USEFULNESS OF THE STROUHAL NUMBER IN EVALUATING HUMAN UNDER-WATER UNDULATORY SWIMMING

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ABSTRACT

The Strouhal number (***St***) it is a dimensionless number, representing the ratio of unsteady and steady motion. The purpose of our study was to compare the values of ***St*** and other kinematic variables related with it, between swimmers of different level of performance during undulatory underwater swimming (UUS). Two groups of swimmers participated in the study. One was composed of international swimmers from Spanish and other countries and the second with age-group swimmers at regional and national level. After 2D calculations some variables (dependent) were selected relating to body displacement and ***St***. Kick amplitude, kick horizontal displacement, ratio of kick, kick frequency, average horizontal velocity of swimmer's body centre of mass and maximum knee flexion and ***St***.
The present study allows us conclude: A smaller ***St*** is related to higher velocities. The analysis of the factors included in the ***St*** will enables the coach to prescribe a more detailed set of stroke modifications to improve the UUS technique. The reduction of kick amplitude plus the increase of kick frequency combined with the increase of the angle of the knee during the down-kick start seems the most best way to increase the swimmer's velocity during underwater undulatory swimming.
Key words: Underwater undulatory swimming, butterfly kick, Strouhal number.

INTRODUCTION

The Strouhal number (St) it is a dimensionless number, representing the ratio of unsteady and steady motion. It 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), f the stroke frequency (Hz) and U the swimming velocity (Fish & Rohr, 1999). A is the width of the wake but is taken to be equal to the maximum excursion of the foil's trailing edge. The ***St*** serves as a dimensionless frequency, just as the drag coefficient works as a dimensionless drag. The relationship between ***St*** and Reynolds number in non-oscillating bodies is different and very specific to the body shape as the Von Karman trail behind the body shows (Vogel, 1994). The swimming speed in fishes measured in ms^{-1}, increases rectilinearly with the tail beat frequency (Hz). The slopes of the lines are different for each body length. The maximum tail beat frequency measured is also size-related, showing the highest values for the smallest sizes. The tail beat frequency range was between 1.5 Hz and 10 Hz and swimming speed between 0.8 and 6.5 ms^{-1} or between 0.2 and 6.5 body lengths by second. The average stride length related to body length was about 0.68 (Videler, 1993).
The ***St*** for swimming fishes and dolphins was between 0.25 and 0.35, as predicted by the theory described by Triantafyllou and Triantafyllou (1995) in maximum efficiency situations. More

recent it was cited by Fish and Rohr (1999) where the values obtained for dolphins were between 0.20 and 0.37. Ungerechts et al. (1998) cited the Strouhal number in a study where butterfly swimmers and dolphins were compared. They estimated ***St*** values for humans at about 1.35, four times higher than dolphins.

The purpose of our study was to compare the values of Strouhal number and other kinematic variables related with it, between swimmers of different level of performance during undulatory underwater swimming (UUS).

METHODS

Subjects: Two groups of swimmers participated in the study. Group 1 was composed of international swimmers from Spain and other countries and group 2 with age-group swimmers at regional and national level (see table 1). Most of these swimmers had not previously performed specific training to develop the UUS technique. 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 deeper than 0.5 m.

Table 1: Basic characteristics of swimmers composing each group.

Group	N	Age	Height	Weight	Arm Span
International	19 (M=12, F=7)	19.9 years	171.7 cm	60.8 cm	175.7 cm
Age Group	13 (M=7, F=6)	15.1 years	169.2 cm	58.2 cm	173.5 cm

Material: A sagital view of the underwater undulatory swimming motion was video-recorded using a 50 Hz S-VHS camera. A two-dimensional analysis was performed utilising the motion analysis software named KA2D (Schleihauf, 2001). The amera arrangement is shown in figure 1 and the calibration frame is shown in figure 2. 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 and cubic spline for the smoothing and differentiation of coordinates data related to time (see figure 3).

