2D Numerical Simulations of Human Underwater Undulatory Swimming

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1 Introduction

In the highly competitive world of elite swimming, underwater phases became predominant in the recent decades (Veiga and Roig, 2016, Veiga et al., 2016). It all started in the late 80s when backstroke swimmers would spend more than half of their races underwater. Later on, swimmers like Michael Phelps proved that doing well and consistently underwater was a huge advantage. In modern swimming, performing well underwater became an indispensable skill to pretend to higher positions. It provides such an advantage that the regulations limit the distance swum underwater (FINA, 2017).
In three out of the four strokes, swimmers perform Underwater Undulatory Swimming (UUS). This technique tries to copy the way of motion of cetaceans. It consists in propagating a wave-like motion along the body, from the tip of the fingers to the toes. This wave amplifies as it goes down along the body and displaces the water surrounding the athlete downstream. The water is pushed down and thrust is produced (Pacholak et al., 2014).
Being underwater helps reducing wave drag (Vennell et al., 2006). It is known to be one of the greatest factor of resistance to swimming. Hence, executing this technique deep enough allow swimmers to maintain greater velocities than their surface swimming and optimize the overspeed phase (obtained from a push on the wall or a dive). For this reason, UUS has been a major focus of research studies in swimming science since late 90s.
The complexity of the motion, its physics and the implication of human swimmers (repeatability, fatigue, non unique body shapes or techniques, ...) makes both experiments and simulations tedious. Experiments are extremely hard to assess as it is difficult to evaluate a swimmer's ability to adapt a stroke he has practiced for years to a requested change (frequency, amplitude, ...). Logically, computational methods seem to be the most convenient way to study UUS.
The most complete simulations feasible at the moment are undoubtedly 3D unsteady simulations (Pacholak et al., 2014). However, they have an important computational cost. This cost dissuades doing studies that would require a great number of simulations (e.g : optimization studies). Thus, would it be possible to reduce our exigencies to have the best simulation and opt for a much simpler model? That would greatly help exploring even more aspects of the UUS performance. Consequently, developing such a tool to perform quick viable simulations seems like a necessity.
LilyPad (Weymouth, 2015b) is a 2D Implicit Large Eddy Simulation (ILES) CFD solver developed to compute fast simulations by using simple high speed methods. LilyPad is written on Processing (Foundation Processing, 2001). Its purpose is solving simple fluid structure interactions problems on Uniform Cartesian Grids using a Boundary Data Immersion Method (BDIM).
Our idea is to realize a simple modeling of a swimmer performing UUS using LilyPad's fast simulations. The goal would be to quickly obtain interesting trends or results to help understand what are the key factors of performance in UUS.

2 Methods

This section describes the methodology we have followed to implement a model of an undulating swimmer in LilyPad. This includes how we defined the kinematics of the swimmer, how we modeled the body and a quick overview of how the simulation is solved and configured.
We assumed that the motion of UUS is almost strictly two-dimensional (in the sagittal plane) and that the distances between consecutive joints along a swimmer's body are constant. These two hypothesizes are not strong but are necessary. They introduce some errors since it is neglecting the natural internal rotation of a swimmer during UUS and the possible extension of the joints during the motion. However, the most important aspect of such simulations is to capture the global physics of the motion and we do not expect

these assumptions to excessively alter the results.
Thus, the UUS kinematics can be defined by the vertical position of seven joints along a swimmer's body and the distance separating these. These joints are the following: fingertips, wrists, shoulders, hips, knees, ankles and toe-tips. We can easily obtain the coordinates of these points through the digitization of recordings of swimmers performing UUS (Fig. 2.b). The vertical position is then fitted with a simple sine function (see Eq. 1). An example of such a fit is provided in Fig. 1.

$$y_i(t) = A_i.cos(2\pi f.t + C_i) + D_i \tag{1}$$

Here, y_i is the function of the time t representing the vertical position of the i^{th} joint of the body, A_i is the amplitude, f is the frequency, C_i is the phase shift of the wave at that position of the body and D_i is the mean vertical position of that joint. Approximating the joints' kinematics with a sine function is viable according to Gavilan et al., 2006. They used Fourier Transformation to study the contribution of the Harmonics of the body-wave. It appeared that the fundamental (first harmonic) contributes to more than 90% of the power production of the motion.
Regarding how our fitting curves seem to be capturing the raw kinematic data of every joint (see Fig. 1), we consider that this sine approximation is completely acceptable.
Because the kinematics are defined by seven joints, there are necessarily six segments linking them :

