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Technical note

Analysis of a swimmer's hand and arm in steady flow conditions using computational fluid dynamics

Barry Bixler[a,*], Scott Riewald[b]

[a] *Honeywell Engines and Systems, Phoenix, AZ, USA*
[b] *USA Swimming, Colorado Springs, CO, USA*

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Abstract

Propulsive forces generated by swimmers' hands and arms have, to date, been determined strictly through experimental testing. As an alternative to these complex and costly experiments, the present research has applied the numerical technique of computational fluid dynamics (CFD) to calculate the steady flow around a swimmer's hand and arm at various angles of attack. Force coefficients computed for the hand and arm compared well with steady-state coefficients determined experimentally. The simulations showed significant boundary layer separation from the arm and hand, suggesting that Bernoulli's equation should not be used to mathematically describe the lift generated by a swimmer. Additionally, "2D" lift was shown to be inaccurate for the arm at all angles of attack and for the hand near angles of attack of 90°. Such simulations serve to validate the chosen CFD techniques, and are an important first step towards the use of CFD methods for determining swimming hydrodynamic forces in more complex unsteady flow conditions. © 2002 Published by Elsevier Science Ltd.

Keywords: Drag; Lift; Computational fluid dynamics; Swimming; Hand; Arm

1. Introduction

Swimming propulsion is a phenomenon not fully understood, and to date, research to determine the propulsive forces exerted by swimmers' hands and arms has been strictly experimental. Initial investigations evaluated steady air or water flow past models of swimmers' hands or hand/arm. Wood (1977) used a wind tunnel to determine the force coefficients of a hand and forearm, but the lift forces were strictly "2D", and the third dimension was neglected. Schleihauf (1979) also developed "2D" lift forces when flume-testing a hand model supported by a rod. Interference drag was not accounted for, since it was assumed that the support rod encountered equal drag force whether the hand was attached or not. Berger et al. (1995) measured force coefficients on a hand and arm using a tow tank. Although lift calculations were "3D", the model pierced the free surface of the water, resulting in wave and ventilation drag. Thayer (1990) and Sanders (1999) concentrated on unsteady flow, and showed experimentally that acceleration and deceleration can significantly affect hand force coefficients. Although both experiments accounted for fixture drag, the effects of interference drag at the wrist were not considered.

These researchers revealed the difficulties involved in conducting such studies experimentally. They had to choose between unwanted wave and ventilation drag or inaccurate interference drag. An alternative approach, previously unused for the evaluation of arm and hand swimming propulsion, is to apply the numerical technique of computational fluid dynamics (CFD) to calculate the solution. In addition to avoiding wave, ventilation, and interference drag, CFD has the advantage of showing detailed characteristics of fluid flow around the hand and arm.

The viability of applying CFD to swimming was shown by Bixler and Schloder (1996), when they used a CFD 2D analysis to evaluate the effects of accelerating a flat circular plate through water. Their results suggested that a 3D CFD analysis of an actual human form could provide useful information about swimming. The present paper presents such a 3D analysis, and reveals that steady-state force coefficients calculated using CFD

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*Corresponding author. 3145 W. Tyson Place, Chandler, AZ 85226, USA.

E-mail address: misterbix@aol.com (B. Bixler).

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methods compare well with coefficients obtained experimentally. Such comparisons serve to validate the chosen CFD techniques, and are an important first step towards the use of CFD methods for determining swimming hydrodynamic forces in unsteady flow conditions.

2. Methods

A CFD model was created based upon an adult male's right forearm and hand with the forearm fully pronated. The thumb was adducted, and the wrist was in a neutral position. The hand/arm boundary was located at the level of the styloid processes of the radius and ulna. This geometry protruded into a dome-shaped mesh of fluid cells from its base. The model's origin and *x–y* plane were in the plane of the dome base, and the *z*-axis extended from the origin through the distal end of the fourth finger (Fig. 1). The *x*-axis was defined by the vector extending from the distal end of the fourth finger to the distal end of the index finger, then projected onto the *x–y* plane. Adaptive meshing was utilized to achieve optimum mesh refinement, and the final mesh contained 215,000 cells.

