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# Analysis of a swimmer's hand and forearm in impulsive start from rest using computational fluid dynamics in unsteady flow conditions

M. Samson *, T. Monnet, A. Bernard, P. Lacouture, L. David

*P' Institute, CNRS-University of Poitiers – ENSMA, UPR 3346, 11 Boulevard Marie et Pierre Curie, Téléport 2, BP 30179, 86962 Futuroscope Cedex, France*

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ABSTRACT

The propulsive forces generated by the hands and arms of swimmers have so far been determined essentially by quasi-steady approaches. This study aims to quantify the temporal dependence of the hydrodynamic forces for a simple translation movement: an impulsive start from rest. The study, carried out in unsteady numerical simulation, couples the calculation of the lift and the drag on an expert swimmer hand-forearm model with visualizations of the flow and flow vortex structure analysis. The results of these simulations show that the hand and forearm hydrodynamic forces should be studied from an unsteady approach because the quasi-steady model is inadequate. It also appears that the delayed stall effect generates higher circulatory forces during a short translation at high angle of attack than forces calculated under steady state conditions. During this phase the hand force coefficients are approximately twice as large as those of the forearm. The total force coefficients are highest for angles of attack between 40° and 60°. For the same angle of attack, the forces produced when the leading edge is the thumb side are slightly greater than those produced when the leading edge is the little finger side.

## 1. Introduction

Competitive swimming aims to achieve high performances by the only mechanical action of the swimmer in the fluid almost at rest. The cyclic action of the arms and legs generates a flow which, by the principle of reciprocal actions (Newton's 3rd law) acts on the body surfaces by pressure (normal to the wall) and friction (tangential to the wall). The propulsive forces, resulting from these actions on body surfaces, thus solely and directly depend on this flow. In swimming, the flow is highly non-linear and turbulent containing complex unsteady vortex dynamics (Toussaint et al., 2002; Takagi et al., 2014). Consequently the experimental and numerical analyses of propulsive mechanisms are very difficult and not yet fully understood. Given these difficulties, the determination of the propulsive forces exerted by swimmers' hands and forearms has mainly been made in quasi-steady conditions.

Initial investigations evaluated steady air or water flow past models of swimmers' hands or hand/arm. (Wood, 1977; Schleihauf, 1979; Berger, 1995). These studies evaluated the propulsive potential of the hands and forearms, which are commonly given in the form of lift ($C_L$) and drag ($C_D$) coefficients:

$$C_L = 2.L.(\rho SU^2)^{-1}, \quad C_D = 2.D.(\rho SU^2)^{-1} \tag{1}$$

where drag force (D) is defined as the force acting parallel to the local flow direction of the studied segment (hand or forearm), and lift forces (L) is defined as the force acting perpendicularly to the drag force, $\rho$ is the fluid density, U is the velocity of the fluid relative to the segment (hand and forearm here), S is the maximum projected area of the segment. In this configuration, the hydrodynamic produced forces do not vary over time. Later, Bixler and Riewald (2002) also calculated these coefficients, always in quasi-steady condition, from a 3D computational fluid dynamics (CFD) study. They highlighted that this CFD methodology was a technically viable and less expensive alternative to experimental analysis but this method should evolve in an unsteady form to take greater account of the flow conditions in swimming. In this way, the lift and drag coefficients have to be expressed with respect to time (t):

$$C_L(t) = 2.L(t).(\rho SU(t)^2)^{-1}, \quad C_D(t) = 2.D(t).(\rho SU(t)^2)^{-1} \tag{2}$$

In addition, many authors have shown that the forces generated by the movements of a body can be related directly to the strength and structure of the resultant wake (Ellington, 1984; Dickinson, 1996). This relation is directly highlighted by the Kutta-Joukowski condition which expresses the lift in function of the circulation generated around the body:

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* Corresponding author.
*E-mail address:* mathias.samson@univ-poitiers.fr (M. Samson).

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$$L' = \rho U \Gamma \tag{3}$$

where L' is the lift per unit span, ρ is the density of the fluid, and Γ is the magnitude of circulation. Vorticity and circulation are interrelated concepts (Dickinson, 1996) and allow to make a more explicit connection between force production and wake structure in particular in three dimensions unsteady flows. These two processes (wake and forces) are inextricably linked, since the forces acting on a swimmer must be countered by an equal and opposite change in fluid momentum.

In this context, numerous studies have been carried out, notably in the biomimetic studies, and some unsteady effects have been shown, which depend directly on the configuration of the flow: delayed stall (Walker, 1931), rotational circulation (Kramer, 1932), wake capture (Dickinson, 1994), added mass (Sedov, 1965), Wagner effect (Wagner, 1925), clap-and-fling mechanism (Weis-Fogh, 1973). More recently a particular attention has been paid to the three-dimensionality of the flow generated by a finite wingspan in translation or revolution movement (Maxworthy, 1979; Van Den Berg and Ellington, 1997). In swimming, three unsteady effects were more particularly highlighted. First, the added mass effect, has been shown experimentally by Pai and Hay (1988) and Kudo et al. (2013), and numerically highlighted by Rouboa et al. (2006), Dabnichki et al. (2011) and Sato and Hino (2013). The second effect is the transversal flow generated by the rotation of the arm around the shoulder, experimentally shown by Toussaint et al. (2002). The third effect is circulatory mechanisms around a hand following a shedded vortex, shown by Matsuuchi et al. (2004), then Takagi et al. (2013), by a coupled PIV – pressure study.