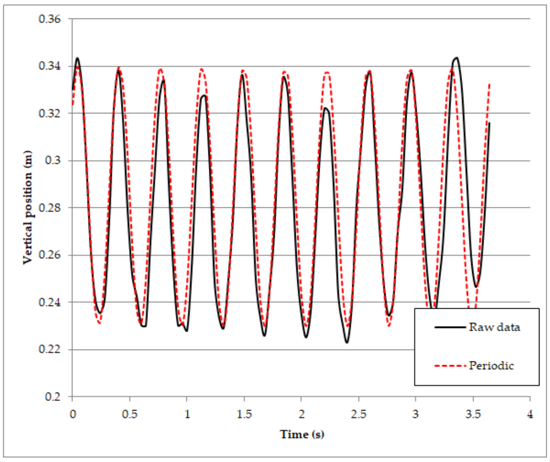

Fig. 1: Periodic sine function fit on the raw vertical position of the toes of a swimmer

hands, arms (elbows are considered to not bend and have a limited impact on thrust production), trunk, thighs, shanks and feet. Each segment is defined by its length and the thicknesses of the two joints it is linking. The simplest body shape model to avoid overlapping, to be able to pilot each segment independently and that would look like a swimmer was a succession of deformed hexagons (see Fig. 2.a). The horizontal position of the hands is fixed and the joints' horizontal coordinates are calculated accordingly to the vertical position and the segments' lengths.
The mesh is based on a Uniform Cartesian Grid (the distance separating a cell to its neighboring cells in the four directions is the same and constant for every cell of the mesh). We chose a squared domain with a side-length of $8m$. This decision was taken arbitrary as it would allow us to observe enough wake behind the swimmer and have enough stream ahead of it while the mesh size reasonable (see Table 1). The length of a human swimmer in streamline position with its arms extended above the head is about $2.5m$ (see Fig 2.b to have a streamline position example). The resolution of the grid is defined by x. As the number of cells along the longitudinal direction n has to be calculated using the following calculation $n = 2^x$.
The convergence study showed that the pressure forces were converging for $x \geq 9$. Table 1 shows the cell size, the approximate number of cells along the modeled swimmer ($\approx 2.5m$) and the total number of cells in the mesh corresponding to x value. For computational cost purposes, we obviously chose $x = 9$ for our studies.
LilyPad uses a BDIM to solve the fluid-body interaction on the grid. The complete theory of this method

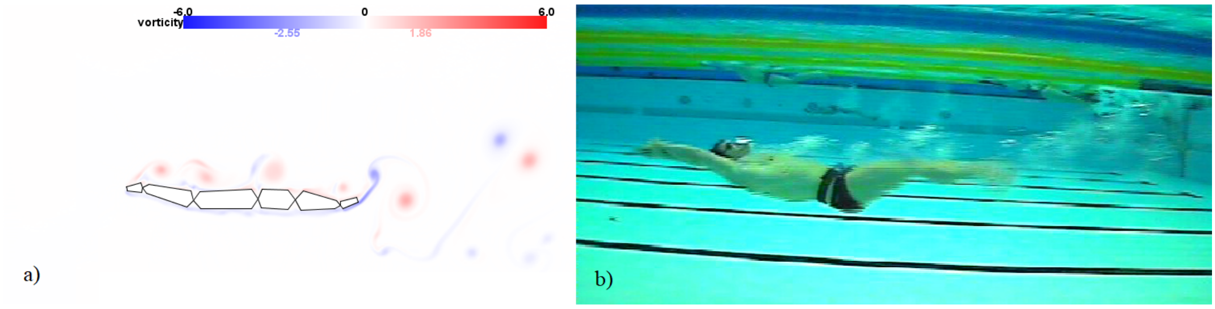

Fig. 2: a) Snapshot of the vorticity of our simulation during the down-kick phase. b) Snapshot of the video footage recording an elite swimmer performing UUS

