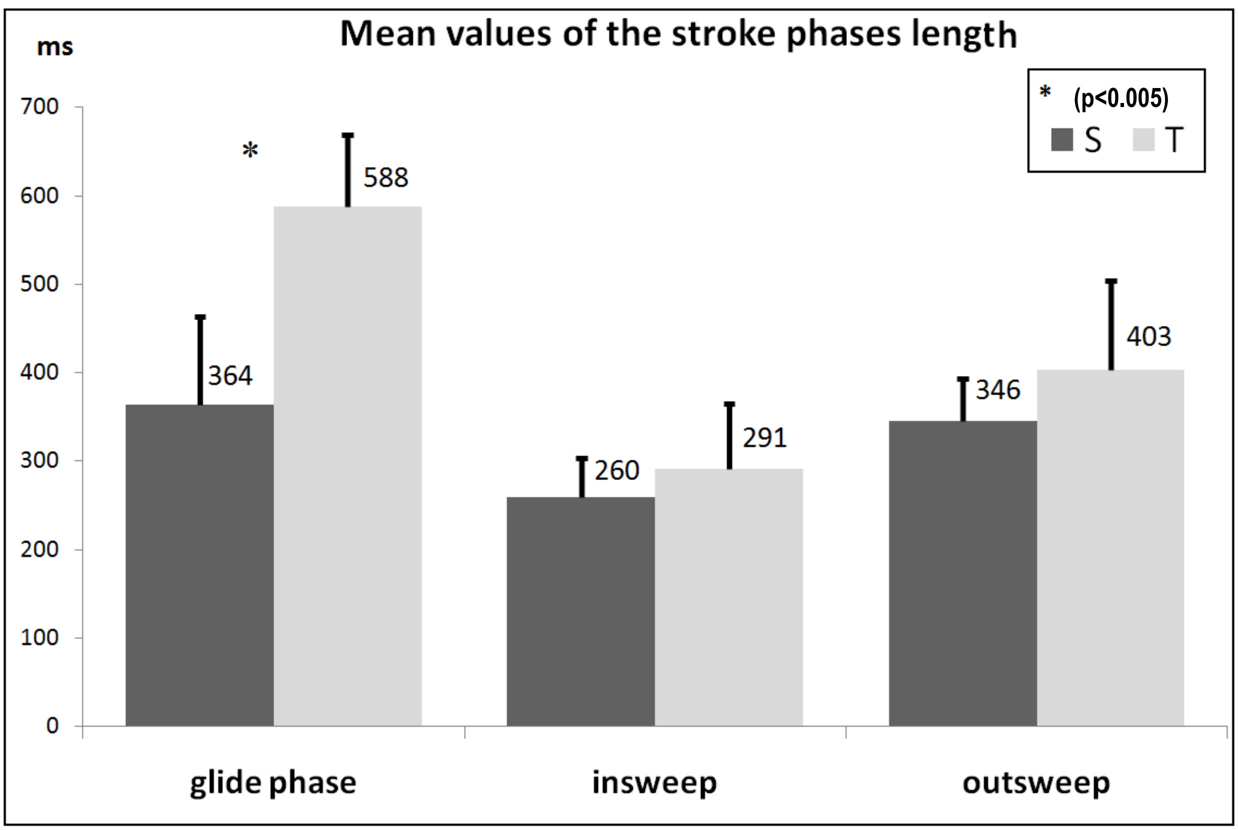

Figure 4. *Mean value of the stroke phases length for T and S.*

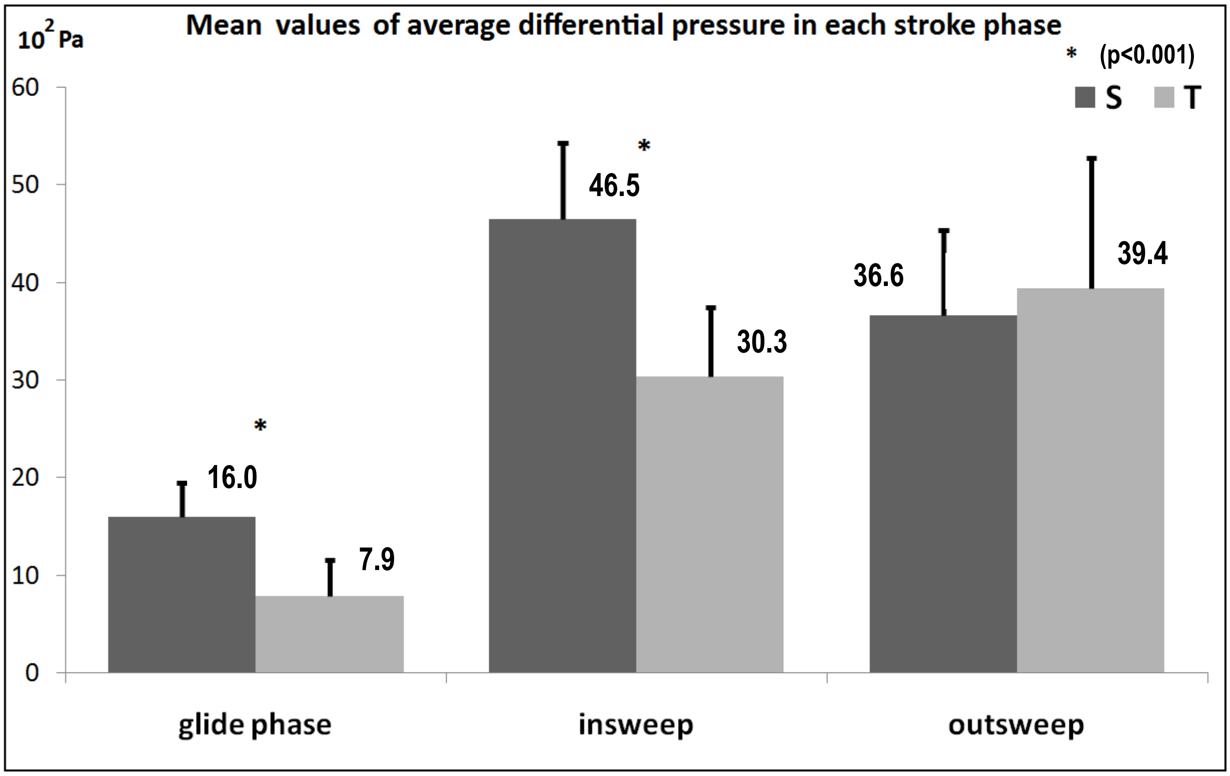

Figure 5. *Mean values of average differential pressure in each stroke phase.*

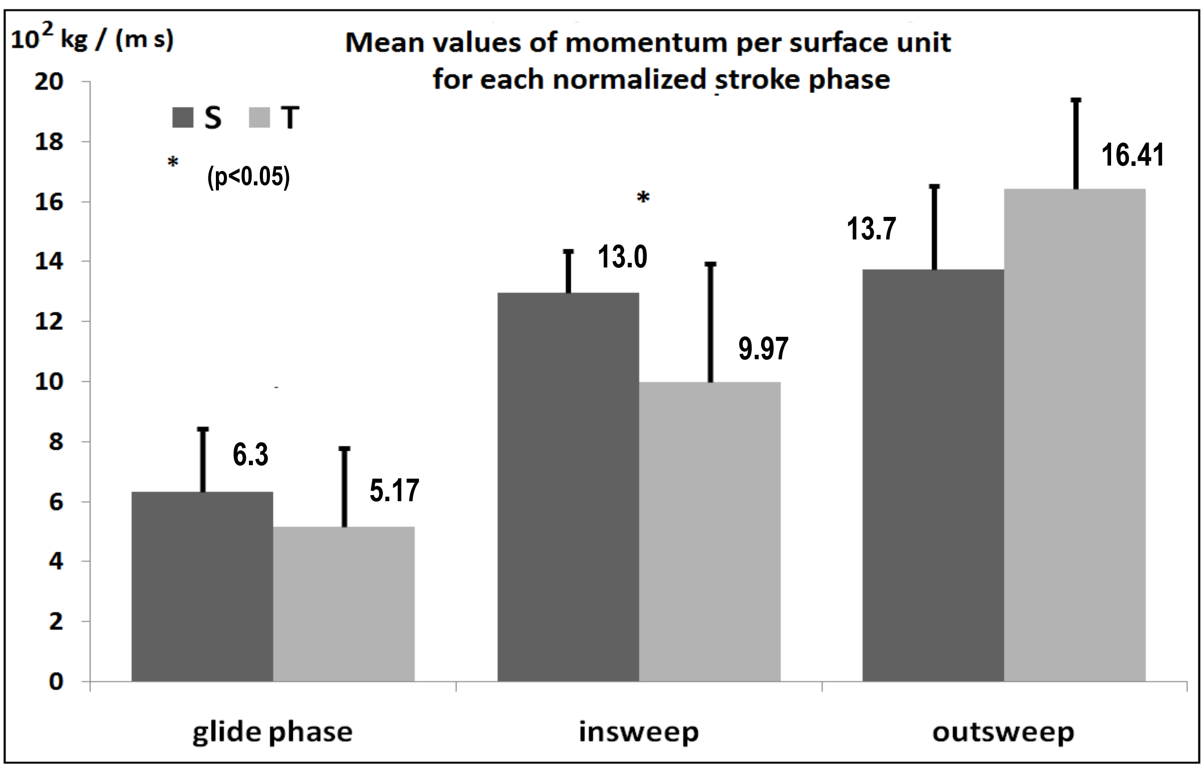

Figure 6. *Mean values of momentum (per surface unit) for each normalized stroke phase.*

DISCUSSION AND CONCLUSIONS

The pressure profiles measured in this study are generally similar to those defined in previous work (Sevec, 1982; Loetz et al.,1988; Takagi, 2002). It is easy in the case of the expert swimmers to see the three phases of the stroke (glide, insweep and outsweep). Each athlete presents a specific shape that he/she tends to keep as long as the swimming technique remain stable. Furthermore each athlete has two characteristic curves, one for the right and one for the left arm, influenced also by the stroke frequency and the breathing side. Figure 7 shows several superimposed curves relevant to subsequent strokes from the same athlete. It is apparent that differences between right and left arm remain during the swimming action. The present findings indicate several technical skill differences between expert swimmers and triathletes. Swimmers can exert a higher mean pressure during the stroke, generating higher additional forces during the insweep phase and during the glide phase so that they achieve higher momentum during the stroke. Figure 8 shows