



**HAL**  
open science

## The Snake: Change in swimming techniques under the pressure of selection

Luc Collard, Damien Hello, Damien Vitiello

► **To cite this version:**

Luc Collard, Damien Hello, Damien Vitiello. The Snake: Change in swimming techniques under the pressure of selection. *Journal of Physical Education and Sport*, 2022, 22 (5), pp.1289-1296. 10.7752/jpes.2022.05161 . hal-03725115

**HAL Id: hal-03725115**

**<https://hal.science/hal-03725115>**

Submitted on 16 Jul 2022

**HAL** is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

## The Snake: Change in swimming techniques under the pressure of selection

LUC COLLARD<sup>1</sup>, DAMIEN HELLO<sup>2</sup>, DAMIEN VITIELLO<sup>3</sup>

<sup>1,2,3</sup>URP 3625, Institut des sciences du Sport Santé de Paris (I3SP), Université Paris Cité, 1 rue Lacretelle 75015, Paris, FRANCE.

Published online: May 31, 2022

(Accepted for publication May 15, 2022)

DOI:10.7752/jpes.2022.05161

### Abstract

We know that natural selection brought marine mammals to favor lift-based propulsion rather than drag-based propulsion. Curiously, none of these techniques is favored in swimming competitions by professional swimmers. Is it possible to invent new swimming styles under the pressure of selection as marine mammals did? We wondered if 61 athletes would be able to replicate the techniques used by the species most adapted to the aquatic environment, without being forced to it and with the sole intention of swimming faster. We imagined a system of shoulder-to-shoulder duel in ascent/descent. There were two swimmers in each lane. In each lane, a weighted object was placed at the bottom of the water, 15 meters from the pool deck. The first to grab the object in his lane won the duel and moved up one lane for the next trial. After eight duels, the best swimmers were in lane eight, the slowest in lane one. Six techniques have emerged from the 244 duels in forced immersion (488 dives followed by 15-meter races): (i) moving with the legs only, arms along the body (beats), (ii) total breaststroke, (iii) hybrid breaststroke (simultaneous and symmetrical arm movements, synchronous to the leg beats), (iv) gallop: undulation of the body with leg beats, (v) undulation of the whole body, (vi) the snake technique: characterized by a leg beat synchronous to an oscillation of the upper part of the body, with the arms along the trunk. Although the matching is not perfect, the processes used by swimmers fit the models presented to describe the odyssey of mammals that have been going back to the water for 60 million years: the fastest swimming techniques are the ones that best mimic the marine mammals that are best adapted to speed ("pectoral oscillation" like sea lions; "caudal oscillations" like whales). The later favor lift forces over propulsive drag forces (drag forces which can be observed in dogs, rats and other swimmers in Johnny Weissmuller's freestyle that use "quadrupedal paddling" and "alternative pectoral paddling"). The competition swimmers observed were able to experimentally reproduce the choices of natural selection. But today, the fastest ways of moving in the water are not found in the Swimming Federation training sessions.

**Keywords:** underwater swimming techniques, swimming speed, innovative swimming techniques, school of sports science student, pectoral oscillations, caudal oscillations

### Introduction

Inventing new swimming techniques under the pressure of selection? That is what marine mammals have kept doing since they started conquering the water environment some 60 million years ago (Thewissen, 2013; Thewissen et al., 1994). The *Packicetus* walking whale started trotting on the surface of the water like a dog, then, progressively its descendants galloped until they undulated in the water as today's cetaceans do (Alexander, 1988; Gingerich et al., 1983). How has the evolution been accomplished for marine mammals from a mechanical point of view? The species that are best adapted to the sea world move quickly and for a long time by immersing themselves deeply into the water (Williams et al., 1992). These species have swapped the forces of propulsive dragging for lift-based propulsion so as not to lose energy because of the underwater return of supports ('lift-based propulsion' (Fish, 1993, 1996)). Even the powerful fore limbs of seals are used only for propulsion or for swift direction changes. When in search of speed, these semi-aquatic animals press their fore limbs on their body and undulate laterally as most fish do. During glides and before starting again 'official' swimming strokes swimmers may be seen to undulate as cetaceans do, but vertically (Peter et al., 2020).

The forces of drag propulsion then alternatively apply from top to bottom and from bottom to top. They contribute to the rising and falling of the body but not to its moving forward. What pushes swimmers forward is not Newton's third law but lift forces. They apply to 90° of the drag forces (Chollet, 1997). Propulsion drag forces are produced by a depolarization effect and enjoy an efficiency that is still puzzling to the scientific community. This is known as 'Gray's paradox' (Gray, 1936). Gray estimated the power necessary for a dolphin to swim as it does (fast and for a long time) by considering the resistance to propulsion in view of the dolphin's shape coefficient ( $C_x$ ) and master torque area ( $S$ , projection of the contours of the dolphin on a two-dimension plan placed at right angles with it). His calculations indicate that, to obtain the performances achieved, the required muscle power should be multiplied by seven.

