

Why have swimmers neglected the "fish kick" technique?

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Abstract

Given that horizontal-plane undulation ("fish kicking") just under the water surface is more effective (from a hydrodynamic point of view) than vertical-plane undulation ("dolphin kicking") (Lighthill, 1975), why then do expert swimmers not use this technique after the turn and before resuming their arm stroking action? Fourteen national-level swimmers (6 males and 8 females) were timed over 15m and 25m trials while dolphin kicking and then fish kicking. A comparative analysis revealed the strong potential of fish kicking (which equates to dolphin kicking on the side). Over 25m, the fish kicking times were only slightly slower than the dolphin kicking times, and this was in the absence of prior training. Over 15m and at no more than 1 metre below the surface, the swimmers went significantly faster in the side position ($p < 0.05$). A multifactorial analysis (MFA) revealed that the determinants of high performance while kicking underwater are relatively independent of the swimmer's absolute speed (e.g. personal best for 50m front crawl), gender, age and weight. In contrast, in the population of swimmers studied here, being a backstroke or butterfly specialist and being short were factors that appeared to favour speed in the undulation trials.

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1. Introduction.

In 50m, 100m and 200m backstroke and butterfly short course swimming events, the best swimmers covering over half the total distance underwater. According to international rules, almost two-thirds of the front crawl ("freestyle"), backstroke and butterfly events can be swum underwater (i.e. up to 15m per 25m length). Hertel (1966) estimated that staying at the surface increases drag by a factor of 5. Likewise, the propulsive potential is 20% lower at the surface than at a depth of 60cm (Costill, Maglischo, Richardson, 1992, Chollet, 2000), explaining the swimmers' preference for immersion (Collard, 2007). In the European short-course championships, the distance swum underwater doubled between 1982 and 2002 (Collard, 2006).

During underwater undulations (dolphin kicks), propulsive forces ("lift-based propulsion", Fish, 1993, 1996) are produced by a depolarisation effect (Brown, Counsilman, 1971, Schleihauf, 1978, Maglischo, 1982, Counsilman, 1986). The efficiency of dolphin kicking continues to astonish the scientific community. In the

laboratory, researchers have studied (but failed to agree on) the contribution of lift-based propulsion to swimming, relative to the drag-based propulsion obtained by pulling the arms backwards according to Newton's 3rd Law (Wood & Holt, 1979, Holt, 1989, Sprigings & Koehler, 1990, Cappaert & Rushall, 1994, Sanders, 1997a, 1997b, 1998, Catteau, 1997, 2006, Vennell, Pease, Wilson, 2006). The surprising efficacy of undulation-based propulsion has been summarized as the "Gray paradox" (Gray, 1968, Webb, 1975, Williams, 1983, Webb, 1984, Williams, Friedl, Fong, Yamada, 1992). In 1936, Gray estimated the power output of a dolphin during its fast, sustained swimming (an average of 30 km/h for hours on end), taking into account the dolphin's drag coefficient (C_x) and frontal surface area (S , projection of the dolphin's outline onto a perpendicular 2-dimensional plane). The calculations indicated that in order to achieve the performance actually observed, more than 7 times the available muscle power would be required (Ungerechts, Daly, Zhu, 1998)!

The undulating action creates a pump effect (the "undulating pump" (Müller, Van Den Heuvel, Stamhuis, Videler, 1997, Müller, Smit, Stamhuis, Videler, 2001) or "suction effect" (Shouveiler, Hover, Triantafyllou, 2005)) over the body surface, which results in the backwards acceleration of low-pressure masses of water (Rayner, 1985). Exploitation of this pump effect is only possible if (i) the swimmer is sufficiently immersed, so that the water can be depressurized on one side of the body and pressurized on the other and (ii) he/she already has enough initial speed to make the depressurized fluid flow backwards along the body. In other words, the pump/suction effect only operates at high Reynolds values: $Re=LU/\nu$, where L is the length of the swimmer's body, U the swimming speed and ν the viscosity of the medium divided by its density (Lighthill, 1969, Arellano, 1999). Hence, starts from rest without a solid surface to push off cannot exploit the undulating pump effect. The swimmer must thus create movement via a sudden change in direction or by using his/her arms for a short time to generate propulsive drag forces. In practice, kicking off the wall after the turn enable swimmers to exploit the suction effect, which is then prolonged by whiplash of the rear part of the body (generating a vortex). Both actions - the suction effect and the vortex - contribute to propulsive lift forces.

