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The use of Computational Fluid Dynamics in swimming research

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The aim of the present study was to apply Computational Fluid Dynamics to the study of the hand/forearm forces in swimming using a 3-D model. Models used in the simulations were created in CAD, based on real dimensions of a right adult human hand/forearm. The governing system of equations considered was the incompressible Reynolds averaged Navier-Stokes equations implemented in the Fluent® commercial 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 pitch angles of 30º, 45º and 60º.

Keywords: *Biomechanics, Swimming, Numerical simulations.*

INTRODUCTION

The creation of propulsive force in human swimming has been recently studied using 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) tried to correct and to complement the backward works using a 2-D model of a hand and a forearm of a swimmer, situation that seems to be an important step forward in the application of CFD to the human propulsion. However, it seems it is possible to go forward, reason why we propose to apply CFD to the studied of the hand and forearm propulsion with three-dimensional (3-D) models, as it was already experimented by Lyttle & Keys (2006) to analyse the dolphin kicking propulsion.

In this sense, with this work we want to continue using CFD as a new technology in the swimming research, applying CFD to the 3-D study of the propulsion produced by the swimmer hand and forearm. Therefore, the aim of the present study is twofold. First, continuing to disseminate the use of CFD as a new tool in swimming research. Second, to apply the method in the determination of the relative contribution of drag and lift coefficients resulting from the numerical resolution equations of the flow around the swimmers hand and forearm using 3-D models under the steady flow conditions.

METHODS

Mathematical Model

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

$$D = C_D \, ½ \, \rho \, A \, V^2 \quad (1)$$

$$L = C_L \, ½ \, \rho \, A \, V^2 \quad (2)$$

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, 30º, 45º, 60º, 90º).

CFD methodology consists of a mathematical model applied to the fluid flow in a given domain that replaces the Navier-Stokes equations with discretized algebraic expressions that can be solved by iterative computerized calculations. This domain consists of a three-dimensional grid or mesh of cells that simulate the fluid flow (figure 1). The fluid mechanical properties, the flow characteristics along the outside grid boundaries and the mathematical relationship to account the turbulence were considered.

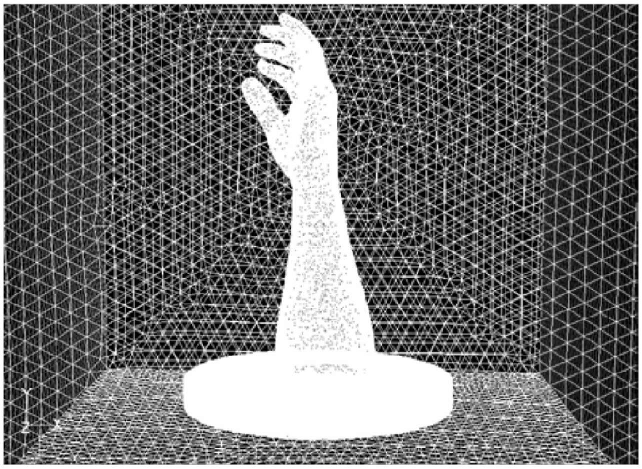

Figure 1: Hand and Forearm Model Inside the Domain with 3-D Mesh of Cells

We used the segregated solver with the standard k-epsilon turbulence model because this turbulence model was shown to be accurate with measured values in a previous research (Moreira *et al.*, 2006).

Resolution Method

The whole domain was meshed with 400000 elements. The grid was a hybrid mesh composed of prisms and pyramids. 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, turbulence kinetic energy and turbulence 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 turbulence kinetic energy and the turbulence kinetic energy dissipation ratio.

The numerical simulation was carried out in three-dimensions (3-D) for the computational whole domain in steady regime.

Application

In order to make possible this study we analysed the numerical simulations of a 3-D model of a swimmer hand and forearm. Models used in the simulations were created in CAD, based on real dimensions of a right adult human hand/forearm.

Angles of pitch of hand/forearm model of 0º, 30º, 45º, 60º 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 (figure 1), 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 0.5 m/s to 4 m/s, with 0.5 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 0.1 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 1 and 2. The independent variables were the angle of pitch and fluid boundary velocity. The dependent variables were pressure and velocity of the fluid within the dome. Post-processing of the results with Fluent® allowed the calculation of component forces through integration of pressures on the hand/forearm surfaces (figure 2).