The circulatory mechanisms, demonstrated by these previous authors, are dependent on the inertial properties of fluids and are inhibited by viscosity. Furthermore, they are relevant for flows at high Reynolds numbers, which is the case in swimming (close to $10^5$ for the hand). They are directly dependent on the spatio-temporal evolution of the vortex structures which are generated on the surfaces of the hand and the forearm. In a quasi-steady condition, these circulatory mechanisms are stable at low angles of attack. In unsteady condition, they are unstable and very time-dependent, especially with a high angle of attack.

Thus, the originality of this study is in the unsteady flow analysis. It aims to analyze, from a parametric study, the propulsive potential of the hand and the forearm, taking into account the time dependence of the flow. This, to our knowledge, had never been made before. This study is based on unsteady RANS methodology (Samson et al., 2017). In this previous paper the propulsive forces and the spatio-temporal evolution of the vortices were calculated during an aquatic stroke in front crawl swimming. To analyze more precisely some unsteady effects, we voluntarily chose the simple movement of impulsive start. This type of movement, widely studied in aerial and aquatic locomotion (Dickinson, 1996; Kawachi, 2006), allows to analyze the effects of the impulse start, and in particular the *delayed stall* effect. To analyze the time dependence of the forces, the lift and drag coefficients calculated from Eq. (2) will be compared at different times: at t = 0.1 s close to the start of the motion (hypothesis of a high unsteady condition) and at t = 1 s after the start, (hypothesis of a more quasi-steady behavior).

## 2. Methods

### 2.1. Numerical model

The numerical simulation was carried out using URANS (Unsteady Reynolds Averaged Navier-Stokes) methodology, with moving mesh method in free surface condition (Samson et al., 2017). The free surface condition allows to take into account the hydrostatic pressure distribution. The governing equations are three-dimensional incompressible Navier-Stokes equations, and spatial discretization is based on a finite-volume method on unstructured meshes. The unsteady RANS equations were closed by a turbulence model (k-ω SST). An overset mesh method is employed in order to simulate the translation of a hand-forearm segment. The computational mesh created for the "overset region" (parallelepiped 5 m × 3 m × 1 m) around the hand-forearm moves in the "background mesh" (sphere of 1 m in diameter) in accordance with a stroke path (Fig. 1). Meshes and boundary conditions were defined in the article of Samson et al. (2017).

### 2.2. Kinematic of the hand-forearm stroke movement

The movement consisted of translating a hand-forearm model from rest to a constant velocity (2 $\mathrm{ms}^{-1}$) during 1 s, by varying the angle of attack from one run to another.

$$\text{at } t = 0\ \text{s},\ V_{hand} = 0\ \mathrm{ms}^{-1};\ \text{when } t\ \in ]0;1\mathrm{s}]\ \text{then } V_{hand} = 2\ \mathrm{ms}^{-1} \tag{4}$$

The hand and forearm segment (with the wrist locked) of an expert swimmer (male, level: 90.2% of world record, height: 1.80 m, weight: 76 kg) were scanned and digitized by a Minolta VI-900 scanner and imported in STL-file format (STereoLithography). A profile was added to the back of the forearm in order to reduce drag arising from the base of the solid (Fig. 2). A wrist angle of 15° was formed between the hand and the forearm in order to get closest to the swimming conditions. The length of the hand is equal to 0.20 m, the width is equal to 0.10 m, and the length of the forearm is equal to 0.32 m. The projected area of hand and forearm are respectively 0.018 $m^2$ and 0.037 $m^2$.

The velocity of the hand-forearm segment is expressed in a fixed pool-centric reference system: ($X_0$, $Y_0$, $Z_0$) where $X_0$-axis is the backward direction, $Z_0$-axis is the vertical upward direction and $Y_0$-axis is perpendicular to $X_0$. Two local reference systems have been defined: ($X_h$, $Y_h$, $Z_h$) linked to the hand, and ($X_f$, $Y_f$, $Z_f$), linked to the forearm (Fig. 2). $X_h$ is the axis which passed through finger tip (FT) and W (wrist) which is the middle of [RS, US] segment (RS: radial styloid, US: ulnar styloid). $Z_h$ was perpendicular to the ($X_h$, RS-US) plane and Yh was perpendicular to Xh and Zh (Monnet et al., 2014; Samson et al., 2015). $X_f$, is the axis from E (elbow) to W, $Y_f$ is perpendicular to the $X_f$-axis, oriented from US to RS, and $Z_f$ is perpendicular to $X_f$ and $Y_f$, oriented from below to the top of the forearm.

### 2.3. Initial positions and variations of the angles of attack

Given the angle of 15° formed between the hand and the forearm, two initial positions (at t = 0 s) were made: a first for the hand (the axes of ($X_h$, $Y_h$, $Z_h$) are parallel to the axes of ($X_0$, $Y_0$, $Z_0$)). This position is that shown in Fig. 1. From this initial position, 19 simulations were made by varying the angle of attack of the fluid on the hand, 10° by 10°. The second initial position is the forearm in the axis of $Z_0$ (the axes of ($X_f$, $Y_f$, $Z_f$) are parallel to the axes of ($X_0$, $Y_0$, $Z_0$)). From this initial position, 19 simulations were made by varying the angle of attack of the fluid on the forearm, 10° by 10°. Angle of attack (α) is defined as the angle between X-axis of local reference system (hand or forearm) and the flow direction (example for the hand, Fig. 2). The angles of attack have been defined from a specific nomenclature which depends on the side of the hand on which the flow arrives. When the fluid arrives on the thumb-side hand, we add "t" as an index to the angle of attack. When it arrives on the little finger-side we add "l" in index (Fig. 2). This nomenclature will allow us in the discussion to compare our results with those of other authors. Thus the angles of attack varied

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