In fact, undulatory actions trigger a pump effect ('undulating pump' (Müller et al., 1997) or 'suction effect' (Schouveiler et al., 2005)) on the surface of the body, which results in making the lower pressure water masses go faster from front to back (Triantafyllou et al., 2016). This pump effect can be exerted if and only if, on the one hand, the animal is sufficiently immersed so that the water can be depressurized on one side of the body and pressurized on the other, and on the other hand, if the animal has reached an initial speed that is sufficient for the depressurized fluid to flow backwards against its body. In other words, the suction effect can only happen at a high Reynolds value:  $Re=LU/\nu$ , where  $L$  is the animal's length,  $U$  its speed, and  $\nu$  the viscosity of the action's environment divided by its density. This is one of the two reasons why, contrary to what is generally believed, when looking to be faster, fish and marine mammals do not try to escape water resistance by jumping out of the water but instead immerse themselves deeper into the water (Lighthill, 1969). The other reason is that when they move on the surface of the water, resistance that does not exist in depth (wave resistance, backwash drags) is created. These resistance then changes from the square to the cube of the swimming speed (Collard, 2020). Hertel estimates that swimming on the surface at 2 m/s can increase the resistance to propulsion fivefold (Hertel, 1966). But fish and marine mammals also jump out of the water to escape predators, to breathe or to communicate. When starting from zero-speed, they make a swift change of directions or use their pectoral fins (Lighthill, 1975) thus having recourse for an instant to the propulsive drag forces. The pump effect is enhanced by a lash turn of their hind part (the caudal fin for fish and marine mammals) that generate vortex. Both vortex and suction effect participate to the propulsive lift forces.

Like semi-aquatic mammals, high-level swimmers spend almost a quarter of their lives as champions inside the water and are able to maintain immersions during 60% of their training (Rhys-Evans, 2020). They are perfectly capable of practicing lift propulsion. Their anatomy does not allow them to undulate as well as an eel. The relative stiffness of their trunks leads them to resort to oscillations of the legs, triggered (controlled) by the undulation of their pelvis (Colobert et al., 2004). The ethologists would class them in the category of the carangiform species (from carangid fish species) or tuniform (from tuna fish) whose bodies are half or three-fourths rigid (Lindsey, 1979). This shape presents the highest potential for speed (Laurent & Piat, 2003; Lighthill, 1960). Therefore, one may wonder why the sports institutions have retained none of the propulsion modes developed by natural selection? It is surprising that the sports institution and school sport have not retained any of the modes of propulsion inspired by natural selection (Monteiro et al., 2021; Scurati et al., 2019). This is a matter of debate. And has been for a long time. "In the present state of our knowledge," wrote (Costill et al., 1991), "we do not know what law swimmers apply to propel their bodies through the water. This may come as a surprise at a time when cosmonauts are being sent into space and it is precisely this enigma that is scientifically stimulating. In the columns of the magazine *Hyper*, (Catteau, 2007) seemed to have found the answer to this problem by giving a singular and unequivocal title: "propulsion in the swimmer's locomotion". For him, and against those who today defend the prevalence of lift-based propulsion in swimming (Counsilman, 1971; Maglischo, 2003; Menzer et al., 2022; Ruiz-Navarro et al., 2022), the swimmer draws his power mainly from drag-based propulsion according to the good sense of action/reaction. Also, swimmers do not benefit from akin to fish or marine mammals, which use the force of lift propulsion (Fish, 1996). The paddle wheel model used by pedal boats and once steamboats is, according to this theory, the cornerstone of human swimming technique. This is the issue at stake in the debate. How do swimmers go fast and even faster? Will there be only chronometric progress linked to training and anthropometric changes? (Byankina et al., 2017; Da Silva et al., 2020; Ganchar et al., 2018; Ildikó et al., 2017) It has not escaped the attention of sports swimming specialists that the 15-meter rule - requiring swimmers to break the surface before this distance from the wall on pain of disqualification - appeared at the time when dissident swimmers began to abuse immersions sometimes up to 35 meters in the Olympic pool. Why do swimmers in all four strokes stay underwater longer today than in the past? Why did swimmers in the old days rush to the surface just after the turn, when there was no rule limiting the distance of the stroke? Isn't it curious that most coaches even today describe this immersive phase of the race as the "non-swimming" part?

This leads us to think that, in competitive swimming, like in track races, the improvement of performances is linked more to predisposition evolution than to sociocultural conditions (Deaner, 2006). Even if many recent scientific works have stressed the potential for the swimmers of the *Underwater Dolphin Kicks* team (Atkison et al., 2014; Averianova et al., 2016; Choi, 2015; Connaboy et al., 2016; Hillmeyer, 2015; Martin, 2015; Rejman et al., 2020, 2020; Stosic et al., 2021; Wei et al., 2014), federal programs go on favoring the on-the-surface actions: the dolphin technique still appears as a secondary element for propulsion (Collard, 2020). The history of competitive swimming is a permanent condemnation of glides (Collard, 2009; Collard et al., 2013). Yet, crawl, butterfly, backstroke, or breaststroke swimmers move much more like horses, elephants, or rats when they are in the water, than like seals, whales, or dolphins, although the latter's propulsion is much better adapted for speed. But, contrary to other animals, men are endowed with a power to learn and to innovate that makes them unique (Blackmore, 2000; Dawkins & Davis, 1976). At the experimental level, would they be capable of reproducing the techniques of species better adjusted to the water environment to go faster?