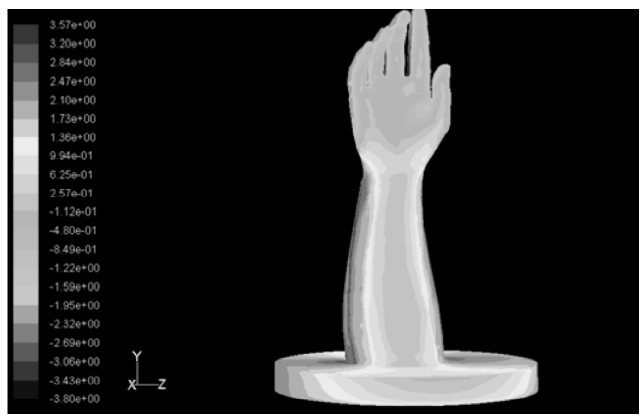

Figure 2: Computational Vision of the Relative Pressure Contours on the Hand/forearm Surfaces

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. It is presented the values found for a flow velocity of 2.00 m/s with a sweep back angle of 0º.

The C_D and C_L values were almost constant for the whole range of velocities (for a given pitch angle).

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. The C_D values increased with the angle of pitch. Moreover, C_L seems to play a residual

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
30º	0.51	0.27
45º	0.63	0.32
60º	0.76	0.29
90º	1.10	0.05

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 angles of pitch of 30º, 45º and 60º.

DISCUSSION

The aim of the present study was to apply Computational Fluid Dynamics to the study of the hand/forearm forces in swimming using a 3-D model and to determine the relative contribution of drag and lift coefficients to the overall propulsive force production.

Computational Fluid Dynamics methodology was developed by engineers to solve numerically complex problems of fluid flow using an iterative optimization approach. The net effect is to allow the user to model computationally any flow field provided the geometry of the object and some initial flow conditions are prescribed. This can provide answers to problems which have been unobtainable using physical testing methods, thereby bridging the gap between theoretical and experimental fluid dynamics. In this research we tried to improve the previous studies that applied CFD to the analysis of swimming propulsion, using a more realistic model of the swimmer hand and forearm (3-D model). Thought, this model still needs to be improved, namely using a model in which the fingers would be extended. This is an issue that should be addressed in future studies.

We are very pleased with the results pointed out in the simulations of our study. 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. The C_D obtained the highest value at an orientation of the hand/forearm plane where the model was directly perpendicular to the direction of the flow. The same result was reported by Berger et al. (1995), in which the drag force increases to a maximum where the plane was the same as the presented in this work (angle of pitch = 90º).

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 important with angles of pitch of 30º, 45º and 60º. These data confirm recent studies reporting reduced contribution of lift component to the overall propulsive force generation by the hand/forearm segment in front crawl swimming, except for the insweep phase, when the angle of attack is within 30º-60º (Berger *et al.*, 1995; Sanders, 1999; Bixler & Riewald, 2002; Rouboa *et al.*, 2006).

Although in this study we had only tested flow in steady regime and this situation does not truly represent what happens during swimming, the present study allowed us to apply CFD in the study of propulsive forces in swimming, using a three-dimensional model of a human hand/forearm. By itself, 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), important fact to the methodological validation of CFD, giving as well conditions to the primary acceptation to the analysis of hydrodynamic forces produced through unsteady flow conditions and through different orientations of the propelling segments.

For the three different orientation models and for the whole studied velocity range, the C_D and C_L remain constant. Similar results were observed as well in other studies using CFD (Bixler & Riewald, 2002; Silva *et al.*, 2005; Rouboa *et al.*, 2006).

CONCLUSION

This study tried to apply CFD to the analysis of swimming propulsion. As conclusions we can state that the computational data found seem to demonstrate an important role of the drag force and a minor contribution of the lift force to the propulsive force production by the swimmer hand/forearm segment.

On the other hand, it was demonstrated the utility of using CFD in the propulsive force measurements, using a more realistic model (3-D) of a human segment. This situation is an additional step forward to the necessary continuation to keep developing this technology in sport studies, in general, and in swimming, as a particular case.

ACKNOWLEDGEMENTS

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