# UNDERWATER UNDULATORY SWIMMING: KINEMATIC CHARACTERISTICS, VORTEX GENERATION AND APPLICATION DURING THE START, TURN AND SWIMMING STROKES.

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**INTRODUCTION:** During the Moscow Olympic Games (1980), we had the opportunity to watch some participants that covered near 25 m underwater in the backstroke events after the start phase. They swam underwater using a different stroke technique: underwater undulatory swimming (UUS). They performed, in most cases, the start and turning-out times better than the others participants who swam on the surface. After these Games, the underwater phase in backstroke started to be prolonged, and the UUS technique utilized by many swimmers including participants in the butterfly and freestyle events. The UUS was performed on the front, the back, the side or rotating between positions.

**Swimming at the surface and wave drag:** But, how can this advantage be explained considering that swimmers do not use their arms for propulsion and they swim longer distances underwater than at the surface because they are going down and then up during this phase? Some explanations have been developed recently:

- Videler (1993) stated that swimming at the surface causes extra drag by generating waves. A stiff, streamlined body just touching the interface between air and water experiences five times more drag than the same body at a depth of more than three times its width or body transversal section. The dimensionless Froude number can express the energy lost by wave generation:

$$F = U / \sqrt{gL} \tag{1}$$

  Where $U$ is the speed of travel measured by body length by seconds, $g$ the acceleration due to gravity and $L$ the length of the water-line. Low wave generation is related to low velocities and large body length that produces a smaller $F$. By applying the Froude number to human swimming it can be concluded that a taller swimmer has a meaningful advantage over the smaller one and swimming underwater reduces the quantity of water lifted up against gravity.

- Vorontsov and Rumyantsev (2000b) showed an equation to find the minimal depth of gliding or swimming ($h_p$), where no waves appear on the water surface:

$$h_p = V^2 / 2g \bullet C_w \tag{2}$$

  Where $V$ is the body velocity, $g$ is the acceleration due to gravity and $C_w$ is a non-dimensional wave-making coefficient. It seems that the depth at which the wave-making resistance is negligible lies between 0.7 and 1.2 m. Wave-making resistance (Fw) can be quantified with the next equation:

$$F_w = \rho \bullet A^3 / \lambda^2 \bullet (V \bullet sin\alpha)^3 \bullet cos\alpha \tag{3}$$

  Where $\rho$ is the water density, $A$ is the amplitude of the wave, $\lambda$ is the length of wave, $V$ is the body velocity and $\alpha$ is the angle between direction of GCM movement and the front of the prime wave. Since wave-making resistance changes with the cube of swimming speed, it becomes a sizeable component of total hydrodynamic resistance. As the gliding speed after a start and turns is much higher than the average racing speed and waves are not produced during

a deep glide, it is beneficial to reach and maintain this high gliding speed for a longer time using a leg kick only.

- Lyttle and Blansky (2000) measured passive drag using a towing machine at different gliding speeds and depths. The results of the study demonstrated a 10-20% decrease in the drag force when travelling at 0.4 and 0.6 m depths relative to gliding at the water surface and a 7-14% reduction when gliding at 0.2 m depth. When kicking movements are introduced as a new factor in the drag recordings, the authors found the total body drag force is reduced when the swimmers are kicking when they are towed at velocities of 1.6 ms$^{-1}$ or 1.9 ms$^{-1}$; no significant differences were found when they were towed at 2.2 ms$^{-1}$ and 2.5 ms$^{-1}$ and less body drag was found when the subjects were towed at 3.1 ms$^{-1}$ at the prone streamline position without kicking.
- Cossor and Mason (2001) found significant negative correlations between the 15 m start time and the distance travelled underwater in the 100 m butterfly, backstroke and freestyle and 200 m butterfly in the men group of finalists in the 2000 Olympic Games. In the women's group the negative correlations were found in the 100 m backstroke and 200 m butterfly, breaststroke and freestyle. The authors stated that the underwater distance covered in the start had the greatest influence on the race start time.
- Mason and Cossor (2001) analysed the turning time. They found the most significant aspect of the turn performance was he underwater phase including the action of pushing against the wall. Underwater distance and time were significantly related to the total turn time in the form strokes for both genders. The further the distance and longer the time spent in the underwater phase of the turn, the faster the total turn performance tended to be.
- Toussaint (2001) stated that: "speed at the water surface is constrained by the formation of surface waves leading to wave drag. As a swimmer swims at the surface, water is pushed out of the way. Waves result from pressure variation due to differential water velocities around the swimmer. As velocity increases, the bow wave, with increased size and inertia, cannot flow out of the way quickly enough and hinders velocity increases of the swimmer".