Like marine mammals (which, over the course of evolution, have abandoned drag-based propulsion for lift-based propulsion (Alexander, 1988, Thewissen, Hussain, Arif, 1994)), swimmers favour undulations in the vertical plane (Colobert, Bideau, Nicolas, Fusco, 2004). In 1997, Misty Hyman beat the women's 100m short-course butterfly world record by covering 35m underwater while dolphin kicking on her side - a technique that specialists refer to as the "fish kick" (Lindsey, 1978, Sfakiotakis, Lane, Davies, 1999). Since then, the technique has not gained many converts, although Alexander Popov and Ian Thorpe have used it extensively in training... In a 2005 video for US swimming coaches, Richard Quick presented the fish kick as a key element for improving underwater performances in short-course events - especially when the swimmer returns to the surface and resumes the arm stroking action. The Reynolds number increases when motor actions are performed in a high-density medium. Just below the surface, the masses of water against which the swimmer pushes have higher inertia when dolphin kicking on the side than when performing the same action on the back or on the front, where the movement may occur "in the air". Hence, after a dive start or an underwater turn, one would expect to see swimmers return to the surface in

the side position - at least in the front crawl and backstroke events, where the arm stroking action can be resumed from this position. However, this is not at all seen in current competitive swimming.

Given that fish kicking just under the surface gives swimmer an incontestable advantage from a hydrodynamic point of view, (Lighthill, 1960, 1975, Guillaume & Piat, 2003), why then is this technique neglected by swimmers in actual practice?

We decided to investigate whether use of the "fish kick" technique enable to swimmers to swim more quickly than conventional dolphin kicking on the front. Since the position on the side perturbs the usual equilibrium, would motor techniques also be perturbed (i.e. problems managing laterality, upper body rigidity and action synchronisation) to the point of limiting swimming speed?

2. Method.

Fourteen national-level swimmers (6 males and 8 females, aged from 15 to 19 years) from the "Stade Nautique" club in Caen (France) volunteered to participate in the study. Half the swimmers (i.e. 3 males and 4 females) were front crawl specialists and thus were not especially familiar with immersed swimming; in competition, these specialists break surface about 5m after the turn, regardless of the event distance. The other 7 swimmers were butterfly or backstroke specialists who were more accustomed to underwater turns. In agreement with their coach, the swimmers were observed during a club training session. We recorded the following background data: age, weight, height and personal best time in a 50m short-course front crawl event.

— We first asked the swimmers to cover 15m in a training pool (specified swimming depth: 0.8 metre to 1 metre below the surface) while dolphin kicking on their front and then on their side, with a 10-minute semi-active recovery interval between the two trials (i.e. alternating a few front crawl lengths and rest periods). The swimmers started by pushing off a specific point on the wall and had to swim to the opposite end while remaining in a defined 1.5-metre-wide lane.

— After full recovery from the two 15-metre trials, the swimmers were timed over a 25-meter short-course event with a dive start - first while dolphin kicking on their front and then (after another 10-minute, semi-active recovery period) on their side. After the dive start, the distance covered underwater was restricted to 15m at most; after this point, the swimmers had to break surface while performing the requested kick. In contrast to the 15m trial, we instructed the swimmers to stay at or near the surface for the remaining 10m, until they reached the end wall.

The data were analysed in two ways: (i) with a Student's T-test, in order to evaluate the statistical significance of any time differences between side and frontal dolphin kicking and (ii) multiple factorial analysis (MFA) in order to determine the elements (personal best crawl speed, stroke specialty, gender, age, height and weight) that best explained the variance in performance times. Multiple factorial analysis was carried out using

version 2.2 of the TRI2 program (Cibois, 2008), which performs regression based on the maximum percentage deviation from independence.

