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Human Kinetics
REVIEW

Effective Propulsion in Swimming: Grasping the Hydrodynamics of Hand and Arm Movements

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In this paper, a literature review is presented regarding the hydrodynamic effects of different hand and arm movements during swimming with the aim to identify lacunae in current methods and knowledge, and to distil practical guidelines for coaches and swimmers seeking to increase swimming speed. Experimental and numerical studies are discussed, examining the effects of hand orientation, thumb position, finger spread, sculling movements, and hand accelerations during swimming, as well as unsteady properties of vortices due to changes in hand orientation. Collectively, the findings indicate that swimming speed may be increased by avoiding excessive sculling movements and by spreading the fingers slightly. In addition, it appears that accelerating the hands rather than moving them at constant speed may be beneficial, and that (in front crawl swimming) the thumb should be abducted during entry, catch, and upsweep, and adducted during the pull phase. Further experimental and numerical research is required to confirm these suggestions and to elucidate their hydrodynamic underpinnings and identify optimal propulsion techniques. To this end, it is necessary that the dynamical motion and resulting unsteady effects are accounted for, and that flow visualization techniques, force measurements, and simulations are combined in studying those effects.

Keywords: swimming, hydrodynamics, hand

Improvements in swimming can be achieved by reducing resistance or by optimizing propulsion, both of which require an in-depth understanding of the hydrodynamics of swimming. Wei et al provided a historical overview of fluid-dynamics-related aspects of human swimming research.[1] In addition, Takagi et al reviewed swimming studies, employing advanced methodologies such as computational fluid dynamics (CFD) and particle image velocimetry (PIV).[2] The focus of the present review is on the hydrodynamic characteristics of a swimmer's hand and arm because, to date, most previous studies on the hydrodynamics of swimming focused on manual propulsion, which plays a major role in the overall propulsion in all stroke types, albeit in different degrees. An increasing number of studies apply advanced numerical and experimental techniques borrowed from the field of fluid dynamics, such as flow visualization, to better understand the swimmer–flow interaction. Recently, Gomes et al provided a review about the manual propulsion in swimming, which only included 6 studies comparing steady and unsteady conditions.[3] The present review provides an up-to-date overview and discussion of the current knowledge about this topic with the aim to identify lacunae in current methods and knowledge, and to distil useful practical guidelines for swimmers and coaches.

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Concepts

Swimmers move their limbs through the water to propel themselves forward. Unlike other cyclic sports, such as running and cycling, the swimmer pushes off against a nonfixed environment, which is brought into motion by the swimmer's movements.[4] These movements generate hydrodynamic forces acting on the limbs, which contribute to the swimmer's forward motion.[5]

Studying propulsion in swimming requires analysis of the forces acting on the entire swimmer and those acting locally on the propulsive body parts such as the hand, as illustrated in Figure 1.

Drag and Lift

Schleihauf[6] was the first to analyze the forces acting on the swimmer's hand and arm in terms of drag and lift. The drag force is always exerted in a direction opposite to that of the motion and can therefore act as a propulsive force, given that the hands and arms often move in a direction opposite to that of the body. Drag can be divided into several components, including pressure drag (form drag), viscous drag (skin friction), wave drag, and minor effects like lift-induced drag. A general expression for the drag and lift forces is:

$$F_{D,L} = \frac{1}{2}\rho A v^2 C_{D,L}, \quad (1)$$

where ρ is the fluid density, A is the surface as projected on a plane perpendicular to the mean flow (for the drag force), v is the velocity, and C_D/C_L is the drag/lift coefficient. The drag coefficient is a dimensionless quantity that includes all aforementioned drag components. It is unique for every object and depends, among other aspects, on the object's shape and the Reynolds number of the flow,