The angle between the model's *x*-axis and the flow direction is called the angle of attack (Fig. 1). Angles of attack between -15° and 195° in maximum increments of 15° were evaluated. Intermediate angles were also included in the analysis when needed. Water velocity was prescribed to the inlet portion of the dome surface and was held steady at values between 0.4 and 3.0 m/s during the simulations. The location of this surface and the direction of prescribed flow changed as the angle of attack was varied. For all flow cases, the prescribed flow was parallel to the *x–y* plane (zero sweepback angle). The skin roughness was smooth (shaved), accomplished by setting the roughness height equal to zero. Water temperature was 22.6°C, water density was $996\,\mathrm{kg/m^3}$, and the viscosity was $8.571 \times 10^{-4}\,\mathrm{kg/m\,s}$. The dome's base was a plane of symmetry, requiring the flow there to remain in that plane. Although this is an approximation to actually modeling an elbow and upper arm, it avoids the edge effects that would have occurred if water were allowed to flow under the bottom of the arm, or the wave and ventilation drag that would have occurred if the dome bottom were modeled as a free water surface.

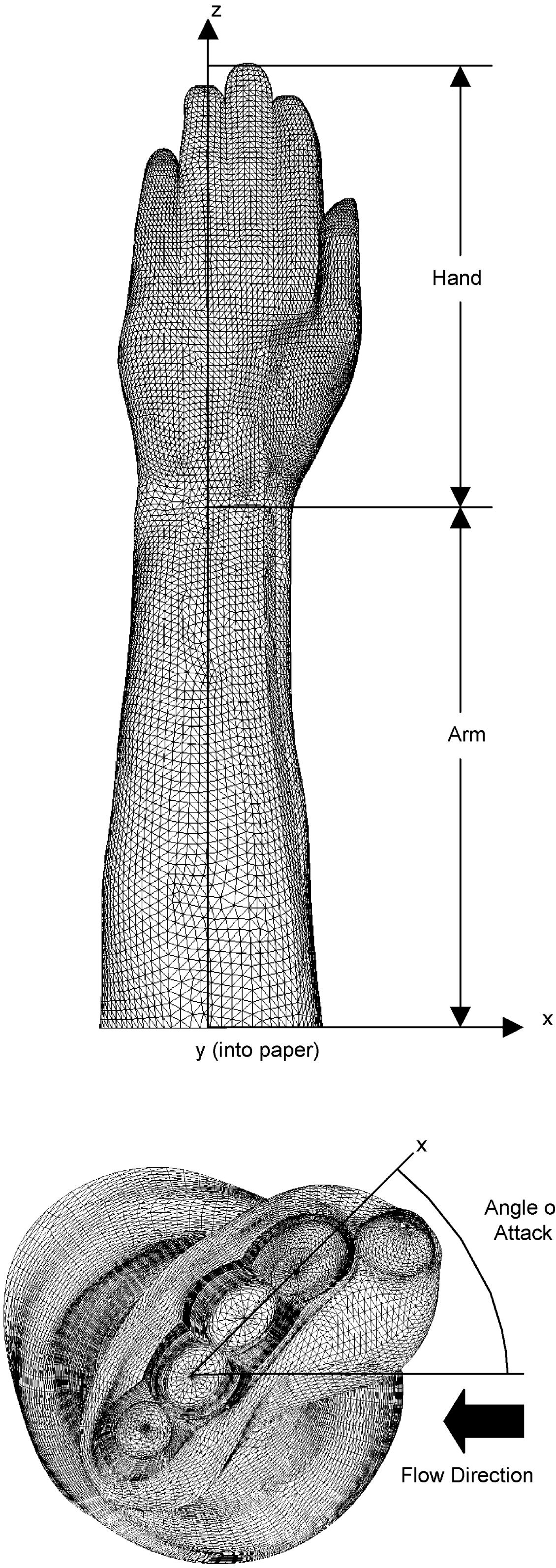

Fig. 1. CFD surface mesh of hand and arm with coordinate system and angle of attack defined.

CFD techniques replace the complex Navier–Stokes fluid flow equations with discretized algebraic expressions that can be solved by iterative computerized calculations. The Fluent CFD code (Fluent Inc., Lebanon, NH) was used to develop and solve these equations using the finite volume approach, where the equations were integrated over each control volume. The flow was incompressible. All numerical schemes were of second order, and non-equilibrium wall functions were chosen to handle boundary layer flow. The standard k–ε turbulence model was applied for a turbulence intensity of 1% and a turbulence length of 0.1 m [for CFD technical background information, see the webpage of the Journal of Biomechanics (http://www.elsevier.com/locate/jbiomech) or Bixler and Schloder, 1996].

