To Appear in ASME Journal of Biomechanical Engineering

Technical Brief

Comparative Analysis of Thrust Production for Distinct Arm-Pull Styles in Competitive Swimming

[1]Alfred von Loebbecke, [2]Rajat Mittal
1Mechanical and Aerospace Engineering, The George Washington University
2Mechanical Engineering, Johns Hopkins University

Keywords: arm pull, freestyle, swimming backstroke, drag, lift, computational fluid dynamics

Abstract

A computational fluid dynamics (CFD) based analysis of the propulsive forces generated by two distinct styles of arm-pulls in front-crawl as well as backstroke, is presented in this Technical Brief. Realistic models of the arm pulling through water are created by combining underwater video footage and laser-scans of an arm with computer animation. The contributions of drag and lift forces on the arm to thrust are computed from CFD and it is found that lift forces provide a dominant contribution to thrust for all the arm-pull styles examined. However, contrary to accepted notions in swimming, pronounced sculling (lateral motion) not only does not increase the contribution of lift forces on the hand to overall thrust, it decreases the contribution of drag forces to thrust. Consequently, pronounced sculling seems to reduce the effectiveness of the arm-pull.

Introduction

In swimming, the hand may be thought of as a quasi-airfoil (Bixler & Riewald, 2002). The drag and lift (or lateral) forces acting on the hand (in a reference frame affixed to the hand) may be oriented upstream thereby propelling the swimmer forward. This is why the swimming research community sometimes refers to propulsion as being “drag-based” or “lift-based.” The relative contribution of drag and lift forces on the hand to overall thrust is the subject of ongoing debate and has significant implications for swimming styles and training techniques.

Counsilman (1968) advanced the idea of drag-based propulsion and for the front-crawl, advocated maintaining the palm facing downstream in a position perpendicular to the flow for as long as possible through the pull. However, observations of championship swimmers which showed lateral movements of the swimmers’ arms (sculling) in freestyle (Brown and Counsilman (1971), Counsilman (1971), Schleihauf et al. (1979), Berger et al. (1995)) suggested a greater emphasis on lift-based propulsion. In fact, it was believed that lift forces would provide a dominant contribution to thrust and Toussaint and Beek (1992) were one group among many, who postulated that utilizing lift rather than drag was a more efficient way of transferring energy to the water.

Wood (1979) studied hand and forearm models in wind tunnels and concluded that both lift and drag play important roles in thrust production and that

Corresponding Author: Rajat Mittal; mittal@jhu.edu

drag forces could not be summarily dismissed. Cappaert and Rushall (1994) used predetermined lift and drag coefficients to estimate lift and drag forces and suggested that drag forces dominated thrust in all swimming strokes except for in the breaststroke. Ito et al. (2003) also used analysis with predetermined coefficients and concluded that the palm should be oriented perpendicular to the relative flow pulled as straight as possible along the long axis of the body to take advantage of the drag forces for maximizing thrust. However, pitching of the hand and sculling should be used in order to recruit lift forces and minimize energy consumption. Rushall et al. (1994) provides a good dissection of the intuitive and non-quantitative arguments of the groups that supported the lift-based propulsion postulate and pointed out the logical and conceptual flaws in the arguments used to support the lift-based propulsion hypothesis. Berger et al. (1995) used hand and forearm models in towing tanks and Bixler and Riewald (2002) used computational fluid dynamic simulations of the hand and forearm to determine the relative contributions of hand and forearm to thrust production but no studies have quantified the contributions in actual swimming situations.

In the current study, we use computational fluid dynamic modeling to perform comparative analyses of two distinct styles of arm-pulls in forward crawl as well as backstroke (see Fig. 1). The strokes are based on videos of elite, Olympic-level swimmers and the two styles in each case are chosen so as to address the relative contribution of lift and drag to propulsion as well as the relative performance of distinct styles that seemingly rely on these different mechanisms for producing thrust.