The aim of the present study was to demonstrate if swimmers are able to reproduce the swimming techniques of animals adapted to water through an experiment based on copying the selective choice of evolution in a swimming pool.

## Methods

### Participants:

Sixty-one (61) sportsmen of aged between 19 and 21 years old, enrolled at the school of sports sciences (i.e., UFR STAPS) of the Université Paris Cité participated in the experiment. They were divided into 3 subgroups of 19, 21 and 21 students, respectively. The students had a homogeneous level in swimming. They could all swim at least 400 meters in 10 minutes without touching the ground and swim 15 meters underwater. The experiment was a pedagogical unit of the mandatory swimming course of their curriculum. The duels lasted for about 20 minutes, thus allowing for long recovery spans to avoid hypoxia.

### Procedure:

The competition consisted of a system of shoulder-to-shoulder duel in an ascent/descent competition mode. The swimming pool was 2-meter deep and divided into eight 2.5-meter-wide lanes. There were 2 swimmers in each lane. In each lane, a weighted object was placed at the bottom of the water, 15 meters from the pool deck. Each pair of swimmers started at the sound signal: 'Ready, Go'. The 2x8=16 swimmers dove at the same time. The first to grab the object in his lane won the duel and moved up one lane for the next trial. Number 1 corresponded to the slowest lane. After 8 duels, the best swimmers were in lane 8, the slowest in lane 1.

During the duels, participants have been forced to leave the surface and to move underwater. Thus, they avoided the temptation to repeat their usual techniques of crawl, butterfly, etc. At the start, they were given an initial speed that made the propulsion lift possible: they started by diving. They must have not exceeded their breath holding (apnea) dynamic capacities. These capacities have been evaluated previously.

This approach that consisted in deciphering sportsmen's behaviors from a motor situation which is akin to motor praxeology (Parlebas, 2018). The method used in this motor action science is close to animal ethology. For a long time, sportsmen have been kept in a zoo, as Pierre Boulle's hero in *Planet of the Apes* (Boulle, 2001). For example, in competition swimming, dozens of scientific papers have presented the contribution to moving forward one's hands or at best one's forearms and hands by using plastic avatars (substitutes) or computer models. What can be drawn from such research except a confirmation of what swimmers already do? Motor praxeology aims more. The science of motor action wants to be predictive.

### Indicators:

At each trial the time was measured to the nearest tenth of a second. The timing has been done by the waiting swimmers and double-checked by the experimenter. The swimmers must also have reported the swimming techniques they used on an open card. Thus, there was no influence on their behavior. They must have described briefly what they did with their legs (*i*) alternate actions such as leg beats, or (*ii*) simultaneous actions such as breaststroke scissors, or (*iii*) oscillating movements. Then, they must have described what they did with their arms: (*iv*) simultaneous actions such as in the breaststroke, (*v*) still arms to the sides of their bodies or (*vi*) arms stretched in front of their heads; and finally (*vii*) others: a box in which to describe the originality of the motor action.

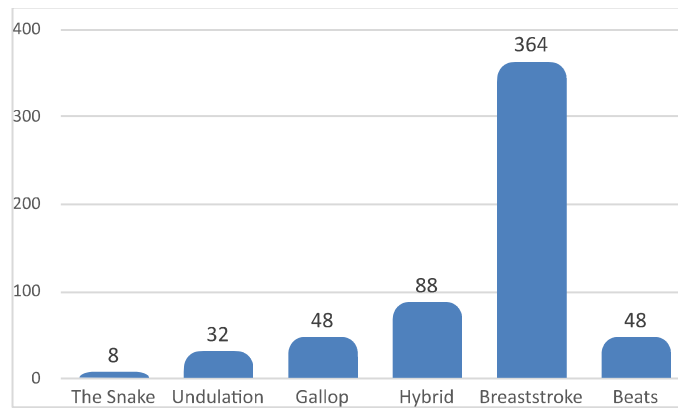
### Data collection and statistical analysis:

Every student had to write on a paper the technic they used. Combined with the technic analysis, a statistical student *T*-test was used to compare two by two the mean time done to swim the duel.

## Results

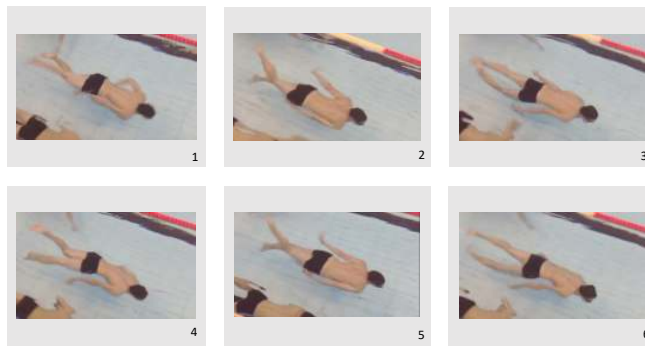
Every swimmer who performed 8 duels had the possibility to move from the slowest lane (n° 1) to the fastest one (n° 8). From one trial to the next, swimmers could change their body technique to obtain better results. Six techniques had emerged from the 244 duels (488 dives followed by 15-meter races) as shown in Fig. 1:

- (i) Moving with the legs only, arms along the body (Beats)
- (ii) Total breaststroke (simultaneous and symmetrical arm movements followed by simultaneous and symmetrical leg scissors). Note that breaststroke is swimming underwater, with pulling one's arms to the thighs, which is illegal in competition swimming once the swimmers have come back to the surface.
- (iii) Hybrid Breaststroke (hybrid: simultaneous and symmetrical arm movements, synchronous to the leg beats).
- (iv) Gallop: undulation of the body with leg beats.
- (v) Undulation of the whole body (*Undulation*: in fact, this impression is due to the association of the oscillations of different body parts).
- (vi) The snake (the observers will cry out 'the Snake' when they watch the top of the swimmer's body undulate from the top not on a vertical plan as do the swimmers (v), but on a horizontal plan with a leg beat undulating horizontally).



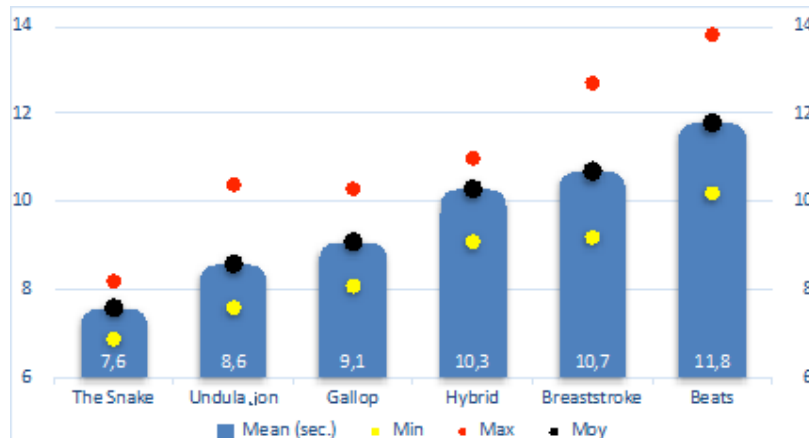
**Fig.1: Distribution of the 488 15-meter glides performed by the 61 sportsmen at the swimming pool.** Six swimming tactics emerge. Breaststroke is by far the most widely used (75% of cases).

A hitherto unseen technique appeared. Indeed, a swimmer undulated laterally with the upper part of his body, as a snake, with his arms stretched along his thighs and accompanies this eel-like propulsion mode by an alternate leg beat. Although a mediocre competitive swimmer, he came first in the ascent/descent competition. (Picture 1).



**Picture 1: Chronophotograph of one of the six swimming techniques:** The Snake was characterized by a leg beat synchronous to an oscillation of the upper part of the body, with the arms along the trunk.

Figure 2 showed the speeds obtained for each technique through the median times taken to swim 15 meters in immersion (M, the blue line, in seconds), and the range of times (from the fastest to the slowest, black line, in seconds) (Fig.2). After The Snake, whose 8 runs ranged from 6.9 to 8.1 seconds, came the swimmers who used *the Undulation* technique (with runs ranging from 7.7 to 10.3 seconds). They performed better than those who used the *Gallop* (minimum time 8.3 seconds, maximum: 10.3 seconds). Then came the Hybrid technique (9.8-11 seconds) and finally the Beats (10.2-12.6 seconds).



**Fig.2: Mean times in seconds to swim 15 meters, and time range (minimum and maximum times) for the six swimming techniques.** The swimming techniques favor lift-based propulsion (Snake, Undulation and Gallop) are the fastest. Although widely used, the Breaststroke comes next-to-last.

A Student's *T*-test revealed significant time differences for the 6 swimming techniques taken two by two (Table 1). For the population observed, it was not peremptory to assert: The Snake > Undulation > Gallop > Hybrid > Breaststroke > Beats (where '>' means 'faster than').

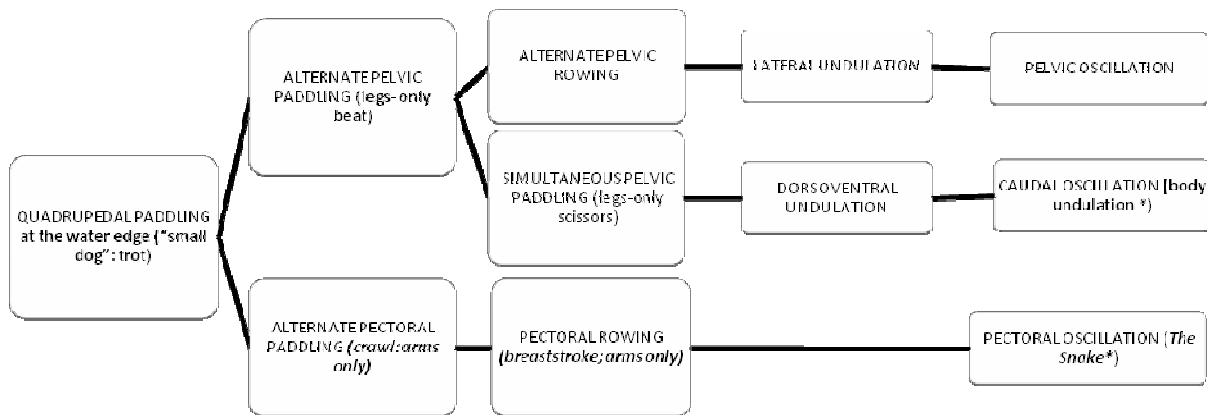
Student <i>T</i> -test	The Snake	Undulation	Gallop	Hybrid	Breaststroke	Beats
The Snake		T = 4.6 p <.001*	T = 5.49 p <.001*	T = 6.18 p <.001*	T = 6.03 p <.001*	T = 12.02 p <.001*
Undulation			T = 3.86 p <.001*	T = 13.24 p <.001*	T = 13.1 p <.001*	T = 18.19 p <.001*
Gallop				T = 11.01 p <.001*	T = 12.61 p <.001*	T = 15.04 p <.001*
Hybrid					T = 5.15 p <.001*	T = 8.72 p <.001*
Breaststroke						T = 6.46 p <.001*
Beats						