**Mechanics of UUS and animal swimmers:** The most effective swimming movements of aquatic animals of almost all sizes appear to have the form of a transverse wave progressing along the body from head to tail (Wu, 1971). This author explains how the body is displaced during UUS as follows:

"As the body performs an undulatory wave motion and attains a forward momentum, the propulsive force pushes the fluid backwards with a net total momentum equal and opposite to that of the action, while the frictional resistance of the body gives rise to a forward momentum of the fluid by entraining of the fluid surrounding in the body. The momentum of reaction to the inertial forces is concentrated in the vortex wake due to the small thickness and amplitude of the undulatory trailing vortex sheet; this backward jet of fluid expelled from the body can, however, be counterbalanced by the momentum in response to the viscous drag. When a self-propelled body is cruising at constant speed, the forward and backward momenta exactly balance; they can nevertheless be evaluated separately."

When a fish performs undulatory swimming the wake generated is very specific in the form of a sequence of vortices that alternate the direction of the rotation. While the tail swings to one side, creating a clockwise vortex, and then to the other, causing a counter-clockwise one (Triantafyllou & Triantafyllou, 1995), see figure 2.
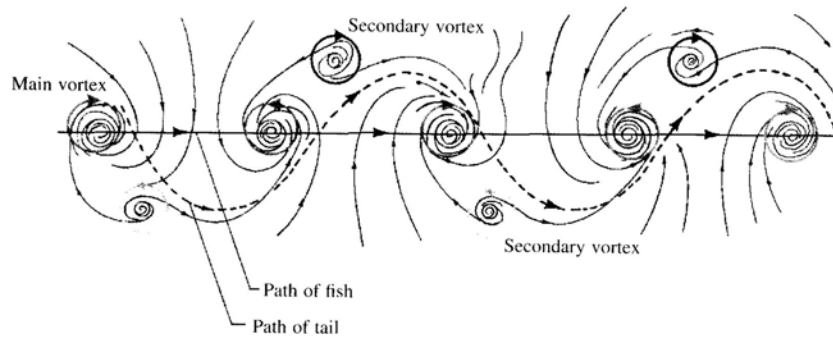
Figure 1. Idealised vortex pattern of swimming fish [from Rosen (1959) cited in Gray (1968) and Videler, Muller, & Stamhuis (1999)].
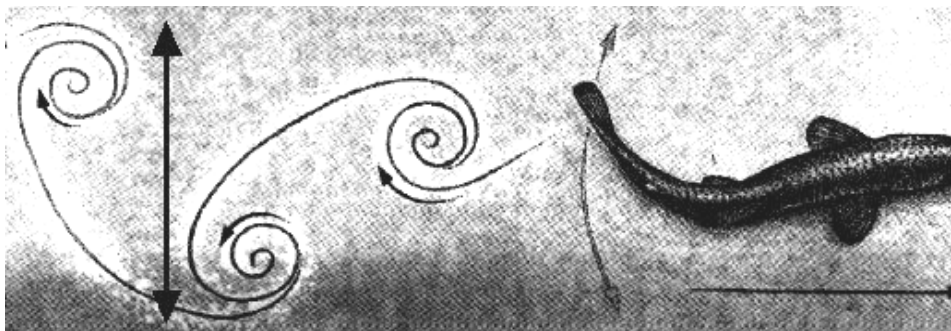


Figure 2. Fish of all kinds flap their tails to create vortices that produce a jet of high propulsive efficiency (Triantafyllou & Triantafyllou, 1995).

One of the first attempts to analyse the fish tail vortices generation was performed by Rosen (1959) using a layer of milk just below the swimming fish. Rosen's vortices interpretation is shown in figure 1.  Modern sophisticated techniques that use particle image velocimetry (PIV) allows quantitative measurements of both the direction and speed of the flow (Videler et al., 1999). The wake observed in figure 2 consists of two vortices per tail beat cycle. A jet of water undulates between the vortices and flows in the direction opposite to the swimming direction (Videler et al., 1999) (see figure 3a). Dickinson (1996) and Videler et al. (1999) explained a second form of vortex production with four vortices after each full cycle of tail beat (see figure 3b). Each vortex pair consists of a tail vortex and a body vortex released during the tail stroke.
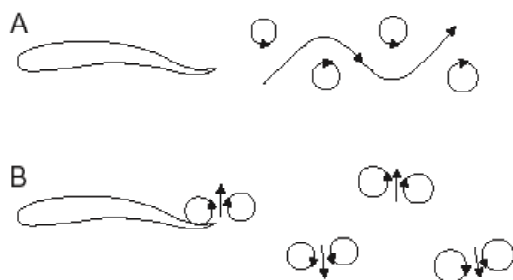


Figure 3: Schematic representation of the medio-frontal plan of two types of wake behind an undulatory swimmer. (Videler et al., 1999)