Method

A finite-difference CFD solver is used to solve the mass conservation and the viscous, incompressible Navier-Stokes equations, i.e.

$$\frac{\partial u_i}{\partial x_i} = 0 \quad \text{and} \quad \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \nu \frac{\partial^2 u_i}{\partial x_j x_j}$$

respectively, on a fixed, non-uniform Cartesian grid using an immersed boundary method. In the above equations, u and p are the flow velocity and pressure respectively, and ν is the kinematic viscosity of the fluid. The simulations are performed in a reference frame moving at the average speed of the swimmer and the no-slip, no-penetration condition **(**$u_i = \left(U_{body}\right)_i$**)** is enforced at the body surface. Furthermore, we employ freestream conditions ($u_i = \left(U_\infty\right)_i$) on the inlet and lateral boundaries, and an outflow boundary condition $n_j \partial u_i / \partial x_j = 0$ on the downstream boundary where n is the normal to the outflow boundary.

This solver has been extensively documented for a variety of flows associated with aquatic propulsion (Mittal et al. 2006, Dong et al. 2010,) as well as competitive swimming (von Loebbecke et al., 2009a,b,c). The simulations are fully unsteady and no quasi-steady assumptions are made. Computational costs limit our Reynolds number ($\mathrm{Re} = U_\infty L_A / \nu$ where U_∞ and L_A are the swimming speed and arm-length respectively) to 10^4, which is two orders of magnitude lower than the actual Reynolds number of 10^6. However, as pointed out by Anderson et al. (1998) and Dong et al. (2010), the hydrodynamic force produced by surfaces undergoing rapid undulatory/flapping motion, is fairly independent of the Reynolds numbers at high enough values of this parameter.

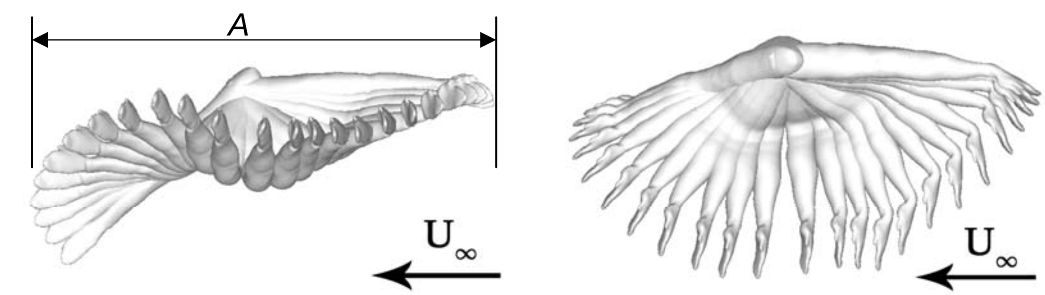
Corresponding Author: Rajat Mittal; mittal@jhu.edu

The key parameter for such configurations is the Strouhal number (Anderson et. al. 2010) which may be defined here as $St = A / \tau U_\infty$ where τ and A are the stroke duration and amplitude (see Fig. 1a) respectively. This number, which ranges from 1.17 to 2.1 for the four particular strokes modeled here, is matched exactly in all the corresponding simulations.

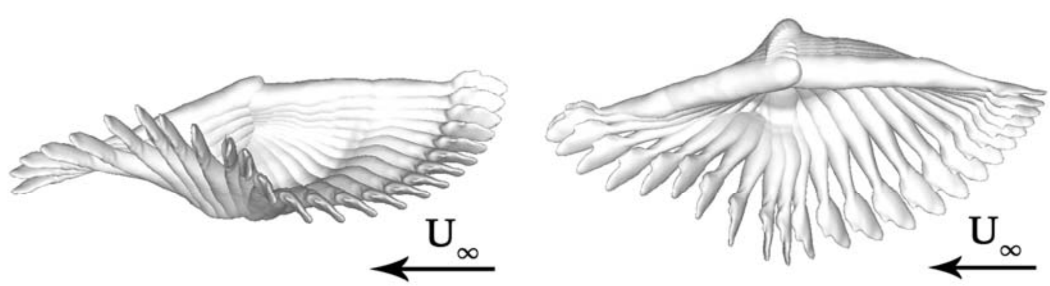
Free-surface effects such as waves and water-entry is neglected and the arm is assumed to be immersed in water throughout the stroke. All simulations involve only the arm, and only the pull (underwater) phase of the arm stroke is simulated. Since the recovery (above-water) phase could not be included and the pull phase does not constitute a complete periodic motion, only one pull was simulated for each stroke.