the average pattern of pressure curves in swimmers and in triathlon athletes on a normalized axis. Despite the strong smoothing effect of the averaging operation, it is apparent that triathletes are weaker in the glide phase and have almost no pressure peak in the insweep phase. The data averaging operation, though, had a flattening effect, which makes this figure unsuitable for an evaluation of maximum and mean pressure values. Takagi et al. (2005) found that the shape of the curves of an expert or novice swimmer is different. Particularly it was found that the competitive swimmer produced peak force later in the stroke but the force profile of the novice was very different and weaker from those of swimmer and triathlon athletes. The fact that the glide phase is longer in T has been deduced by the delay of the pressure peak with respect to swimmers. In fact, during this phase where Bernoulli's effect should be at work, triathletes are not very effective. This can be explained by a weaker sensibility in water with respect to swimmers. On top of the longer glide phase, triathletes have also shown a delay of the insweep pressure peak and a reduction, even an absence in some cases, of this peak. It has been observed that 4 out of the 6 triathletes have as a technical characteristic a delay in breathing (even if they didn't breath during the test, the swimming technique is conditioned by the acquired motion patterns). It is in fact common in triathlon to delay breathing as much as possible in order to keep the athletes who are ahead in sight. This technical difference, coupled with a less developed sense of water of triathletes wrt swimmers can arguably explain the differences observed in pressure curves. Triathletes show pressure leakages more often than swimmers during the stroke. This happens in several instants, however rarely during the outsweep, and could be explained by the weaker sense of water of the triathletes and a higher specific force of the swimmers that enables them to keep contact with the water in every phase of the stroke. Another substantial difference between the two groups is that swimmers show a more repeatable stroke technique than triathletes. This can be verified if we consider the mean value of standard deviation of momentum per m^2 exerted throughout the stroke (Figure 3). The pressure curves of the expert swimmers are in fact much more superimposable. Expert swimmers show a greater variability only in the glide phase. The glide phase looks very important from a technical point of view, and defines the differentiation skill between the groups. Expert swimmers are able to adapt their motion to the changing conditions of the water and they can apply in the glide phase all the minimal changes to the stroke in order to repeat the same stroke action that is what his/her neuromuscular and perceptive ability can perform.