**Table 1: Two by two comparisons of the six techniques using Student's T-test.** The mean performances of each technique are significantly different. Although distinctive, the Snake, Undulation and Gallop results are closer; the same goes for Hybrid and Breaststroke.

**Discussion**

Underwater, most swimmers used the Breaststroke technique they have been taught on the surface (tactics (ii) and (iii)). Out of the 4 official techniques, it is the only one that may be used underwater. Indeed, it is impossible to use Butterfly, Backstroke, or Crawl in immersion. Yet, in the form of breaststroke swimmers retained they systematically used hand movements that went down to the thighs – which is forbidden in competitive swimming, except when diving or after the turns, where only one action of the arm going lower than the hips is allowed. Sea lions use their fore limbs in this manner. Seals, who are faster, prefer to press their pectoral fins along their bodies and oscillate laterally as in *The Snake* (vi).

Although the matching is not perfect, the processes used by the swimmers fit the model presented by Fish (Fish, 1993, 1996) to describe the odyssey of mammals that have been going back to the water for 60,000,000 years (Fig.3): the fastest swimming techniques (v) and (vi) were the ones that best mimic the marine mammals that are best adapted to speed ('pectoral oscillations': seals; 'caudal oscillations': whales). The later favored lift forces over propulsive drag forces (which can be observed in dogs, rats and other crawlers that use 'quadrupedal paddling' and 'alternative pectoral paddling'). Following surface trotting, mammals wishing to conquer the water environment moved to gallop (which was observed in the fast-enough hybrid technique (iv)) before adopting oscillations, whose equivalent on land is the *leap* (Fish, 1993, 1996).



**Fig. 3: Model representing the sequences of transition of the swimming techniques from the surface trotting (on the left) to the underwater pectoral undulation (The Snake is on the right).** This corresponds to the adaptation of lift propulsion modes to the water environment (Fish, 1993, 1996). The swimming techniques experimentally observed at the swimming pool are in bold (and the fastest ones are flagged by an asterisk).

The competition swimmers observed were able to experimentally reproduce the choices of natural selection. The fastest techniques that emerged were far from the ones officially used in competition swimming. This result was surprising since the aim of the International Federation is supposed to be the enhancement of the swimming performances of human beings. Pierre Parlebas was right when, in the *Revue Culture technique* N° 13, he wrote that 'The problem of technique is not a technical problem' (Parlebas, 1985). Just like other body techniques, swimming techniques are not natural but cultural (Mauss, 1936). They are social choices: tactics driven by representations such as the fear of drowning (Chauvaud, 2007). The most astonishing is that the tactics approved by the Federation, by training swimmers to remain on the surface, penalize speed.

Before glides were limited to 15 meters (1988 for the backstroke, 1996 for the Butterfly and 2002 for the Freestyle) Denis Pankratov could beat the 200-meter Butterfly world record in a small pool (25 meters) in 1995, by swimming the first length with only one arm movement. It is noteworthy that at the 2005 European Swimming Championships, in a 25-meter long swimming pool, the German swimmer Thomas Rupprath, came first at 15 meters, was overtaken on the surface, came first again at the next 15 meters and so on and so forth until the end of the race. Using the waterline buoys as landmarks, and a camera that moved on tracks parallel to the pool, the picture-by-picture analysis shows that Rupprath swam twice as fast from meters 5 to 15 (mostly underwater and in undulation) than from meters 15 to 25 (on the surface) and this, four times during the 100-meter backstroke race as well as during the 100-meter Butterfly race. He is not the only one to have done so (Collard, 2007). Just as Dick Fosbury's innovative style quickly found followers among high jump athletes, some swimmers are undoubtedly working relentlessly in the wake of Pankratov and Rupprath. Since water is 800 times denser than air, as soon as swimmers leave the wall, they lose speed. A projectile body merely waiting to reach the surface to become propulsive cannot explain their being able to maintain their maximum swimming speed in immersion for 15 meters or more. Johnny Weissmuller's way of swimming (Weissmuller, 1931), although the state of the art at the beginning of the century may not be the ultimate one: competition swimming can still evolve. But the proponents of the official technique will fight against new body practices. Pankratov stopped being the leader in his category soon after the re-enactment of the 15-meter rules. It is unfortunate that the personal development of a swimmer should be the process by which he learns how to give up his capacities.