Body movements have to be included as propulsive elements during undulatory swimming.  In the undulation each propulsive element, or small segment of the body, moves laterally with respect to the head. As the wave passes, the propulsive element accelerates the water nearby (Webb, 1984). The force obtained is perpendicular to the propulsive element and is inclined toward the head of the fish. Muller et al. (2001) utilised PIV to visualise and measure the form, size and velocity of the vortices generated by the body during undulatory swimming. While a double row of double vortices with little backwards momentum is generated behind body of the fish (*eel*), in the medio-frontal plane of the body the eel generates flows that form semicircles that

travel posteriorly with the body wave. The flow speed increases almost linearly from 0 directly behind the head to maximum at the tail. Contralateral semicircular flows have the same direction of rotation. This structure is called a protovortex and its centre is located between the crest and the trough of the body wave in the regions of elevated vorticity adjacent to the eel's body (Muller et al., 2001).

Body kinematic of the fish and mammal swimmers has been studied frequently during the last decades. The analyses were oriented to the observation of the caudal fin path, stroke frequency, midline body path, velocity of the body, wave form and amplitude, pitch and attack angles and so on. The fluke path follows a sinusoidal pathway that is symmetrical about the longitudinal axis of the body and in time in dolphins in spite of differences between epaxial and hypasial muscle masses (Fish & J.J.Rohr, 1999). Fish species that swim with lateral undulations almost universally increase tail-beat frequency as swimming speed increases (Jayne & Lauder, 1995). The amplitude of the fish tail path showed values between 0.20 to 0.17 body lengths in Tuna fishes (Dewar & Graham, 1994). Fish and Rohr (1999) defined the attack angle as the angle between the tangent of the fluke path and axis of the fluke chord and the pitch angle as the angle between the fluke axis and the translational movement of the animal. The regression analyses developed in dolphins between attack angle and velocity and pitch angle and velocity showed a negative relationship between the angles and velocity. During slow swimming the angle of pitch was nearly 40º and reduced to nearly 20º during speed swimming, while the angle of attack is approximately 20º during slow swimming and reduced to 10º when swimming 6 times faster (Fish & Rohr, 1999).

The Strouhal number is a dimensionless number, representing the ratio of unsteady and steady motion. Strouhal number (St) is defined by the equation: $St = A_{p-p} f / U,$ where $= A_{p-p}$ is the tail-beat peak-to-peak amplitude (the distance from the peak of the tail fluke upstroke to the peak of the tail fluke downstroke; $A_{p-p} = 2h$ ), $f$ the stroke frequency (Hz) and $U$ the swimming velocity (Fish & Rohr, 1999). Strouhal numbers for swimming fish and dolphins were between 0.25 and 0.35, as predicted by the theory described by Triantafyllou (1993) in maximum efficiency situations.

An increase in the research developed to understand fish hydrodynamics was noted during the last decades. The application of the PIV started a new era in the knowledge of the fish body and water interactions.

**Mechanics of UUS and human beings:** Sport practice shows that swimming underwater using only the kick is, at the least, no slower than swimming at the surface using the full stroke (Vorontsov & Rumyantsev, 2000b). Changes in competitive swimming rules were introduced by FINA recently, due to the increase the distances covered by the swimmers underwater in international competitions. The new rule limits the underwater phase after the start and the turn to 15 m. But this distance could be enough for some swimmers to take advantage of the underwater phase of the start or turn.

UUS has not been studied frequently in the human swimming research literature. Previous studies were developed in competitive fin swimming. Manoni (1985) performed a two-dimensional analysis of the fin swimming technique with monofin. The results showed the undulatory path of the centre of mass displacement with a narrow vertical amplitude and only one oscillation per cycle. Arellano (1985) analysed the underwater films recorded during the1984 Junior Fin Swimming European Championships. Values of selected angles were collected from the finalists in this competition. Better performers showed less knee flexion at the start of the down kick and smaller oscillations of the trunk and legs during the undulatory cycle.
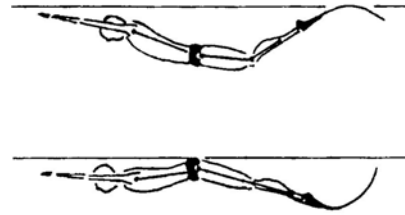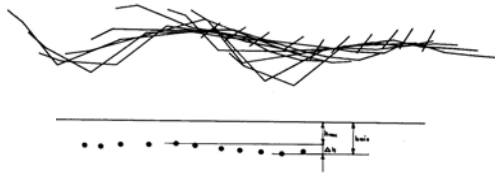
**Figure 4: Samples of analyses developed by Manoni (1985) in fin swimming.**

**Figure 5: Body positions analysed by Arellano (1985) in fin swimming.**

Recent studies were developed to try to analyse the UUS technique thanks to flow visualization techniques, applying the results of the water animal studies or body and extremities kinematics.