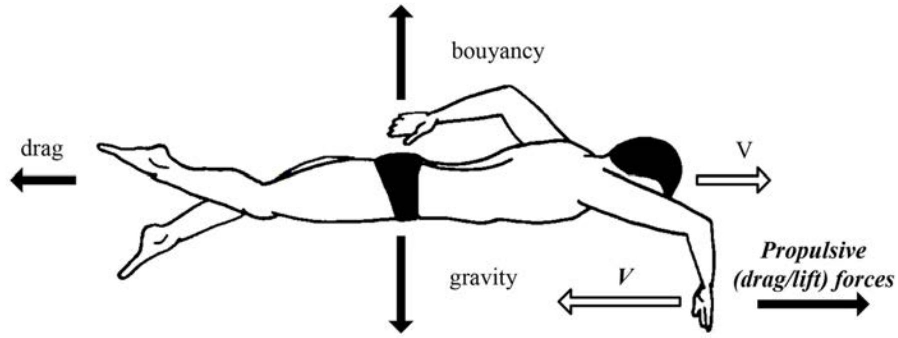

Figure 1 — Schematic overview of the forces acting on the entire swimmer and the swimmer's hand. The propulsive force can be either drag- or lift-based.

a dimensionless quantity representing the ratio between inertia and viscous forces in the fluid. The Reynolds number is defined as $Re = \rho UL / \mu$, with U and L representing the characteristic velocity and length scale, respectively, and μ the dynamic viscosity. At low Reynolds numbers, the flow is laminar, while at high Reynolds numbers, it becomes turbulent. The Reynolds number can be used for scaling to achieve dynamic similarity between experiments and simulations; to this end, the Reynolds number is often a nondimensional velocity.

The lift force is the component of the force perpendicular to the direction of motion. In the studies discussed in this review, 2 definitions of lift are employed. Most studies use the force component perpendicular to the plane of hand motion to define lift, here referred to as 2D lift. There is, however, a second lift component (also perpendicular to drag), which should be included for completeness. Only some studies[5,7] have determined this so-called 3D lift, which is the resultant force of both lift components.

When acceleration is introduced, just using C_D and C_L is insufficient to describe the propulsion dynamics,[8] because acceleration leads to additional forces caused by acceleration of the water around the swimmer. Adding this concept to Equation 1 leads to:

$$F(t) = am_a + \frac{1}{2} A\rho v(t)^2 C_D(v(t)), \qquad (2)$$

where a is the acceleration, $C_D(v(t))$ is the velocity-dependent drag coefficient, and $m_a = C_a \rho V$ the added mass,[9] with V representing the body volume and C_a a constant indicating the ratio of added mass and the total mass of the body.

Swimming researchers have debated fiercely whether drag or lift prevails in generating propulsion.[6] At the dawn of swimming research this debate was mainly theoretical in nature. With the advent of systems for estimating and measuring the drag and lift forces it gradually gained empirical ground. Thus far, several studies have been conducted to assess the influence of arm speed, acceleration, and orientation on the drag and lift forces acting on the hand.

Hand Orientation

In swimming research different hand orientations are considered, which are defined in terms of pitch angle, sweepback angle, and angle of attack. Unfortunately, the definition of these terms varies in pertinent literature. Figure 2 provides a schematic illustration of the most common definitions.

The pitch angle (Figure 2C) is the angle between the flow vector and the hand plane (xy-plane), while the sweepback angle (Figure 2B) is the angle between the y-axis and the projection of the flow vector on the hand plane. The angle of attack (Figure 2A) is actually a combination of the pitch and sweepback angle, but can be defined as the angle between the flow vector and the y-axis of the hand.