All simulations were run on a dense 256x128x128 Cartesian grid (~4.2 million points). The grid consists of a cuboidal region of higher resolution around the arm and a smoothly increasing grid size outside this region to the outer computational boundary. This grid was chosen after a systematic grid refinement study where grids were refined for one chosen case until the change in stroke-averaged forces was less than 5%. Further details of the numerical method and modeling procedure can be found in von Loebbecke et al. (2009a).

The geometry of the swimmer's arm is based on accurate laser scans of a male, Olympic level athlete (von Loebbecke et al. 2009a). For computational purposes, the surface of the arm is represented by an unstructured surface mesh, and consists of 3914 vertices and 7824 triangular elements. Pre-recorded video footage of Olympic level athletes performing the various arm strokes is used in combination with animation software Autodesk MAYA® to reconstruct the arm motion for inclusion into the simulations (von Loebbecke et al. 2009a,b,c). Briefly, as shown in Fig. 1e, the process of creating an animated arm model involves inserting virtual "joints" into the arm and then matching 16 frames of the arm-stroke from the video footage to the articulated arm geometry.



(a)



(b)

Corresponding Author: Rajat Mittal; mittal@jhu.edu

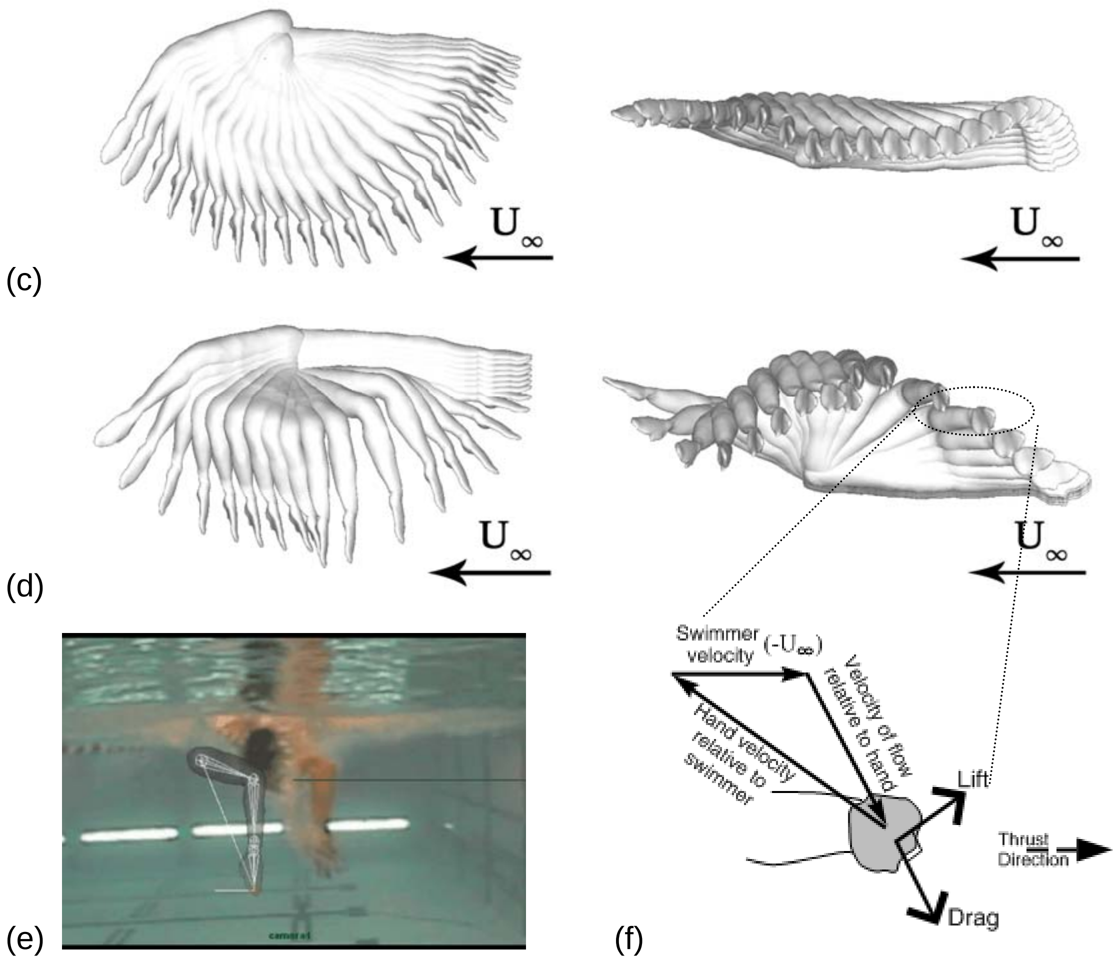


Figure 1. Side (left) and top/bottom (right) views of (a) backstroke-1; (b) backstroke-2; (c) front-crawl-1, and (d) front-crawl-2. (e) Graphic showing matching of stroke kinematics to underwater video using articulated virtual joints. The definition of the stroke amplitude (*A*) is indicated in 1(a). (f) Definition of flow vectors and force components.

Side and top views of the two types of backstroke are shown in figures 1(a) and (b) respectively and the side and bottom views of the two types of freestyle are shown in figures 1(c) and (d). In Backstroke-1 the palm is facing downstream through most of the stroke whereas in Backstroke-2, the palm is mostly oriented obliquely to the freestream. Among the two freestyle strokes, significant sculling is visible in Freestyle-2. The elbow is maintained mostly straight during the stroke in Freestyle-1, whereas the elbow shows considerable articulation in Freestyle-2. Thus, Backstroke-1 and Freestyle-1 are ostensibly designed to employ drag to produce thrust whereas Backstroke-2 and Freestyle-2 attempt to recruit lift forces to produce thrust. No study to-date has evaluated the relative importance of lift and drag to thrust for different arm-stroke styles and that is the primary objective of the current study.