Ungerechts (1983) compared the swimming data from butterfly swimmers and dolphins. Up-beat and down-beat durations related to the cycle time were compared between swimmers and dolphins. Up-beat was faster in dolphins at equal movement frequencies. Ungerechts et al. (1998) stated: "although human swimmers will not be able to set water into rotation as effectively as dolphins because of the shape and inflexibility of their ankles, this deficit can be lessened by swimmers emphasizing the reversal action of the kick, using as much as possible, whip-like action". The kinetic energy of the vortex depends on the mass of water and the square of the velocity of the rotating water.

The Strouhal number was cited by Ungerechts et al. (1998), estimating the values of this number in the next range: dolphins > 0,7; humans > 1,35; and model = 0,51. This data is different from that cited by Fish and Rohr (1999) where the values obtained for dolphins were between 0,20 and 0,37.

Colman et al. (1999) analysed one subject performing UUS and UUS with fins at sub-maximal velocities. Using the dye visualization system they tried to observe the added mass of water movements around the swimmer's body and legs. Acceleration of CM was observed during the downward kick and at the end of the upward kick. During the first part of the upward kick, only hyper-extended knees allow the feet to move almost vertically and to put a mass of water in rotation, which was pulled behind the feet during the preceding kick in the opposite direction.

Vorontsov and Rumyantsev (2000a) stated that the leg actions may be able to create greater hydrodynamic forces than arm actions because: a) greater propulsive surface; b) no backward movements of the feet during the working part and; c) muscles groups significantly stronger than the arms.

Colwin (1985) explained the butterfly leg propulsion observing the natural bubbles created during normal swimming. A mechanism called fling-ring was used to explain this efficient leg propulsion system. As the feet thrust downward a bound vortex forms around each foot. The large size of the ring indicates that a large mass of water has been acted upon while the velocity of the water has remained relatively slow.

Luk et al. (1999) analysed the underwater undulatory fin swimming technique. Their results showed that the peak value of horizontal velocity of the total body CM occurred when the tail reached its maximum downward velocity.

Sanders et al. (1995) analysed the wave characteristics of butterfly swimming, their results showed that a wave moved consistently from vertex to ankle during the stroke cycle. An increased amplitude of oscillation from hip to ankle suggested a 'whip-like' action that will influence the production of a propulsive 'rotating vortex'.

Arellano (1999) after utilising two methods of flow visualisation, injected bubbles and the bubble wall, observed differences between efficient and inefficient undulatory underwater swimmers. Efficient swimmers created a big static vortex at the end of the

downward kick and a small vortex at the end of the upward kick. Smaller and translating vortices are created at the end of the downward kick by inefficient swimmers. No vortices are created at the end of upward kick in this group of swimmers.

**UNDERWATER UNDULATORY SWIMMING: BODY KINEMATICS.** The purpose of our kinematic study was to evaluate the differences between different levels of swimmers performing the UUS. Two groups of swimmers were analysed: international ranked senior and junior swimmers and national ranked age group swimmers. The age and the level of the swimming performance defined the group differences. Most of these swimmers did not previously perform specific training to develop the UUS technique**.**

| Group | N Male (age) | N Female (age) |
|---|---|---|
| International (Sen-Jun) | 12 (19.9) | 7 (18.5) |
| National (age-group) | 7 (15.1) | 6 (15.1) |

**Table 1: Number of swimmers composing each group and mean ages.**

A two-dimensional analysis was performed utilising the motion analysis software named KA2D (Schleihauf, 2001). The underwater images were captured in AVI files (50 Hz) and then processed for digitising in the KA2D program. Two-dimensional direct linear transformation (2D-DLT) was performed to obtain the movement space coordinates (see figure 6) and cubic spline for the smoothing and differentiation of coordinates data related to time.

Camera arrangement is shown in figure 5. The swimmer performed two trials of 15 m of UUS at maximum effort. The area video-recorded was more than 7.5 m from the initial impulse wall; this distance assured us that the velocity of the body was obtained from the leg and body self-propulsion. The swimmers were asked to perform the trial at more than 0.5 m of deep.
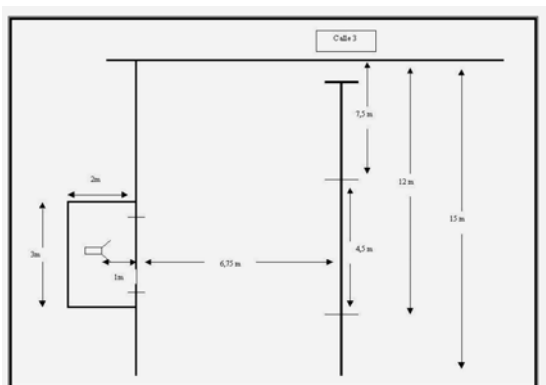