The 10 potentially explanatory factors were coded into 29 modes, as follows:

- 1/ GENDER: gender (female – male)
- 2/ AGE: age (≤ 16 YEARS – 17 YEARS – ≥ 18 YEARS)
- 3/ HEIGHT: height ($< 1.7\text{M}$ – $[1.7-1.8\text{M}[$ – $\geq 1.8\text{M}$)
- 4/ WEIGHT: weight ($< 57\text{KG}$, $[57-67\text{KG}[$, $\geq 67\text{KG}$)
- 5/ 50M: personal best time for a short-course 50M front crawl event ($< 26\text{SEC}$ – $[26-28\text{SEC}[$ – $\geq 28\text{SEC}$)
- 6/ SPE: specialty (front crawl – butterfly – backstroke)
- 7/ 15F: timed performance over 15m, undulations on the front: dolphin kick ($< 8.4\text{SEC}$ – $[8.4-9\text{SEC}[$ – $\geq 9\text{SEC}$)
- 8/ 15S: timed performance over 15m, undulations on the side: fish kick ($< 8.4\text{SEC}$ – $[8.4-9\text{SEC}[$ – $\geq 9\text{SEC}$)
- 9/ 25F: timed performance over 25m, undulations on the front: dolphin kick ($< 16\text{SEC}$ – $[16-17\text{SEC}[$ – $\geq 17\text{SEC}$)
- 10/ 25S: timed performance over 25m, undulations on the side: fish kick ($< 16\text{SEC}$ – $[16-17\text{SEC}[$ – $\geq 17\text{SEC}$)

3. Results.

The differences between the 2 undulation techniques were small but sometimes significant. On average, the 14 swimmers were faster over 15m when dolphin kicking on the side than on the front: 8.75 sec versus 8.98 sec, respectively. The opposite order was found for the 25m swim with a dive start, with mean times of 15.95 sec for dolphin kicking versus 16.20 sec for fish kicking (Tab. 1).

Table 1. Times (in seconds) for dolphin kicking on the front and on the side over distances of 15m and 25m.

15M			25M		
NAME	FRONT	SIDE	NAME	FRONT	SIDE
SA	7.62	7.5	RA	14.12	14.23
RO	7.94	7.44	SA	14.29	14.41
AN	8.22	7.94	RO	14.38	14.26
CH	8.37	7.94	CH	14.48	15.91
HE	8.62	8.72	AN	14.67	14.51
MA	8.69	9	ME	15.36	15.86
JI	8.75	8.69	HE	16.07	16.98
RA	8.85	7.83	AL	16.21	16.04
ME	9	8.37	JI	16.23	16.37
AL	9.19	8.88	MA	16.69	16.72
CO	9.75	10.12	CA	17.29	17.33
CA	9.88	9.99	CO	17.51	17.57
ED	9.99	9.62	ED	17.94	18.11
HL	10.88	10.44	HL	18.13	18.55
<i>mean</i>	<i>8.98</i>	<i>8.75</i>	<i>mean</i>	<i>15.95</i>	<i>16.20</i>

In a two-sided Student's T test, the mean front/side difference was significant ($p = 0.039$) for 15m and indicative (0.057) for 25m.

Factorial calculation of the 29 modes in our experiment yielded a Φ^2 value of 0.570560. Φ^2 is merely Khi^2 divided by the total number of data items recorded and represents 100% of the relevant variance. Hence, as shown in Table 2, the first 3 constitutive factors in the factorial analysis represent eigenvalues of 0.212168, 0.141899 and 0.137635 of the overall Φ^2 respectively, i.e. $37.2\% + 24.9\% + 24.1\% = 86.2\%$ of the overall variance. Most of the data fall within the first few factors of the MFA - a sign of convincing results. For each factor, the factorial coordinates (either positive or negative) of each mode are specified, together with the contribution per factor (CPF). Philippe Cibois (1984) suggested focusing only on modes with above-average CPF values. There are 29 modes and the sum of the CPFs is 1000. If each mode accounted for the same amount of variance, each would have a mean CPF of $1000 \div 29 = 34$. In fact, only the modes above this mean (>34) were analysed further, since these are the ones that lend the factor its significance and give substance to the observed data. In order to avoid interference by modes with lower CPFs (i.e. <34), we removed the latter from our presentation of the results (Table 2).