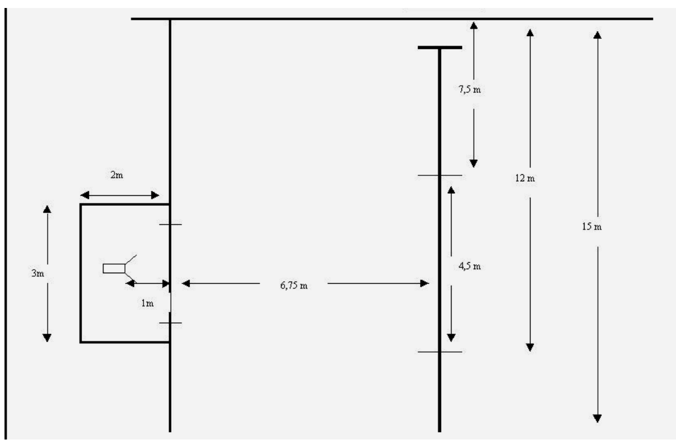

Figure 1: Camera arrangement and subject swimming displacement line.

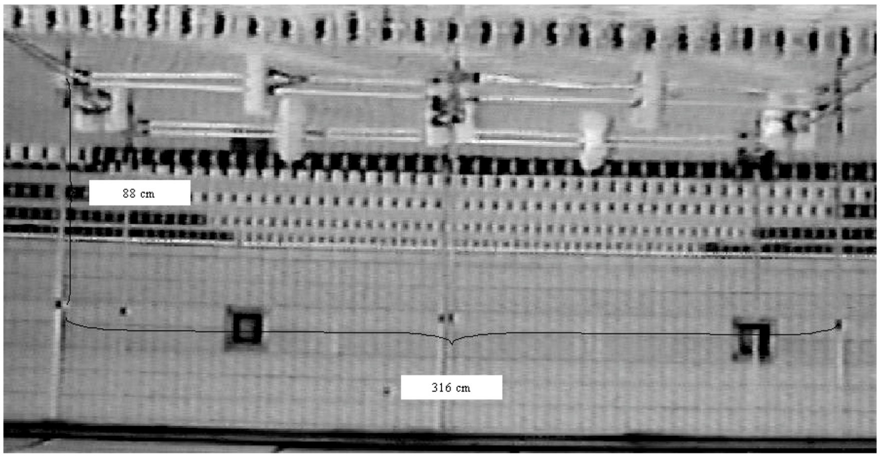

Figure 2: Calibration frame utilised. The size is big enough to include more than one cycle of movement.

Variables: After 2D calculations some dependent variables were selected relating to body displacement and ***St***. Kick amplitude (KA) of foot beat or vertical distance travelled by the toe from the peak of up-kick to the peak of the down-kick (see figure 3), kick horizontal displacement (KHD) or horizontal distance travelled by the toe during a kick cycle, ratio of kick (RK) or KHD divided by KA, kick frequency (KF) or number of cycles divided by the time, average horizontal velocity (VCM) of swimmer's body centre of mass, maximum knee flexion (KnF) and ***St***. The groups described in the subjects section were the two levels of the independent variable or grouping factor.
Statistical analysis: Descriptive statistics, matrix correlations between all the variables and t-test for independent groups were performed using the Statistica computer software (StatSoft, 1994). The level of significance was set at $p<0.05$.

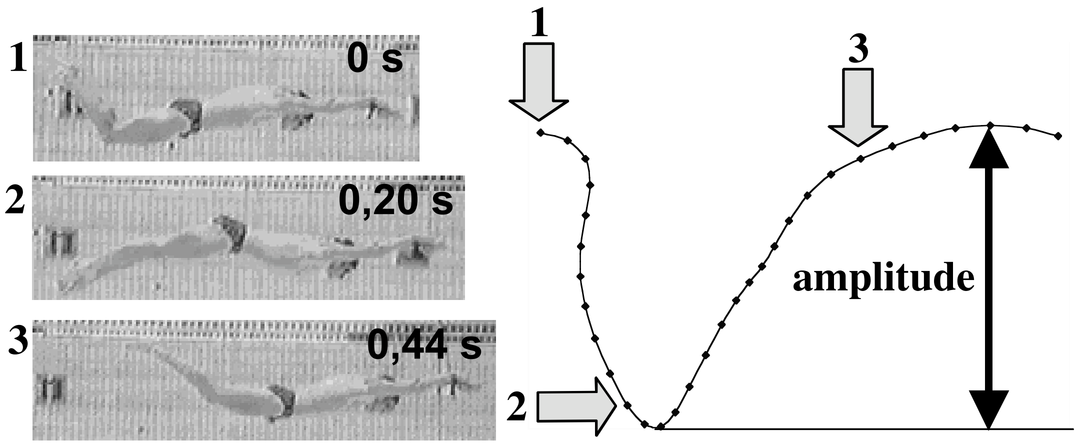

Figure 3: Sample pictures of a swimmer and the footpath obtained after digitising. The figure on the right shows how the amplitude is obtained.