Table 1: Resolution of the mesh and its size regarding values of x

x	Cell length (mm)	Number of cells along the model swimmer	Total number of cells in the mesh
9	15.7	160	262,144
10	7.82	320	1,048,576
11	3.91	640	4,194,304

is explained in Maertens, Audrey P. and Weymouth, Gabriel D., 2015. The flow is resolved using ILES because of its performances and to get rid of the modelling of sub-grid turbulences (which do not really have a physical meaning in two dimensions). The two different schemes that are implemented are a flux-limited QUICK or a Semi-Lagrangian convection scheme (Weymouth, 2015a). Our simulations are computed using the QUICK scheme.
The time stepping is calculated internally by LilyPad in order to optimize the computational time of the simulations. The repeatability is excellent and successive simulations using the same conditions give exactly the same results.
Now that the methodology has been presented, we are going to discuss about the validations and some preliminary results to estimate the viability of this method.

3 Validation

The simulations being 2D, we do not expect to obtain precise values of the forces, having a good order of magnitude is enough. Thus, the validation's goal is to check if the code captures correctly the physics of the unsteady motion.
The numerical validation is done by two means : verifying the evolution of the drag with parameter sweeps (frequency, inflow velocity and amplitude) and verifying the maintained swimming speed of a swimmer in the simulation (regarding its measured velocity).
We gathered kinematics from an international elite swimmer (previously world record holder) performing UUS in a backstroke position (see Fig 2.b). He was told to push from the wall and perform a maximum velocity trial. His speed is acquired using a built-in device which consists in a rotating sensor (sampling frequency of $250Hz$) linked to a reel of fishing string. The string is attached to the swimmer's hips using a belt-like system and his instantaneous velocity is obtained (Fig. 3). On the trace of the velocity we can clearly observe successive acceleration and deceleration phases. Two successive acceleration peaks correspond to the up-kick and the down-kick. Here, the up-kick is having greater performance (as the swimmer is on the back). Determining the timing between consecutive up-kick velocity peaks gives us the swimming frequency of the undulation. According to the velocity trace, the kicking frequency of that swimmer is $2.76Hz$. The average velocity, once the global deceleration has settled (after $2s$ on Fig. 3) is $1.86m.s^{-1}$.
The kinematics input in the code are obtained from a video footage of the trial discussed previously (see

Fig. 2.b.). The segments lengths is measured on the swimmer and the sine approximation to fit the raw data is done.
We ran a simulation with the kinematics and frequency chosen to correspond to the video trial's values.

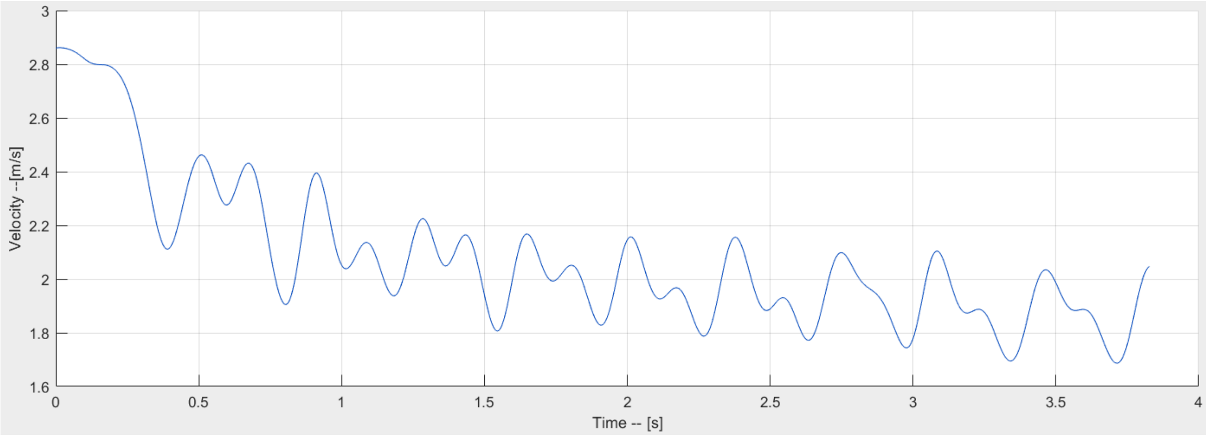

Fig. 3: Trace of the instantaneous velocity of the swimmer recorded using a built-in device