**Figure 5: Camera arrangement and subject swimming line.**
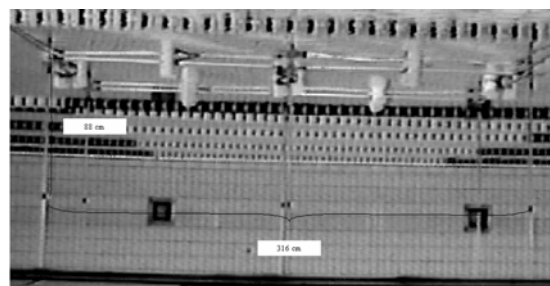


**Figure 6: Calibration frame utilised. The size is big enough to include more than one cycle of movement.**

A large number of variables were calculated after the 2D analysis in order to determine where the differences were between both experimental groups. After the analyses the kick cycle was divided into three phases: 1) downward kick; 2) first upward kick and; 3) second upward kick. The difference between the second and third phases was that the feet trajectory changes direction abruptly, from a more vertical direction to a more horizontal direction. This change was due to the start of the knee flexion during the upward movement. When these phases are related to the centre of gravity horizontal

and vertical velocities, it was observed that horizontal velocity increased during the downward kick, obtaining its maximum value before finishing this phase. A second peak velocity value, sometimes similar to the previous velocity values, was obtained during the transition between the upward vertical phase and the upward horizontal phase of the kick. The vertical velocity followed a similar pattern with smaller values of absolute velocity. The vertical velocity was increased during the downward kick movement, achieving the highest values when the feet are before the end of this phase. Maximum vertical values are obtained before the change of phase during the vertical feet movements. In this case, the values of the absolute vertical velocities were different, two times higher for the downward compared to the upward.
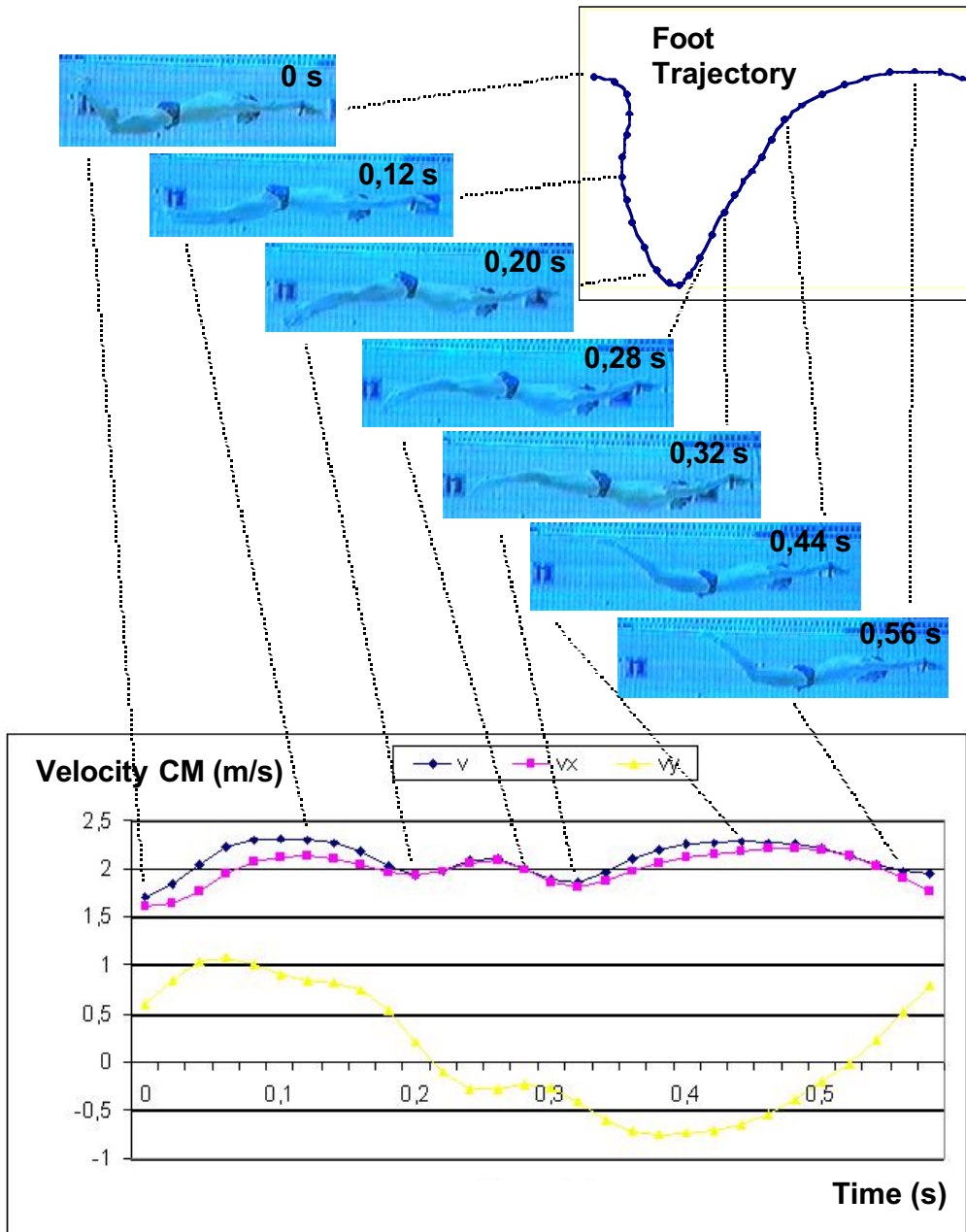