A revolution in swimming took place during the 2015 World Swimming Championships. During the flows following the Freestyle turns, Ryan Lochte, an American swimmer maintained the dorsal position he had taken for the somersault (forward roll with feet pressed on the wall and toes pointing upward to execute the turn) then swam 10 meters in deep dorsal (then costal) undulation while his mates were already crawling on the surface on their bellies. He won the 200-meter four-stroke championship thanks to the use of this new body tactic when shifting from Breaststroke to Freestyle, thus compelling the International Swimming Federation (FINA) to react. Even though this technique is not allowed in a four-stroke competition, it is valid in freestyle and apnea work should be enhanced to promote its development. He kept his first place, which proves that the Federation is raising the good question: how long will a swimmer be disqualified for swimming too fast?

This event confirms the results of the present study. The question: can men swim faster by adopting the techniques used by species better adapted to the water environment? On a quasi-experimental mode, and without prior training, we rediscovered the evolutionary steps described by the paleontologists who studied how mammals have been reconquering the oceans for the past 60 million years. To gain speed, swimmers will have to move away from the trot of alternately pushing the water back and forth with their arms. They will gain by using pectoral or pelvic oscillations. These experimental results confirm the most recent laboratory data (Menzer et al., 2022; Ruiz-Navarro et al., 2022). Today, the fastest ways of moving in the water are not found in the swimming federation training sessions. It is the responsibility of motor action sciences to anticipate their emergence and future.

## Conclusion

The purpose of this article was to test and compare the underwater swimming techniques used during an ascent/descent exercise. The exercise itself reflects natural selection as the fastest technique will allow its user to ascend while the slowest technique will be relegated. The results show that out of 488 trials, six techniques were used. From the most to the least used technique, they are: breaststroke (364), hybrid (88), beats (48), gallop (48), undulation (32), the snake (8).

After analysing the time taken to do the exercise, it turns out that the fastest techniques are 'The snake' followed by the 'Undulations'. The other techniques, although more widely used, are statistically slower. The results of this article therefore show that swimming techniques that promote lift-based propulsion are the most efficient ones. This shows that the propulsion favored under the pressure of the selection is the lift-based one instead of the drag-based one whereas in today's competitive environment we almost see drag-based propulsion techniques.

These results allow us to have a different point of view on the techniques taught in swimming lessons and could also constitute a basis for reflection on the rules of the international swimming federation.

