THE STUDY OF SWIMMERS'S HAND AND FOREARM USING COMPUTATIONAL FLUID DYNAMICS

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Computational Fluid Dynamics has been widely used in biomechanics studies applied to medicine and sport. In this study we developed a 3-D model for swimmer's hand/forearm forces using Computational Fluid Dynamics. Models used in the simulations were created in CAD, based on realistic dimensions of a right adult human hand/forearm. The governing system of equations considered was the incompressible Reynolds averaged Navier-Stokes equations implemented with Fluent® code. The drag coefficient was the main responsible for propulsion, with a maximum value of force propulsion corresponding to a pitch angle of 90º. The lift coefficient seemed to play a less important role in the generation of propulsive force with pitch angles of 0º and 90º but it is important with a pitch angle of 45º. It was demonstrated the relevance of applying CFD in the propulsive force measurements, using a more realistic model of a human segment.

KEY WORDS: swimming, propulsion, computational fluid dynamics.

INTRODUCTION:

The creation of propulsive force in human swimming has been studied recently through numerical simulation techniques with computational fluid dynamics (CFD) models (Bixler & Schloder, 1996; Bixler & Riewald, 2002; Silva et al., 2005; Rouboa et al., 2006; Gardano & Dabnichki, 2006). Nevertheless, some limitations still persist, regarding the geometrical representation of the human limbs. In the pioneer study of Bixler & Schloder (1996), these authors used a disc with a similar area of a swimmer hand, while Gardano & Dabnichki (2006) used standard geometric solids to represent the superior limb. Rouboa et al. (2006) complemented the backward works using a 2-D model of a hand and a forearm of a swimmer. This study constitutes an important step forward to the application of CFD in the human propulsion. Lyttle & Keys (2006) proposed a 3-D model for dolphin kicking propulsion. The aim of the present study is to apply CFD in human swimming establishing a three-dimensional (3-D) model for the upper body propulsion. Relative contribution of drag and lift coefficients of fluid flow around swimmer's hand/forearm were determined using 3D-models under the steady flow conditions

METHOD:

Mathematical model: The dynamic fluid forces produced by the hand/forearm, lift (L) and drag (D), were measured in this study. These forces are functions of the fluid velocity and they were measured by the application of the equations 1 and 2.

$$D = C_D \, ½ \, \rho \, A \, V^2 \qquad (1)$$
$$L = C_L \, ½ \, \rho \, A \, V^2 \qquad (2)$$

In equations 1 and 2, V is the fluid velocity, C_D and C_L are the drag and lift coefficients, respectively, ρ is the fluid density and A is the projection area of the model for different angles of pitch used in this study (0º, 45º, 90º).
CFD methodology consists in a mathematical model applied to the fluid flow in a given domain that replaces the Navier-Stokes equations with discretized algebric expressions and solved by iterative calculations. This domain consists in a three-dimensional grid or mesh of cells that simulate the fluid flow. The fluid mechanical properties, the flow characteristics

along the outside grid boundaries and the mathematical relationship to account the turbulence were considered.
The incompressible Reynolds averaged Navier-Stokes equations with the standard k-epsilon (k-ε) model was considered and implemented in CFD commercial code fluent® (Moreira et al., 2006).

Resolution method: The whole domain was meshed with 400.000 trapezoidal elements of 4 nodes each. The numerical method used by fluent is based on the finite volume approach. The steady solutions of the governing system equations are given in each square element of the discretized whole domain. In order to solve the linear system, Fluent® code adopts an AMG (Algebraic Multi-Grid) solver. Velocity components, pressure, turbulent kinetic energy and turbulent kinetic energy dissipation rate are a degree of freedom for each element.
The convergence criteria of AMG are 10^{-3} for the velocity components, the pressure, the turbulent kinetic energy and the turbulent kinetic energy dissipation ratio.
The numerical simulation was carried out in three-dimensions (3-D) for the computational whole domain in steady flow. Models used in the simulations were created in CAD, based on realistic dimensions of an adult right hand/forearm.

Application: In order to make possible this study we analysed the numerical simulations of a 3-D model of a swimmer hand and forearm.
Angles of pitch of hand/forearm model of 0º, 45º and 90º, with a sweep back angle of 0º (thumb as the leading edge) were used for the calculations (Schleihauf, 1979).
On the left side of the domain access, the x component of the velocity was chosen to be within or near the range of typical hand velocities during freestyle swimming underwater path: from 0.50 m/s to 4.00 m/s, with 0.50 m/s increments. The y and z components of the velocity were assumed to be equal to zero. On the right side, the pressure was equal to 1 atm, fundamental pre requisite for not allowing the reflection of the flow.
Around the model, the three components of the velocity were considered as equal to zero. This allows the adhesion of the fluid to the model.
It was also considered the action of the gravity force ($g = 9.81\ m/s^2$), as well as the turbulence percentage of 1% with 0.10 m of length.
The considered fluid was water, incompressible with density ($\rho = 996.6 \times 10^{-9}\ kg/mm^3$) and viscosity ($\mu = 8.571 \times 10^{-7}\ kg/mm/s$).
The measured forces on the hand/forearm model were decomposed into drag and lift components. The combined hand and forearm drag (C_D) and lift (C_L) coefficients were calculated, using equations 2 and 3.

