IMPACT OF KINEMATIC MODIFICATION ON THE UNDERWATER UNDULATORY SWIMMING PERFORMANCE OF A SWIMMER

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This work is a case study observing the impact of various kinematics modifications in the simulated pressure forces and hydrodynamic work done by an athlete performing maximum effort Underwater Undulatory Swimming (UUS). The studied athlete was recorded using a Motion Capture methodology. Seven key joints were identified to represent the athlete's motion and their position were fitted with a fourth order Fourier series. This kinematic data was then modified to reduce or amplify the upper-body and lower-body motion but also to have a linear wave propagation. The kinematics (10 in total) were inputted in an unsteady 2D Computational Fluid Dynamics (CFD) solver, Lily Pad. Results suggest directions for improvement in the execution of the athlete's swimming style, whether it is for reducing the hydrodynamic work done or minimising resistive forces.

KEYWORDS: CFD, hydrodynamics, propulsion, biomechanics, human motion, modelling.

INTRODUCTION: In competitive swimming, athletes will often perform Underwater Undulatory Swimming (UUS) following a push or a dive. This consists of replicating the locomotion of cetaceans. This motion is performed in a streamline position (hands held together above the head) and a wave with increasing amplitude is propagated from the tip of the fingers to the tip of the toes. As this wave moves along the body, the water surrounding the athlete is accelerated backwards resulting in a force propelling the body forward. UUS can be beneficial as it is executed underwater, minimising wave drag (Vennell et al., 2006) and helping swimmers maintain higher velocities than surface swimming speeds. It is a key aspect in race performance, where a fast underwater section is related to a faster race time (Born et al., 2021; Marinho et al., 2021). For this reason, some Research has been done looking at how UUS variables are linked to performance (West et al., 2022).
A few studies on UUS have been done using Computational Fluid Dynamics (CFD) to compute the generation of propulsive forces and the flow surrounding the athlete (Hochstein et al., 2012; von Loebbecke et al., 2009). These simulations usually have a high computational cost. Thus, it limits the range of applications. This research uses a 2D CFD solver with well-captured swimmers' kinematics. By lowering the amount of computing resources, it is possible to investigate the potential benefits of various kinematic modifications.
This work will discuss the impact on the fluid forces and hydrodynamic work that some kinematic modifications have on the UUS performance of a university level athlete (Butterfly event specialist, FINA points 600). The modifications will be the following: increased and reduced oscillation of the upper-body or lower- body kinematics, and linear wave-propagation along the body. The objective of this work is to obtain indications on how to improve this specific athlete's UUS by either reducing the hydrodynamic work done or minimise resistance.

METHODS: One male University level swimmer (recruited in accordance with the University's Ethics committee) was asked to perform UUS at his maximal pace from a push from the wall and at a constant depth (1m below the surface). Six Qualisys underwater camera tracked the position of 29 reflective spherical markers attached to one side of his body. Markers possibly increase the drag of the athlete. However, athlete's feedback was positive concerning their presence not affecting UUS technique. From processing these markers' positions, it is possible to recreate the location of seven key joints that are used to describe the UUS motion: fingertips, wrist, shoulder, hip, knee, ankle, and tip of the toes. The distance between these joints is measured (i.e.: segments' lengths) and their vertical positions are fitted using fourth order Fourier series (see Fig 1). The Fourier coefficients and segments lengths are then inputted in Lily Pad, a 2D CFD solver. Lily Pad was developed with the idea of being a quick and efficient flow solver for moving rigid bodies (Weymouth, 2015). It uses implicit LES (Large Eddy Simulation) and an Immersed Boundary Method to calculate the flow around moving rigid bodies. The swimmer is represented by six rigid segments (hands, arms, trunk, thighs, shins, feet) that are moving accordingly to the kinematic data inputted. Lily Pad resolves the fluid equations and the resultant of the pressure forces along the swimmer and the hydrodynamic work done by them is calculated. The parameters of the simulation are the inflow velocity of $1.62\ \mathrm{m.s^{-1}}$ (averaged hip velocity across the calibrated volume) and a grid size of $15\ \mathrm{mm}$ (153 grid points along the athlete's, total of $262{,}144$ grid points in the domain). The results presented are averaged for the duration of the last kick cycle of the simulation.