**Conflicts of interest** The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

**Funding** The authors received no financial support for the research, authorship, and/or publication of this article.

## References

- Alexander, R. M. (1988). Why mammals gallop. *American Zoologist*, 28(1), 237-245. <https://doi.org/10.1093/icb/28.1.237>
- Atkison, R. R., Dickey, J. P., Dragunas, A., & Nolte, V. (2014). Importance of sagittal kick symmetry for underwater dolphin kick performance. *Human Movement Science*, 33, 298-311. <https://doi.org/10.1016/j.humov.2013.08.013>
- Averianova, A., Nikodelis, T., Konstantakos, V., & Kollias, I. (2016). Rotational kinematics of pelvis and upper trunk at butterfly stroke : Can fins affect the dynamics of the system? *Journal of Biomechanics*, 49(3), 423-428. <https://doi.org/10.1016/j.jbiomech.2016.01.004>
- Blackmore, S. (2000). *The Meme Machine* (Vol. 25). OUP Oxford.
- Boulle, P. (2001). *Planet of the Apes*. Julliard. [in French]
- Byankina, L. V., Byankin, V. V., Vorotilkina, I. M., Prokopyeva, M. M., & Sokorutova, L. V. (2017). Using high-intensity interval training during swimming classes in higher educational institutions. *Journal of Physical Education and Sport*, 17(02), 770-774. <https://doi.org/DOI:10.7752/jpes.2017.02117>
- Catteau, R. (2007). Propulsion in the locomotion of the swimmer Hyper-EPS n° 237. *Hyper*, 237, 26-29. [in French]
- Chauvaud, F. (2007). *Submerged Bodies, Sunken Bodies: A History of drowning and drowning from antiquity to the present day*. Amherst Media, Inc. [in French]
- Choi, T. (2015). Learning from the Dolphins : How Anterior Motion Affects the Dolphin Kick. *Bulletin of the American Physical Society*, 60(11). <https://meetings.aps.org/Meeting/4CF15/Session/F1.27>
- Collard, L. (2007). Average swimming speeds for 6 sections of the 50-meter backstroke race : Comparison of performance in zones swum underwater or at the surface in 12 international short course events. *International Journal of Performance Analysis in Sport*, 7(3), 37-45. <https://doi.org/10.1080/24748668.2007.11868408>
- Collard, L. (2009). *The fifth stroke: Swimming and the theory of evolution*. Atlantica. [in French]
- Collard, L. (2020). *Swimming in apnea* (Désiris). Adverbium. [https://www.adverbium.fr/editions-desiris/luc-collard/nager-en-apnee\\_7p951qlvuack.html](https://www.adverbium.fr/editions-desiris/luc-collard/nager-en-apnee_7p951qlvuack.html) [in French]
- Collard, L., Gourmelin, E., & Schwob, V. (2013). The fifth stroke : The effect of learning the dolphin-kick technique on swimming speed in 22 novice swimmers. *Journal of Swimming Research*, 21(1), 1-15.
- Colobert, B., Bideau, B., Nicolas, G., Fusco, N., & Delamarche, P. (2004). Theory of elongated bodies for swimming with fins. *3ème Journées Spécialisées de Natation*, 131-132. [in French]
- Connaboy, C., Naemi, R., Brown, S., Psycharakis, S., McCabe, C., Coleman, S., & Sanders, R. (2016). The key kinematic determinants of undulatory underwater swimming at maximal velocity. *Journal of Sports Sciences*, 34(11), 1036-1043. <https://doi.org/10.1080/02640414.2015.1088162>
- Costill, D. L., Maglisco, E. W., & Richardson, A. B. (1991). *Handbook of Sports Medicine and Science Swimming* (J. M. Stager & D. A. Tanner, Eds.). Blackwell Scientific Publications Ltd.
- Counsilman, J. E. (1971). *Swimming* (Limpert-Verlag). [in German]
- Da Silva, J. K., Enes, A. A. N., Sotomaior, B. B., Ruy Barbosa, M. A., De Souza, R. O., & Osiecki, R. (2020). Analysis of the performance of finalist swimming athletes in Olympic games : Reaction time, partial time, speed, and final time. *Journal of Physical Education and Sport*, 20(02), 539-545. <https://doi.org/DOI:10.7752/jpes.2020.02080>
- Dawkins, R., & Davis, N. (1976). *The Selfish Gene*. Oxford University Press.
- Deaner, R. O. (2006). More males run fast : A stable sex difference in competitiveness in U.S. distance runners. *Evolution and Human Behavior*, 27(1), 63-84. <https://doi.org/10.1016/j.evolhumbehav.2005.04.005>
- Fish, F. E. (1993). Power output and propulsive efficiency of swimming bottlenose dolphins (*tusiops truncatus*). *Journal of Experimental Biology*, 185(1), 179-193. <https://doi.org/10.1242/jeb.185.1.179>
- Fish, F. E. (1996). Transitions from Drag-based to Lift-based Propulsion in Mammalian Swimming1. *American Zoologist*, 36(6), 628-641. <https://doi.org/10.1093/icb/36.6.628>
- Ganchar, O., Terentieva, N., & Ganchar, I. (2018). Swimming skill assessment based on swimmers' achievements at the XVII World Aquatics Championship in Budapest-2017. *Journal of Physical Education and Sport*, 18(02), 725-730. <https://doi.org/DOI:10.7752/jpes.2018.02106>
- Gingerich, P. D., Wells, N. A., Russell, D. E., & Shah, S. M. I. (1983). Origin of Whales in Epicontinental Remnant Seas : New Evidence from the Early Eocene of Pakistan. *Science*, 220(4595), 403-406. <https://doi.org/10.1126/science.220.4595.403>
- Gray, J. (1936). Studies in Animal Locomotion : VI. The Propulsive Powers of the Dolphin. *Journal of Experimental Biology*, 13(2), 192-199. <https://doi.org/10.1242/jeb.13.2.192>
- Hertel, H. (1966). *Structure, form, movement*. Reinhold.
- Hillmeyer, S. (2015). The Effect of Different Styles of Underwater Kicking on Velocity in Swimming. *South Carolina Junior Academy of Science*, 219. <https://scholarexchange.furman.edu/scjas/2015/all/219>
- Ildikó, V., József, K., Ladislav, B., L'ubomíra, B., & Matús, P. (2017). Results of a five-year test program to develop the swimming skills and physical abilities of freshman pedagogy students in Nitra. *Journal of Physical Education and Sport*, 17(03), 1089-1094.