The independent variables were the angle of attack 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/arm surfaces. Force coefficients were then calculated for the hand, arm, and hand/arm combined using

$$C_i = \frac{F_i}{1/2\rho V^2 A}, \tag{1}$$

where F_i are the drag, lift, and axial forces and C_i are the corresponding coefficients, ρ is the fluid density, V is the steady free stream velocity of the fluid relative to the hand and arm, A is the maximum projected area of the hand, arm, or hand/arm combination.

Drag force is defined as the force acting parallel to the flow direction, and 2D lift forces lie perpendicular to the drag force and in the x–y plane. The axial force acts along the z-axis in the model. The total or 3D lift force is defined as the square root sum of squares (SRSS) of the axial and 2D lift forces. Although drag and 3D lift forces are always positive, axial and 2D lift forces can be either positive or negative.

3. Results

Force coefficients measured using CFD and calculated as a function of angle of attack (Fig. 2), showed predictable trends that closely resembled the data collected in previous experimental studies. Arm drag was essentially constant ($C_d = 0.65$), and arm 2D lift was zero. Hand drag was minimum near angles of attack of 0° and 180° and peaked at 95° ($C_d = 1.15$). Hand 2D lift was zero at 95° and peaked near 55° and 140°, with more lift generated when the little finger leads than when the thumb leads the motion. Axial coefficients were large for the arm at all angles of attack and for the hand near angles of attack of 90°. These findings suggest that force component evaluations should incorporate forces generated in all the three dimensions, rather than focus only on the forces acting in the x–y plane. All force coefficients were constant for velocities between 1.0 and 3.0 m/s (for a given angle of attack). As the velocity was decreased from 1.0 to 0.4 m/s, the axial and 2D lift coefficients remained constant while the drag coefficient began to slightly increase (Fig. 3). However, from a practical standpoint, the drag coefficients may also be considered constant, since the forces at speeds <0.4 m/s are relatively small.