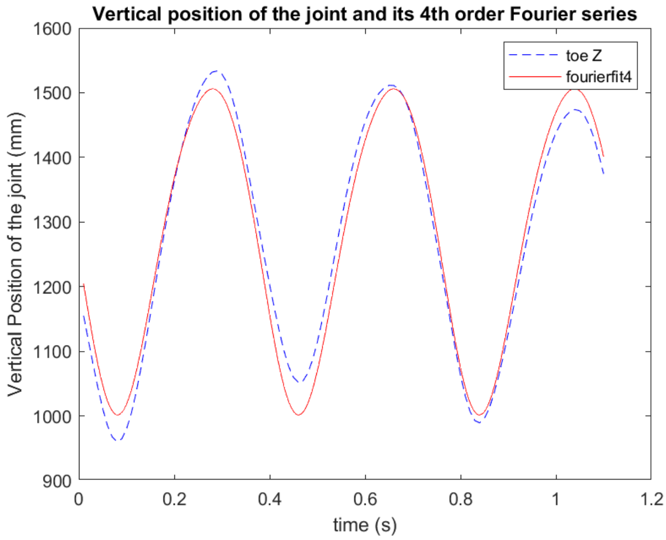

Figure 1: Vertical position of the toe marker and its fourth order fitted Fourier series

The kinematics are modified by multiplying a coefficient to reduce or increase the angular rotation of the successive joints. The average vertical position of the joints remains the same. The angular coefficients for the upper-body motion modifications (trunk, arms and hands) were: 0.5, 0.8, 1.2 and 1.5. The lower-body coefficients (thighs, shins and feet) were: 0.8. 0.9, 1.1 and 1.2. Concerning the phasing correction, it is done by delaying or forwarding the timing when joints reach their peak position to have a linear body wave propagation along the body (see Fig. 2).

RESULTS: Results of the different simulations are presented in Table 1. It highlights the difference in the mean longitudinal force coefficient, and the hydrodynamic work done compared to the baseline kinematics. The Force coefficient is obtained by dividing the longitudinal pressure force by $\frac{1}{2}\rho A V^2$ where ρ is the density of water, A the projected surface area of the swimmer and V the inflow velocity. A positive force coefficient means the swimmer should accelerate and, if it is negative, the swimmer should be slowing down.

It appears that when motion is reduced (coefficient < 1), whether it is upper-body or lower-body, there is a reduction of the hydrodynamic work done. Contrarily, when the amplitudes increase, hydrodynamic work increases.

The Force Coefficient is not greatly affected when the angular motion of the lower limbs is reduced (-0.005 and 0.003 for coefficients of 0.9 and 0.7). However, when the coefficient is

greater than 1, there is a significant increase in the propulsive forces (0.160 and 0.164 higher). Results also highlight that reducing the upper-body amplitude (coefficients of 0.5 and 0.8) reduces the resistance. Similarly, a coefficient of 1.2 also reduces the force coefficient. Increasing upper-body motion even more (coefficient of 1.5) increases resistance.
With a linear wave propagation, there is a large reduction in the hydrodynamic work done (16% reduction). Nevertheless, the athlete appears to create more resistance (-0.170 compared to baseline).