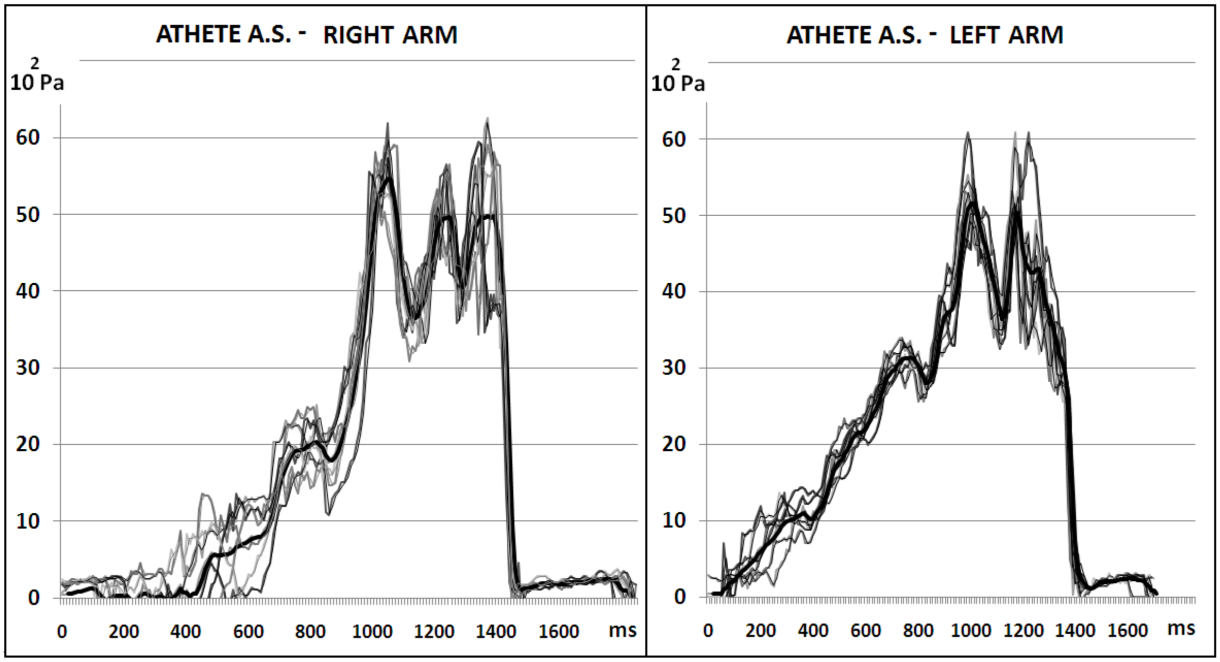

Figure 7. *Several superimposed curves of differential pressure. Right and left arm by the same athlete (thicker line=average).*