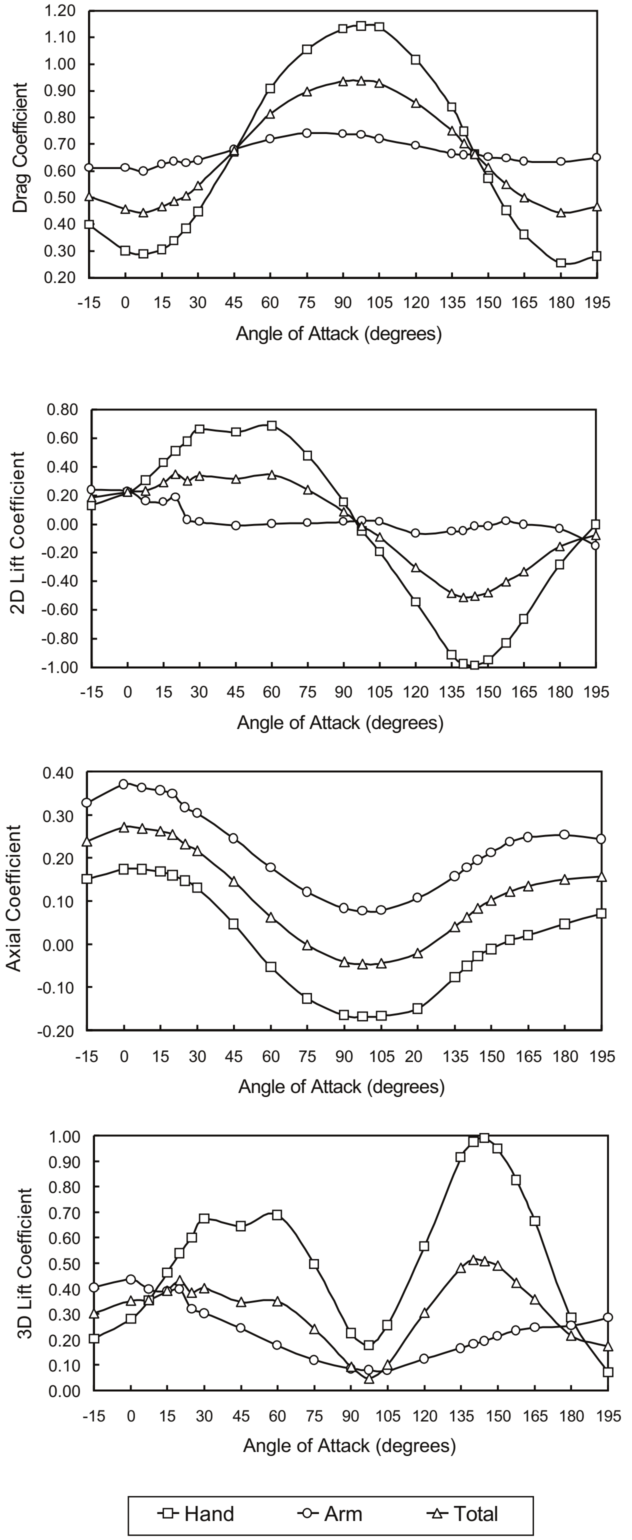

Fig. 2. Force coefficients vs. angle of attack turbulence: intensity = 1%, length = 0.2 m, velocity = 2 m/s, and sweepback angle = zero.

Flow visualization using CFD is easy and informative, and color oilfilm and flow pathline plots clearly reveal significant boundary layer separation from the skin on the downstream side of the hand and arm [see webpage of the Journal of Biomechanics (http://www.elsevier.com/locate/jbiomech)]. Flow separation

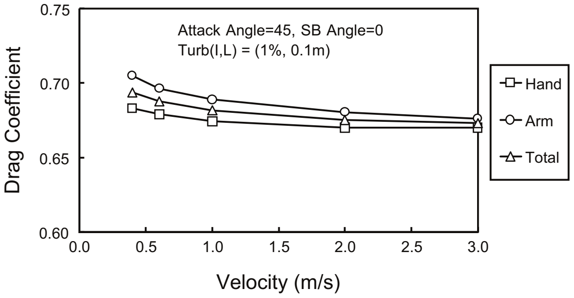

Fig. 3. Drag coefficient vs. velocity.

occurred at all angles of attack and for all velocities evaluated. This indicates that Bernoulli's equation should not be used to explain the lift forces that swimmers generate with their hands, since Bernoulli's equation is applicable only to ideal flow (Bixler, 1999).

4. Discussion

To validate the chosen CFD techniques, the steady-state force coefficients calculated using CFD methods were compared to steady-state coefficients obtained experimentally by Wood (1977), Schleihauf (1979), and Berger et al. (1995). Such comparisons are an important first step toward the use of CFD methods for determining swimming hydrodynamic forces in unsteady flow conditions. Wood (1977) tested a hand and half of a forearm in a wind tunnel, and the CFD drag and 2D lift coefficients (using only a half of the forearm) compare very well with Woods' coefficients (Fig. 4a). Schleihauf (1979) modeled a hand alone in a flume, and the CFD results are compared to the flume results using the force sign convention of the CFD model (Fig. 4b). (Note: The 0° angle of attack was defined differently in each experiment, and prior to comparison with CFD results, the differences in 0° orientation were accounted for.) Although the comparison is satisfactory, the flume drag coefficients are consistently slightly higher than the CFD drag coefficients. A likely reason is flume turbulence, which increases lift and especially drag. There was also a local divergence of the CFD and experimental results near an angle of attack of 15°, where the flume lift coefficient showed a localized peak. This occurrence could be caused by a partial abduction of the thumb in the flume model, where the thumb acts as the forward slat does in a slotted airplane wing, increasing the lift by delaying boundary layer separation.