**Figure 7: Velocity of centre of mass during a cycle of UUS related to the pictures of the real movement and the foot trajectory. The swimmer performing the trial was able to swim over 2 m/s (CM velocity) during 75% of the kick cycle.**

One of the most surprising pieces of information observed in figure 7 was that the CM horizontal velocity was very uniform throughout the kick cycle. Only at the end of the knee flexion (the upward finish) did the horizontal velocity decrease to 1.6 m/s. For 75% of the kick cycle the horizontal velocity was over 2 m/s. This indicates the extraordinary performance of the swimmer analysed taking into account that the analysed cycle was swum without the effect of the wall impulse.

**Correlation analysis**: When the international group was analysed (n=19), we found significant correlations with the mean velocity of CM and: a) mean horizontal velocity of CM; b) hip mean velocity, hip horizontal and vertical velocities; c) mean velocity of the CM during the downward kick; d) mean velocity of the CM during the upward kick phase one; e) mean velocity of the CM during the upward kick phase two; f) the maximum value of the CM velocity correlated significantly with the mean value but the minimum value of the CM velocity obtained higher correlation; g) mean velocity of the foot toe; h) kick horizontal displacement and; i) angle of the knee while it is at maximum flexion.

Low and no significant correlations were found between the mean velocity of CM and: a) mean vertical velocity of the CM and b) kick amplitude.

**Sex differences**: The international group showed similar values in all the variables analysed between sexes. Only the body angle related with the horizontal reference revealed differences at the beginning and the end of the kick (men 0º and - 17º and women 7.8º and – 6.9º). The body position of the men tended to be inclined in relation the horizontal line while the women oscillated almost symmetrically around this horizontal line.

**Level of performance:** When the international and national group were compared, the velocity of CM and hip, horizontal velocity of CM and hip and, velocity of the toe showed significant higher values in the international group than the national group. No differences were found in the vertical velocity of CM (see table 2).

| Variable | Average Int. | Average Nat. | *t* | *p* |
|---|---|---|---|---|
| V of CM (m/s) | 1.614 | 1.152 | 6.891 | 0.000 |
| Vx of CM (m/s) | 1.604 | 1.137 | 7.041 | 0.000 |
| Vy of CM (m/s) | -0.020 | -0.045 | 0.965 | 0.342 |
| V of hip (m/s) | 1.696 | 1.258 | 6.547 | 0.000 |
| Vx of hip (m/s) | 1.587 | 1.161 | 6.434 | 0.000 |
| Vy of hip (m/s) | 0.022 | -0.042 | 2.735 | 0.010 |
| V of toe (m/s) | 3.218 | 2.811 | 3.568 | 0.001 |
| Vx of toe (m/s) | 1.622 | 1.137 | 7.329 | 0.000 |
| Vy of toe (m/s) | -0.066 | -0.042 | -0.793 | 0.434 |
| Kick amplitude (m) | 0.618 | 0.619 | -0.013 | 0.989 |
| Horizontal displac. of kick (m) | 0,760 | 0.669 | 1.750 | 0.090 |
| Amplitude / Hor. Displac. k. | 1.259 | 1.073 | 3.416 | 0.002 |
| Kicking frequency (Hz) | 2.139 | 1.755 | 3.780 | 0.001 |
| Maximal knee flexion (º) | 113.7 | 104.9 | 3.214 | 0.003 |
| Maximal V of CM (m/s) | 1.869 | 1.381 | 7.410 | 0.000 |
| Minimal V of CM (m/s) | 1.419 | 0.951 | 7.004 | 0.000 |
| Range of V of CM (m/s) | 0.450 | 0.427 | 0.474 | 0.639 |
| Strouhal number | 0.794 | 0.950 | -3.328 | 0.002 |
| Body Height (m) | 1.801 | 1.692 | | |

**Table 2: Averages of variables analysed in the study related to the UUS. Two groups were defined: International senior and junior swimmers and national age-group swimmers. Results of t-test for independent groups are shown as well.**

The kick amplitude showed no differences between groups, but the international group were taller. The percentage of amplitude related to body height was 34,31% for the international group and 36,58% for the national group. In aquatic animals such as dolphins the percentage is a 20% (Fish and Rohr, 1999).