RESULTS:

In table 1 it is possible to observe the C_D and C_L values produced by the hand/forearm segment as a function of pitch angle. The values found for flow velocity of 2.00 m/s with a sweep back angle of 0º are indicated**.**

Table 1 Values of C_D and C_L of the hand/forearm segment as a function of pitch angle. Sweep back angle = 0º and flow velocity = 2.00 m/s.

Pitch angle	C_D	C_L
0º	0.35	0.18
45º	0.63	0.32
90º	1.10	0.05

According to the obtained results, hand/forearm drag was the coefficient that accounts more for propulsion, with a maximum value of 1.10 for the model with an angle of pitch of 90º. C_L seems to play a residual influence in the generation of propulsive force by the hand/forearm segment at angles of pitch of 0º and 90º, but it is important with an angle of pitch of 45º.

In figure 1 we can observe the values of C_D and C_L produced by the hand/forearm segment as a function of pitch angle and flow velocity. The C_D and C_L values were almost constant for the whole range of velocities (for a given pitch angle).

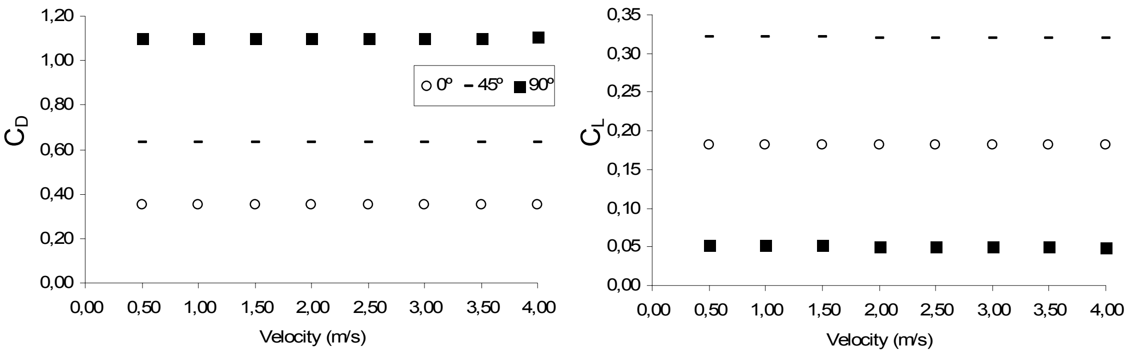

Figure 1: Values of C_D and C_L as a function of flow velocity and pitch angle. Sweep back angle = 0º.

DISCUSSION:

C_D was the main responsible for propulsion, with the maximum value of force production corresponding to an angle of pitch of 90º, as expected. C_L has a residual influence in the generation of propulsive force by the hand/forearm segment for angles of pitch of 0º and 90º, but it is relevant with an angle of pitch of 45º.
These data confirm recent studies reporting reduced contribution of lift component to the overall propulsive force production by the hand/forearm in front crawl swimming, except for the insweep phase, when the angle of attack nears 45º (Berger et al., 1995; Sanders, 1999; Bixler & Riewald, 2002; Rouboa et al., 2006).
Although in this study we only tested flow in steady regime which does not represent truly what happens during swimming, the present study allowed us to apply CFD in the study of propulsive forces in swimming, using a more realistic model of a human hand/forearm. This situation seems to be an important step to the advancement of this technology in sports scope.
The results of the values of C_D and C_L are similar to the ones found in experimental studies (Wood, 1977; Schleihauf, 1979; Berger et al., 1995; Sanders, 1999). These results also contribute to the analysis of hydrodynamic forces produced through unsteady flow conditions and through different orientations of the propelling segment.
For the three different orientation models and for the whole studied velocity range, the C_D and C_L remain constant. Similar results were as well observed in other studies using CFD (Bixler & Riewald, 2002; Silva et al., 2005; Rouboa et al., 2006).

CONCLUSION:

This study applies CFD in the analysis of swimming propulsion. Propulsive force production by the swimmer hand/forearm segment is mainly due to drag force whereas lift force has a minor contribution
This study is an additional step forward to the development of a more realistic model (3-D) of a human segment using CFD in sport studies, in general, and in swimming, in particular.

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