Results and Discussion

Table 1 summarizes the key quantities and computed results for the four cases simulated here. The forces on the arm are computed by integrating the computed pressure and shear forces on the surface of the entire arm. Given that our simulations show that most of the thrust is generated by the hand, we define

Corresponding Author: Rajat Mittal; mittal@jhu.edu

drag as the force in the direction of the flow relative to the hand, and lift as the force perpendicular to the drag force. These directions of the lift and drag are shown schematically in figure 1(f).

In the table, T refers to the total thrust in Newtons generated by the arm and T_D and T_L are the drag and lift contributions to the thrust. Instantaneous values of lift, drag and thrust are averaged over the entire stroke (for instance, $\bar{T} = (1/\tau)\int_0^{\tau} T(t)dt$), and the table shows these stroke-averaged values. We also note that while both backstrokes are recorded at the same swimming speed, the swimming speeds for the two forward-crawl strokes are different. This difference is factored in by comparing the coefficient of thrust force $\bar{C}_T = \bar{T} / \left(0.5\rho_w U_\infty^2 A_h\right)$ where ρ_w and A_h are the density of water and the surface area of the hand respectively. The stroke frequency for the two forward-crawl pulls also varies by about 20% and this is possibly associated with the particular style of swimming.

Case	U_∞ [m/s]	τ [sec]	A (m)	$St = \frac{A}{\tau U_\infty}$	$\bar{T}_D$ [N] ($\bar{T}_D / \bar{T}$)	$\bar{T}_L$ [N] ($\bar{T}_L / \bar{T}$)	$\bar{T}$ [N] ($\bar{C}_T$)	$\bar{T}_L / \bar{T}_D$
Backstroke-1	1.6	0.68	1.50	1.38	8.5 (30%)	19.0 (70%)	27.5 (0.108)	2.2
Backstroke-2	1.6	0.69	1.59	1.45	5.4 (23%)	17.9 (77%)	23.3 (0.091)	3.3
Front-Crawl-1	1.2	0.60	1.50	2.1	17.8 (48%)	19.3 (52%)	37.0 (0.257)	1.1
Front-Crawl-2	1.8	0.73	1.53	1.17	6.1 (25%)	18.4 (75%)	24.5 (0.076)	3.0

Table 1: Summary of parameters and computed stroke-averaged forces for the four different arm-pulls modeled in the current study.