The Strouhal number showed smaller values in the international group than the national group. The group results were higher than the values obtained by the more efficient fishes (between 0.35 – 0.25) (Triantafyllou and Triantafyllou, 1995).

The percentage of phase duration was similar in both groups as shown in table 3.

| Groups | Downward kick | Upward kick I | Upward kick II |
|---|---|---|---|
| International | 44% | 26.1% | 29.9% |
| National | 45.3% | 24.8% | 29.9% |

**Table 3: Percentage of the total duration of the kick cycle.**

Observing the variation in velocity of CM during a kick cycle in both groups, we found parallel velocity changes during the cycle, in spite of the differences in velocity between groups (see figure 8). The same results were observed in the velocity variation of the hip and the toe (see figure 9).
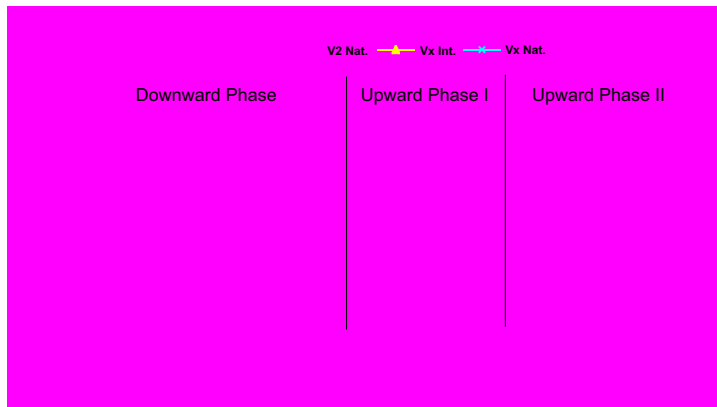


**Figure 8: Mean velocities and horizontal velocities of CM at ten percent intervals of the total kick cycle (interna-tional and national groups)**
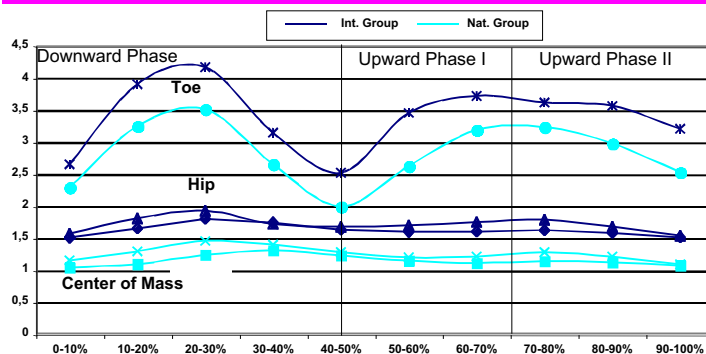


**Figure 9: Mean velocities of CM, hip and toe at ten percent intervals of the total kick cycle (interna-tional and national groups)**