Table 2. Factorial coordinates and contributions per factor (CPF) over the mean (>34) for the first 3 factors in the MFA.

Factor 1

Eigenvalue = 0.212168

Percentage of the variance = 37.2

J	NAME	Fact. coord.	CPF	Full name
21	15C1	-775	101	15S<8.4SEC
18	15V1	-857	99	15F<8.4SEC
24	25V1	-623	78	25F<16SEC
27	25S1	-623	78	25S<16SEC
17	SPE3	-675	46	BACKSTROKE
6	TAI1	-513	44	<1.70M
15	SPE1	358	35	CRAWL
20	15V3	619	77	15F>9SEC
23	15C3	756	96	15S>9SEC
26	25V3	867	101	25F>17SEC
29	25C3	867	101	25S>17SEC

Factor 2

Eigenvalue = 0.141899

Percentage of the variance = 24.9

J	NAME	Fact. coord.	CPF	Full name
22	15C2	-714	103	15S8.4-9SEC
19	15V2	-667	90	15F8.4-9SEC
25	25V2	-647	84	25F16-17SEC
28	25C2	-647	84	25S16-17SEC
12	50M1	-588	52	50M<26SEC
11	POI3	-422	45	>67KG
8	TAI3	-422	45	>1.80M
18	15V1	491	49	15F<8.4SEC
9	POI1	721	52	<57KG
16	SPE2	790	94	BUTTERFLY

Factor 3

Eigenvalue = 0.137635

Percentage of the variance = 24.1

J	NAME	Fact.	coord.	CPF	Full name
8	TAI3	-561	82		>1.80M
11	POI3	-561	82		>67KG
2	SEX2	-504	79		MALE
13	50M2	-381	45		50M26-28SEC
6	TAI1	423	46		<1.70M
10	POI2	396	57		57-67KG
1	SEX1	378	59		FEMALE
28	25C2	681	96		25S16-17SEC
25	25V2	681	96		25F16-17SEC
14	50M3	715	133		50M>28SEC

The prime factor (Table 2) contrasts the swimmers with the best fish kick times (15S<8.4SEC, 25S<16SEC) and dolphin-kick times (15F<8.4SEC, 25F<16SEC) with the slower swimmers in these events (15F>9SEC, 15S>9SEC, 25F>17SEC, 25S>17SEC). These variables are linked to the swimmers' height and specialty. The most efficient swimmers in the 4 undulation trials were short (<1.70M) backstroke specialists (BACKSTROKE). The front crawl specialists (CRAWL) were the least efficient.

The second factor (Table 2) contrasts tall (>1.80M), heavy (>67KG) swimmers with a fast personal best crawl time (50M<26SEC) and who were moderately but significantly quicker in the fish kick and dolphin kick trials (15S8.4-9SEC, 15F8.4-9SEC, 25F16-17SEC, 25S16-17SEC) with lighter (<57KG) butterfly specialists (BUTTERFLY) who were particularly rapid in the dolphin kick (while remaining no more than 1 meter under the water surface) over the shorter trial (15F<8.4SEC).

The third factor (Table 2) contrasts several modes related to the female gender (FEMALE) with those related to the male gender (MALE), such as height and weight (>1.80M and >67KG for the males; <1.70M and 57-67KG for the females) and the personal best front crawl time (50M>28SEC for the females).

Taken as a whole, our results show that the determinants of high performance in the fish kick and dolphin kick are relatively independent of personal best swimming speed (Factor 2) and gender (Factor 3). In contrast, being short and being a backstroke specialist constituted an advantage in the 4 undulation speed trials (Factor 1). The butterfly specialty appeared mainly to improve performance in the short-distance (15M) dolphin-kick trial.