This same local lift force peak was seen in a study by Berger et al. (1995) where coefficients for the hand and arm were developed by towing a model through a towtank. Comparisons with CFD, now using total surface area as the reference area, are good for the hand alone (Fig. 4c), but less favorable for the hand/arm combination (Fig. 4d). The larger towtank coefficients could be the result of wave and ventilation drag caused by the arm piercing the free water surface. Deformation of the free surface of the water accompanies such drag, and may be the reason that Berger et al. found the axial

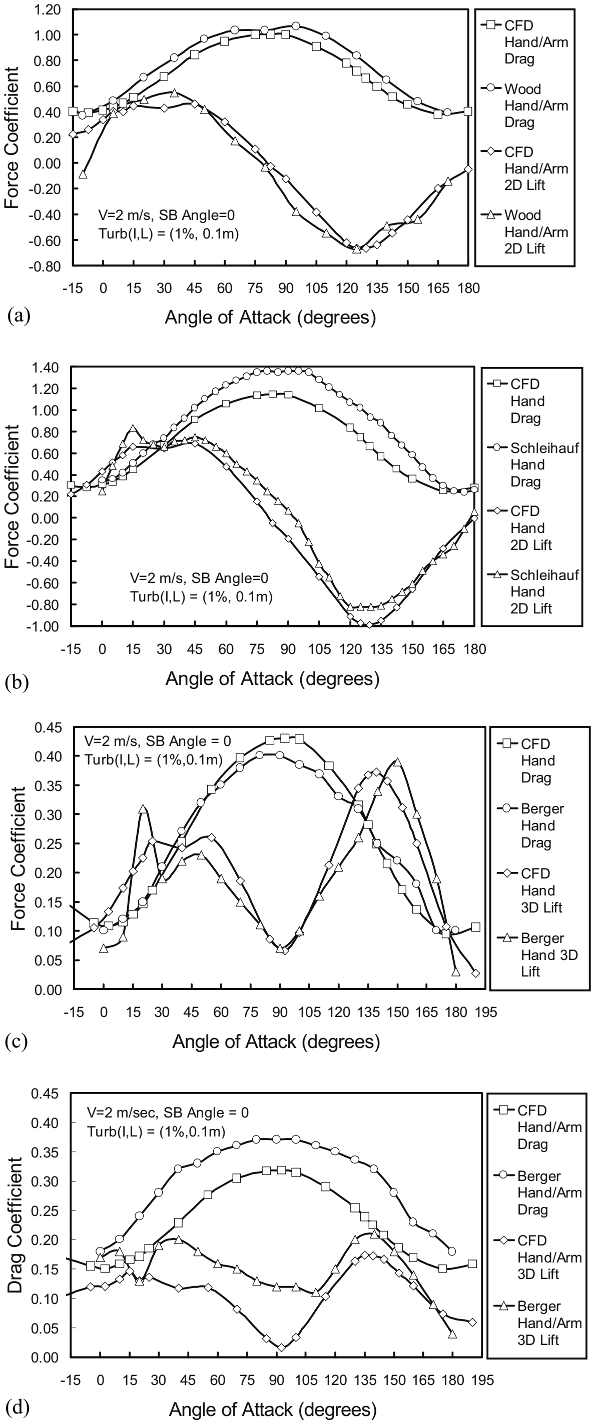

Fig. 4. (a) Comparison of hand/arm force coefficients for CFD and Wood (based upon maximum projected area); (b) comparison of hand force coefficients from CFD and Schleihauf (based upon maximum projected area); (c) comparison of hand force coefficients from CFD and Berger et al. (model 2) (based upon total surface area); and (d) comparison of hand/arm force coefficients for CFD and Berger et al. (model 2) (based upon total surface area).

forces (Fz) to be small, while the CFD analyses found the axial forces to be significant.

The results of this study were limited to steady flow and to sweepback angles of 0°. The symmetry plane at the end of the forearm prevented errors resulting from wave, ventilation, or interference drag, but is still only an approximation to actually modeling an upper arm. Swimmers do not move their hands and arms in a steady direction and velocity, and research by Berger et al. (1999) and by Toussaint (2000) show that unsteady and steady motion can give different results. However, the present study serves to establish CFD methodology as a technically viable and less expensive alternative to experimental testing of swimming propulsion. In the future, the hand and arm model could be used to evaluate various aspects of unsteady motion, such as accelerations, decelerations, and multi-axis rotations. This could be accomplished by performing transient time-dependent CFD analyses using user-defined functions and/or moving meshes, and adding an upper arm to the model. The effects of water turbulence and skin roughness could also be determined by varying the turbulence intensity and length, and changing the skin roughness parameters. The ultimate goal of dynamically evaluating complete arm strokes and "designing" the optimal pulling pattern, is obtainable using CFD methods.

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