RESULTS

KA and KHD did not show significant differences between groups. All other variables were significantly different ($p<0.01$) between both groups. It should be noted that the VCM differences were similar to the KF differences. ***St*** was smaller in the international group than the age-group swimmers. The international swimmers started the downward kick with the legs less flexed (see table 2).

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

Variables	Average International	Average Age-Group	***t***	***p***
KA (m)	0.618	0.619	-0.013	n.s.
KHD (m)	0,760	0.669	1.750	n.s.
RK	1.259	1.073	3.416	**
KF (Hz)	2.139	1.755	3.780	**
VCM (m/s)	1.614	1.152	6.891	**
KnF (º)	113.7	104.9	3.214	**
St	0.812	0.950	-2.642	*

* p<0.05, ** p<0.01, n.s.=not significant

Kick amplitud correlated positively and significantly with KHD and negatively and significantly with KF. KHD correlated positively and significantly with RK and VCM, and negatively and significantly with ***St.*** RK correlated positively and significantly with KHD and VCM, and negatively and significantly with ***St.*** KF correlated positively and significantly with VCM and KnF, negatively and significantly with KA. VCM correlated positively and significantly with KnF and negatively and significantly with ***St*** (see table 3).

Table 3: Coefficient of correlation matrix between the variables analysed.

	KA	KHD	RK	KF	VCM	KnF
KHD	0.573*					
RK	n.s.	0.757**				
KF	-0.485*	n.s.	n.s.			
VCM	n.s.	0.630*	0.736**	0.519*		
KnF	n.s.	n.s.	n.s.	0.663*	0.701**	
St	n.s.	-0.633**	-0.914**	n.s.	-0.639**	n.s.
*p<0.05	**p<0.01	n.s.= not significant				

DISCUSSION

The factors affecting the ***St*** were VCM and KF, and they were significantly different between groups while the amplitude was not. The constant value of amplitude while the KF increased in the international group produces a different VCM and ***St***. These results were confirmed by the analysis of correlation where VCM and ***St*** were negatively related. Higher velocities are related to smaller ***St***. No correlations were found between ***St*** and the other factors KA and KF. This may mean that to obtain the same velocity different combinations of KA and KF can be utilised by the swimmer, but according to the ***St*** theory it is better to approach the values to those obtained by the more efficient swimmers. The group results (0.81 and 0.95 respectively) were higher than the values obtained by the most efficient fish, between 0.35 – 0.25 (Triantafyllou and Triantafyllou, 1995). Our data differ from those obtained by Ungerechts et al. (1998), where they estimated ***St*** values for humans about 1,35 , four times higher than dolphins, while our data was two or three times higher only. The differences may be due to the stroke performed. In this study the swimmer performed butterfly, in our study the trials were swam using UUS. In our study significant but medium values in the correlation between VCM and KF were found. This situation is different from that obtained in fish swimming studies where a linear relationship was found (Videler, 1993).

Average horizontal velocity (VCM) of swimmer's body centre of mass correlated significantly with the kick horizontal displacement, ratio of kick, kick frequency, knee flexion value during the start of the kick and the St. Other significant correlations were found between the ratio of kick and the St and kick horizontal displacement and knee flexion and St.

The kick amplitude showed no differences between groups, but the international group swimmers were taller. The percentage of amplitude related to body height was 34,3% for the international group and 36,6% for the age-group swimmers. In aquatic animals such as dolphins the percentage is a mere 20% (Fish and Rohr, 1999). Large amplitudes can produce more body drag than propulsion in some phases, but to analyse this factor properly it has to be related to body length.

The downward footpath showed more vertical displacement in the international group plus less drag foot position. This, together with stronger leg muscles explains the higher values obtained in kick frequency observed in this group.

The present study allows us to conclude: A smaller ***St*** is related to higher velocities. The analysis of the factors included in the ***St*** will let the coach prescribe a more detailed set of stroke modifications to improve the UUS technique. The reduction of kick amplitude plus the increase of the kick frequency combined with the increase of the angle of the knee during the start of the down-kick seems the best way to increase the velocity of the swimmer during underwater undulatory swimming.

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