Analysing the downward kick phase we observed more vertical paths in the international group than the national. This suggest that the knee extension tranfers more horizontal impulse to the body. This is accompanied by the correct angle of attack of the feet.
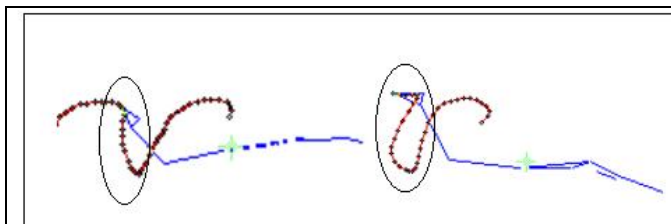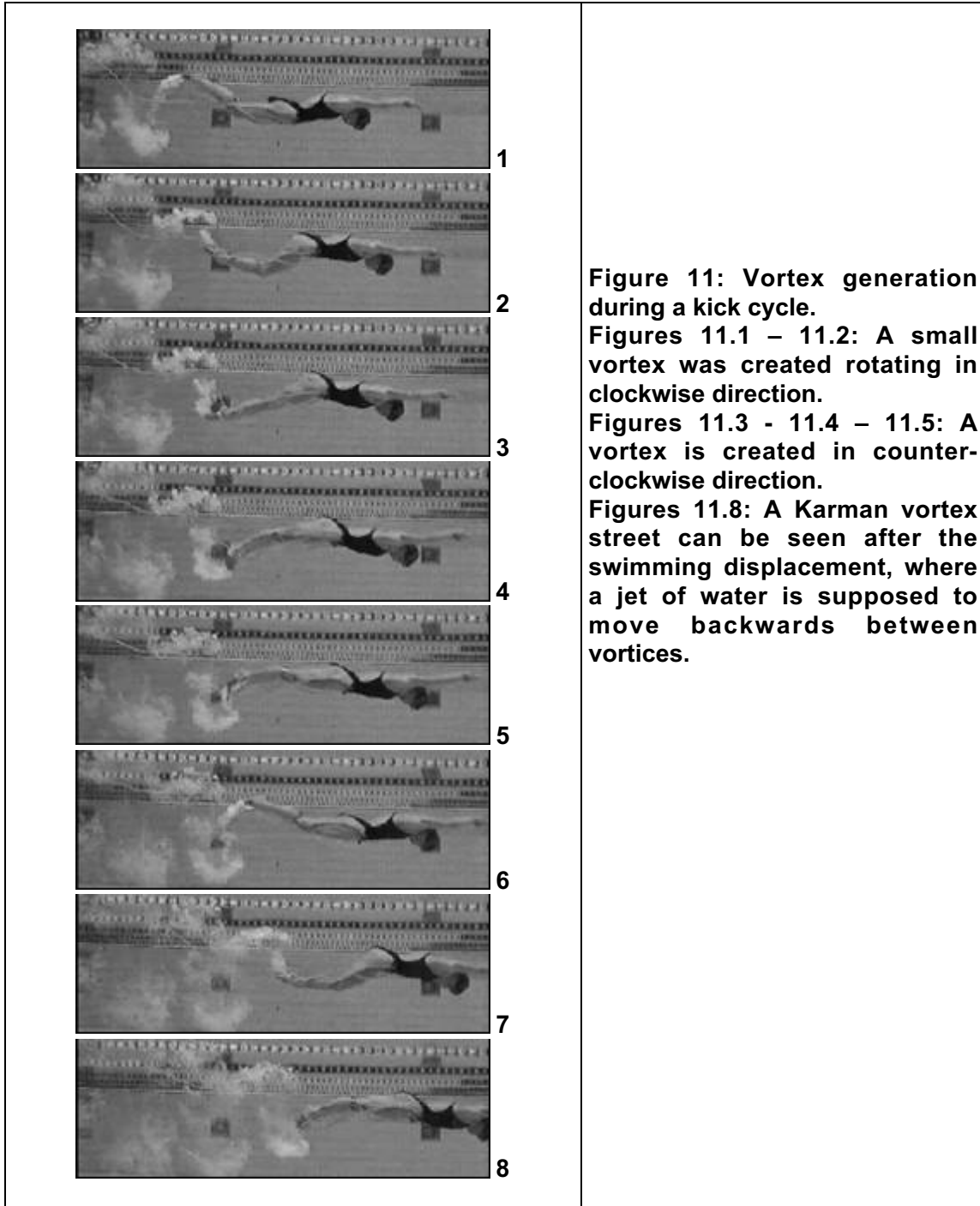


**Figure 10: Differences in the toe trajectory during a kick cycle between international and national swimmer.**

**VORTEX GENERATION:** Using the bubble injection method to visualise the water movements around the feet we observed how the wake is generated. The water started to rotate during the downward kick reaching the maximum volume of the water in rotation when the upward kick was just starting. In the pictures shown in the figure 11 the vortex can be seen in a counter-clockwise direction. After finishing the upward kick (2nd phase) while the knee attains maximum knee flexion another small vortex is created, the water was rotating in clockwise direction. Less efficient swimmers did not create this vortex.



**Figure 11: Vortex generation during a kick cycle.**
**Figures 11.1 – 11.2: A small vortex was created rotating in clockwise direction.**
**Figures 11.3 - 11.4 – 11.5: A vortex is created in counter-clockwise direction.**
**Figures 11.8: A Karman vortex street can be seen after the swimming displacement, where a jet of water is supposed to move backwards between vortices.**

**APPLICATION DURING THE START, TURN AND SWIMMING STROKES:** The drag reduction and efficient vortex creation obtained during UUS reduces the total time in the start and turn phases after the initial impulse. The limits imposed by the rules still leave enough opportunity for the efficient UUS swimmers to benefit from it, as demonstrated in international competition, where an increasing number of swimmers are using this technique.

As a further step forward, some swimmers introduced the UUS in the freestyle technique, coordinating one arm stroke with an undulatory kick, as was seen in finswimming twenty years ago. This technique showed its efficiency when it was used to bet a new world record in 100-m freestyle at the last Olympic Games.

**CONCLUSIONS:** UUS shows a simple vortex generation (in spite of its complexity) in relation to other propulsive techniques, as flow visualisation confirms. The high velocities obtained by some swimmers using UUS forces this technique to be used by all competitive swimmers specially in short course competition where the number of turns is greater. This fact demands more training in this technique and not only during the start practices. Each turn has to be followed by longer UUS distances. Simple methods of flow visualization, as shown in text, can be used by the coach to evaluate this technique. The surprising performances of some swimmers including UUS in the freestyle opens the way to new research in swimming technique.

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