The resolution of the mesh is chosen as $x = 9$. We match the inflow velocity to have an average drag coefficient over a few cycles, from 9^{th} till 14^{th}, of 0. This resulted in a maintained UUS simulated speed of $1.87 m.s^{-1}$. That value is extremely close to the actual swimmer's speed and comforts us in the idea that such simulations can be viable. Different sets of kinematics will be used for further validation as one case might not be enough.
With the kinematics gathered, we realized three parameter sweeps to check how the output of the simulations is affected. The idea of these preliminary studies is to vary only one parameter and keep all the others constant. The way the forces evolve gives us a verification that the unsteady physics of UUS are well captured.
The three tests we did gave the following results:

- Velocity sweep : we varied the inflow velocity of the simulation around the natural maintained swimming speed. When the velocity increases, the mean drag coefficient (from the 9^{th} to the 14^{th} cycle) decreases and, reciprocally, when the velocity decreases, the average drag coefficient increases. A positive average drag coefficient means that the swimmer is giving, overall, more energy to the flow. Hence, if it is positive, the swimmer should be going faster and similarly, if the value is negative, the swimmer should be slowed down by the flow.

- Frequency sweep : we varied the kicking frequency of the swimmer. His performance decreased when kicking slower and increased when kicking faster.

- Amplitude sweep : by using a coefficient to reduce all the vertical amplitudes of every joints (by the same amount), we observed that the maintained swimming speed was reduced and that the more we reduced the amplitude the poorer were the performances.

These results comforted us in the fact that such simulations could be used to study UUS. This method could eventually help us identify different key factors of UUS performance.
The next section will describe the development perspectives for the method, and gives some example of studies that could be carried on in the near future.

4 Next Steps

Even though the results are really encouraging, further validations will be required. We will study different set of kinematic data (of different swimmers?) and verify the hierarchy of the simulated maintained velocity swimming speed between these different strokes while also checking if they correspond to the

measured velocities. Making sure that a stroke having a slower recorded velocity than another faster stroke, also reaches a slower velocity in the simulation.
Moreover, we will have to establish how much does the 2D affect the flow and the forces applied on the swimmer. This aspect of the simulation needs to be explored as we do know that it affects the flow representation and the forces (Taira and Colonius, 2009, Lei et al., 2001 and Mittal and Balachandar, 1995) but, no studies considered looking at how much it altered the forces on such unsteady simulations. Extending the exact same model in the third dimension would allow the turbulence to happen and eventually help dampen smaller flow structures and thus changing the forces applied on the body. Comparing the output of the 2D and the extended 2D simulations could give us an idea of how much the forced 2D turbulence is impacting our computations.
Next, I will present a succession of studies that could be led later using the same method:

- A calculation of the hydrodynamic efficiency (von Loebbecke et al., 2009b) could be easily added and would help to quickly assess the hydrodynamic cost of different techniques.
- Doing a velocity sweep for techniques of different amplitudes in overspeed situation to study the trade off between thrust production and drag.
- It is possible to study the repartition and the direction of the pressure forces along the body. Similarly to von Loebbecke et al., 2009a and Nakashima, 2009 it would be interesting to look at how these two parameters are affected by a change of technique.
- Studying the relevance of the Strouhal number St on UUS. The Strouhal number is a dimensionless number describing oscillating flow oftenly used to describe fish locomotion (Zhu et al., 2002) and used in many other underwater swimming studies (Colomina et al., 2003). We would realize different simulations having the exact same St value. We now know that this number is not likely to describe the hydrodynamic efficiency (von Loebbecke et al., 2009b, Shimojo et al., 2014, Yamakawa et al., 2017). But, can that number help understand the flow mechanism in the wake? Could it describe the propulsion mechanism?

Developing such a method for numerical simulations of UUS could be an asset as such studies, that require a lot of simulations, would be doable. Hopefully, using this method would broaden the spectrum of things we know about swimming science.

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