A number of observations can be made from the data in the table:

1. For all the four strokes, the contribution of lift to thrust ranges from 52% to 77% and that of drag from 25% to 48%. Thus, the current simulations clearly indicate that lift plays a dominant role in producing thrust for all the strokes studied here. The ratio of the contributions of lift and drag to thrust ranges from 1.1 to 3.3 which also served to reaffirm the importance of lift for thrust.

2. Backstroke-1 has higher thrust than Backstroke-2 and Front-Crawl-1 produces significantly more thrust (as well as a higher thrust coefficient) than Front-Crawl-2. This suggests that the arm-pulls with excessive sculling (Backstroke-2 and Front-Crawl-2) are not as effective in producing thrust as styles where the hand is kept mostly normal to the direction of thrust and moved primarily parallel to this direction.

3. The case made in the previous point is stronger for the backstrokes since the Strouhal numbers for the two backstroke cases are quite similar and the primary difference is therefore in the stroke "style." In the case of the front-crawl, the comparison of net thrust between the two strokes is confounded by the large difference in the Strouhal numbers. The significantly higher thrust for Front-Crawl-1 is not unexpected given the much higher Strouhal number for

Corresponding Author: Rajat Mittal; mittal@jhu.edu

this case. As shown by Anderson et al. (1998), thrust produced by flapping foils can increase very rapidly with Strouhal number. It should however be noted that this higher thrust would either be balanced by a higher body drag in the case of steady swimming, or result in an instantaneous acceleration of the swimmer. With regard to the former, “active” drag on swimmers can itself depend strongly on style and speed (Kolmogorov and Duplishcheva 1992). With regard to the latter, while the current study attempted to examine steady state swimming, transitory accelerations in the swimmers remain a possibility.

4. Backstroke-1 and Front-Crawl-1, where sculling is limited, still produce a significant proportion of their thrust (70% and 52% respectively) from lift. Thus, the notion that these strokes correspond to “drag-based” propulsion seems incorrect.
5. The primary effect of sculling in Backstroke-2 and Front-Crawl-2 is a significant reduction in the contribution of drag to thrust as well as a marginal reduction in the contribution of lift to thrust. Thus, sculling does not have the expected effect of increasing the lift contribution to thrust.

Summary

Computational fluid dynamics coupled with realistic geometric and kinematic representation of arm strokes has enabled a detailed and quantitative analysis of the thrust production of distinct arm-stroke styles. The objective of the study was to understand the relative importance of lift and drag forces in thrust production, and its implication for distinct arm-pull styles employed by elite swimmers. While the four strokes selected might not represent the entire range of styles employed, they do capture the general features of arm-pulls that are currently used in competitive swimming. The limitations of the current study include a lower than full-scale Reynolds numbers and lack of free-surface effects.

The simulations indicate that lift is a major and often dominant contributor to the thrust produced by the arms. In fact, contrary to conventional understanding, even strokes that are ostensibly designed to employ drag-based propulsion actually produce a majority of their thrust from lift. Also contrary to conventional wisdom, exaggerated sculling motions that are designed to exploit lift, actually reduce both the lift and drag contributions to thrust. Consequently, while lift is important for thrust generation, these latter styles are found to be less effective in producing thrust. The current results therefore provide a unique, and somewhat contrarian view of the effectiveness of arm-pull styles in competitive swimming.

References

Anderson, J. M.; Streitlien, K.; Barrett, D.S.; Triantafyllou, M.S. (1998) Oscillating foils of high propulsive efficiency. *Journal of Fluid Mechanics*, 360, p.41-72.

Berger, M., De Groot, G., Hollander, A.P. (1995) Hydrodynamic drag and lift forces on human hand/arm models. *Journal of Biomechanics*, 28, 125-133.