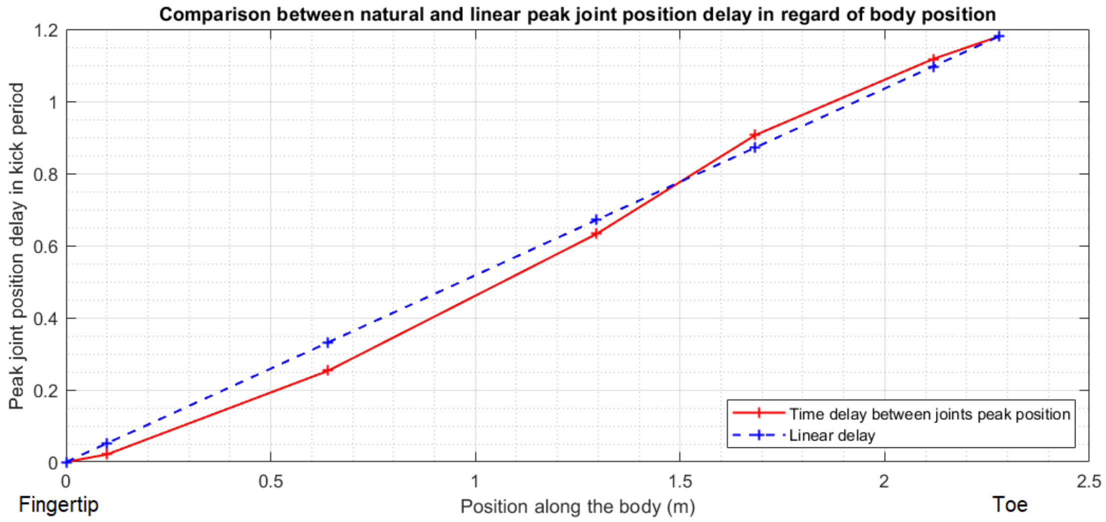

Figure 2: Delay between peak positions of the joints against a linear body wave propagation

Table 1. Summary of Performance Results for the different simulations

	Coefficient	Force Coefficient	Force Coefficient against Baseline	Work Done per Kick vs Baseline (%)
Baseline	-	-0.097	0	100
Lower-body	0.8	-0.102	-0.005	46.9
	0.9	-0.094	0.003	71.0
	1.1	0.062	0.160	146
	1.2	0.067	0.164	195
Upper-body	0.5	-0.068	0.029	81.3
	0.8	-0.040	0.057	91.6
	1.2	-0.078	0.019	120
	1.5	-0.132	-0.035	141
Linear Phase	-	-0.170	-0.073	84.0

DISCUSSION: For this athlete, the simulations suggest that, as already shown in (Nakashima, 2009), increasing the lower-limb amplitude (kick amplitude) could have a benefit in increasing propulsive forces. The hydrodynamic work done, compared to the baseline kinematics, is also significantly larger (increased by 46% and 95% respectively for 1.1 and 1.2 coefficients). It is also interesting to observe that, between the lower-body amplitude increase of 1.1 and 1.2, there is not a significant change in the propulsive forces (force coefficient increased compared to baseline by 0.160 and 0.164 respectively). This would suggest that there is a trade-off optimum where producing a larger kick amplitude increases the propulsion but also increases resistive forces. In addition, by reducing the kick amplitude of the athlete, with a coefficient of 0.9 and 0.8, it appears that the athlete generates a similar amount of longitudinal force. That means that with a reduced kick amplitude, they reduced propulsion and resistive forces by the same amount.

Reducing the upper-body motion does not seem to have as much of an impact on the force coefficient. It could be possible to reduce energy expenditure by reducing the upper-body motion without having an impact on performance. However, the role of the upper-body in UUS is still unclear and it could be important to generate a strong undulation (Veiga et al., 2022). Slightly reducing both the upper-body and lower-body motion may be achievable and could offer a technique with a similar swimming speed for a reduced amount of work done. Also, if it is assumed that the maximum amount of work done by the athlete is achieved at maximum pace, adapting the technique by reducing the upper and lower body amplitude while increasing the kick frequency (to match the hydrodynamic work done by the baseline technique) could provide insight on how to maximise swimming speed for a similar effort.

Having a linear wave propagation seems reduce the work done. Despite a reduction of performance, this result suggests that there could be interesting gains by identifying key joints that are sequenced early or late in order to benefit from a reduced energy expenditure.

CONCLUSION: This study aimed to observe the impact of modified kinematics on a human swimmer performing maximum effort UUS using a 2D unsteady CFD methodology. Different modifications in the kinematics of the athlete proved to provide different results in the simulations. By combining performance, in the form of a longitudinal force coefficient, and energy expenditure, hydrodynamic work done by the athlete, it is possible to obtain clues on what the athlete studied could focus his training on to improve their UUS technique, whether the goal is to maximise performance (swimming speed) or minimise hydrodynamic work done. This work highlights the potential benefit of a low-cost computation CFD methodology to inform coaches of specific improvements on an athlete's UUS techniques. An interest of this method is that it is using a technique that an athlete can already perform and observing the impact of various modifications on it.

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