In conclusion, the characteristic profile of the measured pressure is based on the individual athlete technical ability during the swimming stroke. The possibility of pointing out some differences in stroke propulsion between top level swimmers and high level athletes in triathlon could give some useful insights for coaches in planning triathlon training. Many other issues remain open to investigation for further studies. For the analysis of the propulsive force generation it is required a measure of pressure combined with qualitative analysis of video in order to consider the direction of the forces. Some tests have shown that expert endurance swimmers and sprinters present different pressure shapes, and this can be a useful tool for an early swimming talent screening. Finally, it could be very interesting to examine how fatigue affects swimming technique during training or competition simulation, to give coaches further help in planning training.

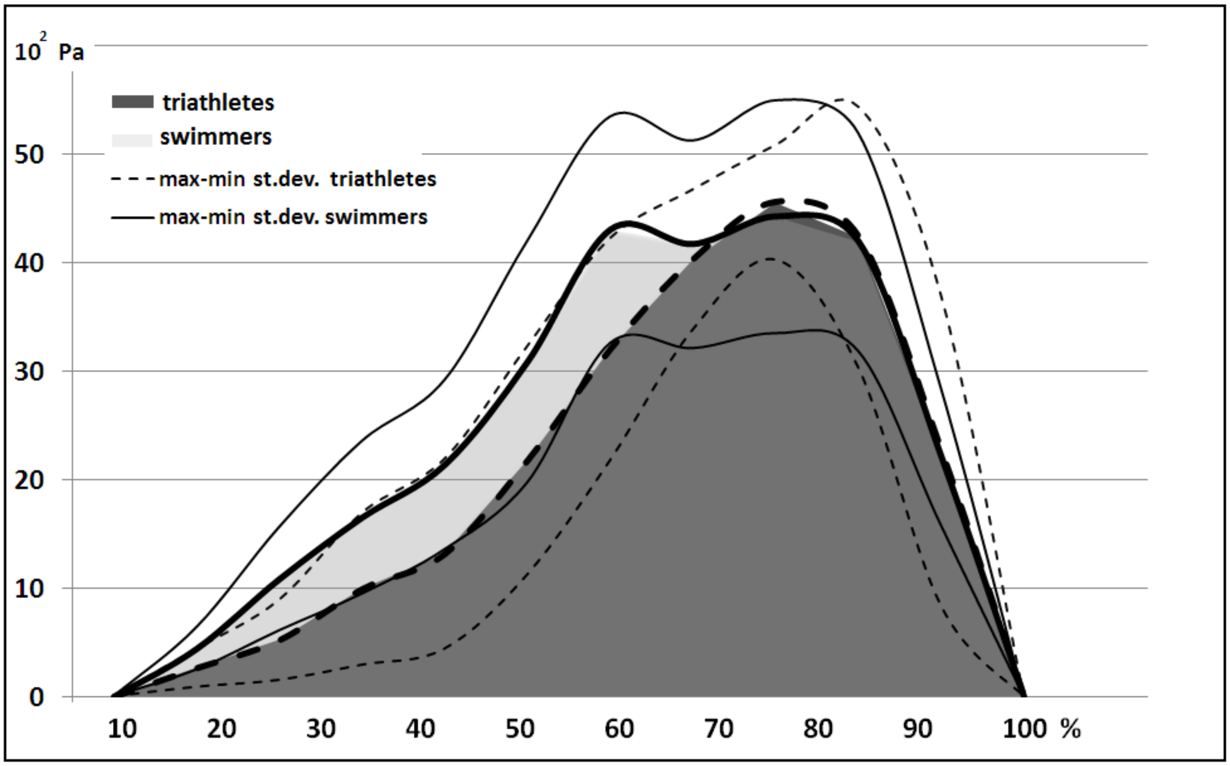

Figure 8. *Average pattern of pressure curve for swimmers and triathletes.*

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