4. Discussion.

Over 25m and after a dive start, the swimmers had trouble finding a sideways posture which enabled efficient propulsion. Returning to the surface after the dive start is easier when dolphin kicking on the front. This is probably why the times are noticeably faster over this distance for dolphin kicking than for fish kicking (Table 1). Furthermore, given that part of the swimmer's body had to break surface in the second section of the

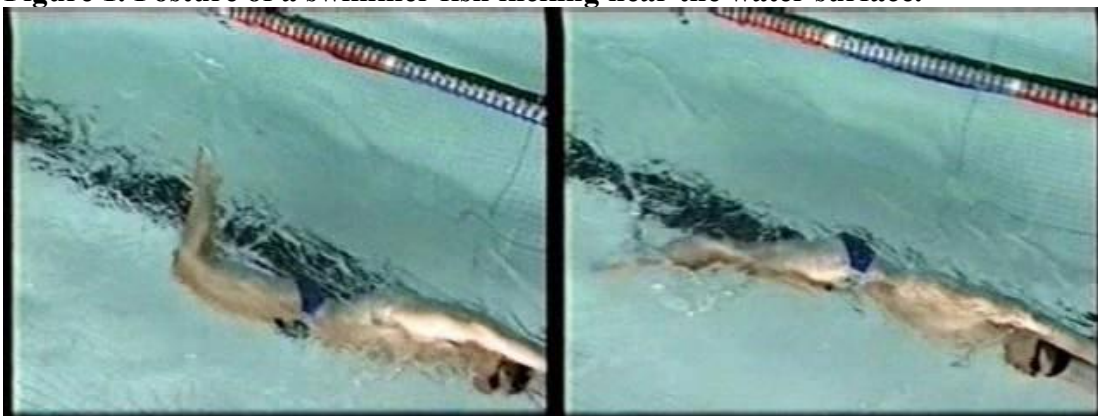
25m trial, the fish kick swimmers seemed to be somewhat disorientated. With just one shoulder out of the water, (Fig. 1), it was not easy for them to maintain the rigidity of the upper part of the body - a characteristic of the "carangiform" or "thunniform" propulsion, where between $\frac{1}{2}$ and $\frac{3}{4}$ of the body is relatively rigid (Lindsey, 1978). This is precisely the shape with the greatest speed potential (Lighthill, 1960, Guillaume & Piat, 2003).

In contrast, when equilibrium is assisted by kicking off the wall (a projectile body in the 15m trial), the swimmers gained greater advantage from dolphin kicking on the side (i.e. fish kicking) just below the water surface. Since the body was rigid, the swimmers maximized the efficiency of their actions because the adjacent masses of water offered less resistance. Even though the swimmers were very used to dolphin kicking, this action was less effective over 15m, due to the lower propulsive lift forces in the push phase (given the body's position just under the surface).

In theory, butterfly and backstroke specialists should be more at ease in underwater undulation trials, since they are more used to staying underwater for longer after the turn. Strikingly, gender was not a determinant of performance and the shorter swimmers were generally faster when dolphin/fish kicking than their taller clubmates. This observation may have been due to the characteristics of our population of swimmers and so we shall refrain from over-analyzing this aspect.

The fact that in the absence of prior training, fish kicking was almost as fast as dolphin kicking on average (and in some cases significantly faster - $p < 0.05$ in the 15m trial) is a striking result in itself. It tends to confirm the theory whereby fish kicking has more speed potential than dolphin kicking (Lighthill, 1975). Our observations should prompt interest from swimming coaches. In humans, swimming is learnt rather than inborn and the "right ways to swim" constitute "behavioural rites" which are revealed when swimmers successfully imitate the locomotion of fish.

Figure 1. Posture of a swimmer fish kicking near the water surface.



The photos show the two extremes phases of leg oscillation. The creation of propulsive drag forces occurs via a reaction to the leg action: since these forces are perpendicular to the direction of travel, they tend to sum and cancel each other out. The propulsive lift forces are always generated at an angle of 90° to the drag forces and are oriented forwards. They are primarily generated by the creation of a vortex following the whiplash movement of the feet. Given that the knee joint is locked explosively when straightening the leg, the extension phase is always more propulsive than the flexion phase (adapted from Sfakiotakis, Lane, Davies, 1999).

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