- Laurent, G., & Piat, E. (2003). Design and modeling of a swimming microrobot. *Journal Européen des Systèmes Automatisés*, 37(1), 31-48. <https://doi.org/10.3166/jesa.37.31-48> [in French]
- Lighthill, M. J. (1960). Note on the swimming of slender fish. *Journal of Fluid Mechanics*, 9(2), 305-317. <https://doi.org/10.1017/S0022112060001110>
- Lighthill, M. J. (1969). Hydromechanics of Aquatic Animal Propulsion. *Annual Review of Fluid Mechanics*, 1(1), 413-446. <https://doi.org/10.1146/annurev.fl.01.010169.002213>
- Lighthill, M. J. (1975). *Mathematical biofluidynamics* (Nachdr.). Society for Industrial and Applied Mathematics.
- Lindsey, C. C. (1979). Form, function and locomotory habits in fish. In W. S. Hoar & D. J. Randall, *Fish Physiology* (Vol. 7, p. 1-100). Academic Press.
- Maglischo, E. W. (2003). *Swimming Fastest*. Human Kinetics.
- Martin, J. (2015). Go Fast With the Flow. *Mechanical Engineering*, 137(05), 40-45. <https://doi.org/10.1115/1.2015-May-2>
- Mauss, M. (1936). *Body techniques* (Vol. 32). Journal de Psychologie. [in French]
- Menzer, A., Gong, Y., Fish, F. E., & Dong, H. (2022). Bio-Inspired Propulsion : Towards Understanding the Role of Pectoral Fin Kinematics in Manta-like Swimming. *Biomimetics*, 7(2), 45. <https://doi.org/10.3390/biomimetics7020045>
- Monteiro, Nelli, G., Araújo, Dias, N., Mazzardo, Tatiane, Francisco, Soares, P., Ribas, Schelyne, Aburachid, & Campos, L. M. (2021). Practice schedule analysis and pedagogical feedback in swimming classes. *Journal of Physical Education and Sport*, 21(3), 1950-1957. <https://doi.org/DOI:10.7752/jpes.2021.s3248>
- Müller, U. K., van den Heuvel, B. L. E., Stamhuis, E. J., & Videler, J. J. (1997). Fish foot prints : Morphology and energetics of the wake behind a continuously swimming mullet (*Chelon labrosus* Risso). *Journal of Experimental Biology*, 200(22), 2893-2906. <https://doi.org/10.1242/jeb.200.22.2893>
- Parlebas, P. (1985). Sports dissipation. *Culture technique*, 13, 19-37. [in French]
- Parlebas, P. (2018). Game, Sport and Society: Lexique de praxéologie motrice. In *Jeux, sports et sociétés : Lexique de praxéologie motrice*. INSEP-Éditions. <http://books.openedition.org/insep/1067> [in French]
- Peter, M., Martina, M., & Romana, P. (2020). The impact of special strength intervention in water on the flutter kicking performance in swimming. *Journal of Physical Education and Sport*, 20(02), 774-782. <https://doi.org/DOI:10.7752/jpes.2020.02111>
- Rejman, M., Siemontowski, P., & Sieminski, A. (2020). Comparison of performance of various leg-kicking techniques in fin swimming in terms of achieving the different goals of underwater activities. *PLOS ONE*, 15(8), e0236504. <https://doi.org/10.1371/journal.pone.0236504>
- Rhys-Evans, P. (2020). *The Waterside Ape : An Alternative Account of Human Evolution* (Vol. 134). CRC Press. <https://www.cambridge.org/core/journals/journal-of-laryngology-and-otology/article/abs/waterside-ape-an-alternative-account-of-human-evolution-p-rhysevans-crc-press-taylor-and-francis-group-2019isbn-978-0-36714-548-4-pp-226-price-2199/25B6AA11F197FB15B43558C701E06815>
- Ruiz-Navarro, J. J., Cuenca-Fernández, F., Sanders, R., & Arellano, R. (2022). The determinant factors of undulatory underwater swimming performance : A systematic review. *Journal of Sports Sciences*, 1-12. <https://doi.org/10.1080/02640414.2022.2061259>
- Schouveiler, L., Hover, F. S., & Triantafyllou, M. S. (2005). Performance of flapping foil propulsion. *Journal of Fluids and Structures*, 20(7), 949-959. <https://doi.org/10.1016/j.jfluidstructs.2005.05.009>
- Scurati, R., Michielon, G., Signorini, G., & Invernizzi, P. L. (2019). Towards a Safe Aquatic Literacy : Teaching the breaststroke swimming with mobile devices' support. A preliminary study. *Journal of Physical Education and Sport*, 19(5), 1999-2004. <https://doi.org/DOI:10.7752/jpes.2019.s5298>
- Stosic, J., Veiga, S., Trinidad, A., & Navarro, E. (2021). How Should the Transition from Underwater to Surface Swimming Be Performed by Competitive Swimmers? *Applied Sciences*, 11(1), 122. <https://doi.org/10.3390/app11010122>
- Thewissen, J. G. M. (2013). *The Emergence of Whales : Evolutionary Patterns in the Origin of Cetacea*. Springer Science & Business Media.
- Thewissen, J. G. M., Hussain, S. T., & Arif, M. (1994). Fossil Evidence for the Origin of Aquatic Locomotion in Archaeocete Whales. *Science*, 263(5144), 210-212. <https://doi.org/10.1126/science.263.5144.210>
- Triantafyllou, M. S., Weymouth, G. D., & Miao, J. (2016). Biomimetic survival hydrodynamics and flow sensing. *Annual Review of Fluid Mechanics*, 48(1), 1-24. <https://doi.org/10.1146/annurev-fluid-122414>
- Wei, T., Mark, R., & Hutchinson, S. (2014). The fluid dynamics of competitive swimming. *Annual Review of Fluid Mechanics*, 46(1), 547-565. <https://doi.org/10.1146/annurev-fluid-011212-140658>
- Weissmuller, J. (1931). *The Art of swimming freestyle*. Trémois. <https://www.abebooks.fr/Lart-nager-crawl-Weissmuller-Johnny-Tr%C3%A9mois/15039145449/bd> [in French]
- Williams, T. M., Friedl, W. A., Fong, M. L., Yamada, R. M., Sedivy, P., & Haun, J. E. (1992). Travel at low energetic cost by swimming and wave-riding bottlenose dolphins. *Nature*, 355(6363), 821-823. <https://doi.org/10.1038/355821a0>