Bixler, B., Riewald, S. (2002) Analysis of a swimmer’s hand and arm in steady flow conditions using computational fluid dynamics. *Journal of Biomechanics*, 35, 713-717.

Corresponding Author: Rajat Mittal; mittal@jhu.edu

Brown, R.M., Counsilman, J.E. (1970) The role of lift in propelling the swimmer. In J.M.Cooper(Ed.) Selected Topics on Biomechanics, Proceedings of the CIC Symposium of Biomechanics, 179-188. Chicago: The Athletic Institute.

Cappaert, J. and Rushall, B.S. (1994) Biomechanical Analysis of Champion Swimmers. Spring Valley: Sport Science Associates.

Counsilman, J.E. (1968) The Science of Swimming. Englewood Cliffs: Prentice Hall, Inc.

Counsilman, J.E. (1971) The application of Bernoulli's principle to human propulsion in water. In J.P.Clarys and L.Lewillie(Eds.), Swimming I, 59-71. Brussels, Belgium: Universite Libre de Bruxelles.

Dong, H. Bozkurttas, M. Mittal, R. Madden P. and Lauder G. V. "Computational modeling and analysis of the hydrodynamics of a highly deformable fish pectoral fin", *Journal of Fluid Mechanics*, 2010, Vol. 645, pp. 345-373.

Ito et al. (2003) Ito, S., Okuno, K. (2003) A fluid dynamical consideration for armstroke in swimming. In J. C. Chatard(Ed.), Proceedings of the IX International Symposium on Biomechanics and Medicine in Swimming, 39-44. France: University of Saint-Etienne.

Kolmogorov, S.K., Duplishcheva, O.A., (1992) Active drag, useful mechanical output and hydrodynamic force coefficient in different swimming strokes at maximum velocity. *Journal of Biomechanics*, 25, 311-318.

Mittal, R., Dong, H., Bozkurttas, M., Lauder, G.V., Madden, P. (2006) Locomotion with Flexible propulsors:II. Computational modeling of pectoral fin swimming in sunfish. *Bioinspiration & Biomimetics: Learning from nature, vol. 1*, S35-S41, Boulder, 26 June 2006.

Mittal, R., Dong, H., Bozkurttas, M., Najjar, F.M., Vargas, A., von Loebbecke, A. (2008) A versatile sharp interface immersed boundary method for incompressible flows with complex boundaries. *Journal of Computational Physics*, **227**, 4825-4852.

Rushall, B.S., Sprigings, E.J. (1994) A re-evaluation of forces in swimming. *Journal of Swimming Research*, **10**, 6-30.

Schleihauf, R.E., (1979) A hydrodynamic analysis of swimming propulsion. In J.Terauds and E.W.Bedingfield (Eds.), *Swimming III,* 70-110. Baltimore: University Park Press.

Toussaint and Beek (1992) Toussaint, H.M., Beek, P.J. (1992) Biomechanics of competitive front crawl swimming. *Sports Medicine*, 13, 8-24.

Corresponding Author: Rajat Mittal; mittal@jhu.edu

von Loebbecke, A., Mittal, R., Mark R. and Hahn, J. "A computational method for analysis of underwater dolphin kick hydrodynamics in human swimming", *Sports Biomechanics*, 2009a, 8(1), pp. 60-77.

von Loebbecke, A., Fish, F.E., Mark, R., Mittal, R. (2008) "A comparison of the kinematics of the dolphin kick in humans and cetaceans", *Human Movement Science*, 2009b, Vol.28, pp.99-112.

von Loebbecke, A., Mittal, R., Fish, F.E. and Mark, R. "Propulsive Efficiency of the Underwater Dolphin Kick in Humans", *Journal of Biomechanical Engineering*, 2009c, Vol. 131(5), 054504

Wood, T.C. (1979) A fluid dynamic analysis of the propulsive potential of the hand and forearm in swimming. In J.Terauds and E.W.Bedingfield(Eds.), Swimming III, 62-69. Baltimore: University Park Press.

Corresponding Author: Rajat Mittal; mittal@jhu.edu