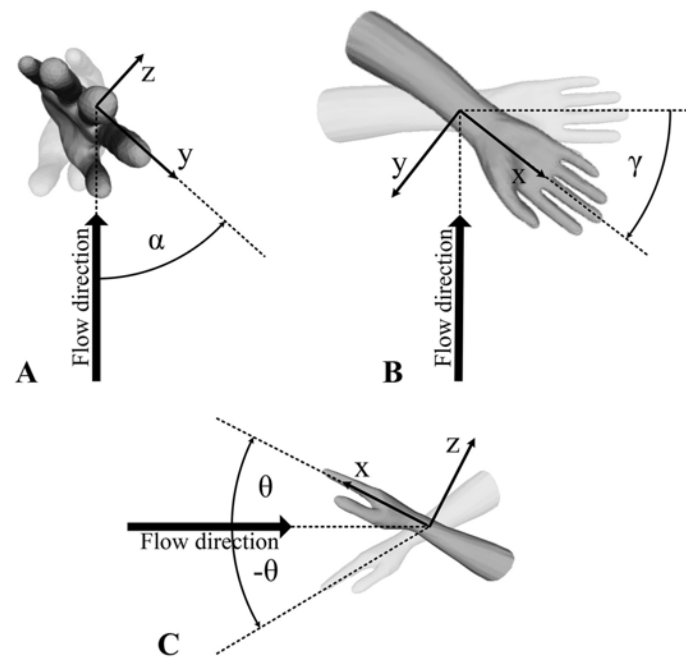

Figure 2 — Definitions of different hand orientations. (A) Angle of attack, α (thumb leading: α = 0–90°, little finger leading: α = 90–180°). (B) Sweepback angle, γ (with γ = 0°). (C) Pitch angle, θ (with γ = 90°). The x-axis is defined positive from the center of the wrist to the long finger's tip, the y-axis is defined positive from little finger to thumb side, and the z-axis is defined positive from the palmar to the dorsal side of the hand. (B and C based on formulation by Schleihauf[6] and Sanders[33].)

Overview

Following the focus of the present review, we conducted an extensive but nonsystematic literature search for experimental and numerical studies focusing on the hydrodynamic properties of hand and arm movements in swimming, regardless of stroke type, as we were interested in generic hydrodynamic properties. The search was nonsystematic since a significant portion of the pertinent literature has been published in books and book chapters. In the following 2 subsections the experimental and numerical methods of the reviewed studies are discussed. The Findings section shows the corresponding results in an organized manner.

Experimental Studies

Table 1 provides an overview of experimental studies on the hydrodynamics of hand and arm movements in swimming. Most experiments were performed using hand and arm models in water

Table 1 An overview of the experimental studies on the hydrodynamics of the swimmer's hand

Article	Method	Research Topics	Result/Conclusions
Schleihauf[6]	Hand model in water channel force measurement	Steady state sweepback + pitch angle, finger spread, thumb position	C_D increases with θ; C_L characteristics vary with γ; C_L increases up to θ ≈ 40°; hand shape influences C_D and C_L
Berger et al[5]	Hand model in towing tank force measurement	Steady state sweepback + pitch angle, velocity, immersion depth	C_D increases with θ, C_D max at α = 90°; C_L max at α = 50,130°
Payton & Bartlett[13]	Video-recording of hand movements	Estimating propulsive forces from 3D kinematic data	Average measurement errors of drag and lift coefficients were 27 and 20%, respectively
Sanders[33]	Hand model in towing tank force measurement	Sweepback + pitch angle, acceleration	C_D increases with θ; forces are dependent on orientation; acceleration coefficients required for better estimates
Takagi et al[30]	Hand model in wind tunnel pressure measurement	Steady-state thumb position, angle of attack	Thumb position influences hydrodynamic forces on the hand, especially lift generation
Takagi & Sanders[40]	Swimmer in water channel pressure measurement	Unsteady 4 strokes	Pressure method could be useful in describing technique; peak force and direction are different regarding level of swimmer
Sidelnik & Young[27]	Hand model in towing tank force measurement	Unsteady sculling motion, finger spacing	Small finger spread (10°) creates more stroke force than fingers held together
Gardano & Dabnichki[21]	Hand model in wind tunnel force measurement	Steady-state pitch angle, elbow angle	Drag profiles differ substantially with elbow angles
Kudo et al[10]	Hand model in water channel force + pressure measurement + kinematic analysis	Unsteady imitate pull-down phase front crawl by simple rotation at various accelerations	Fluid forces can be accurately predicted with pressure method, validity confirmed with kinematic data
Kudo et al[32]	Hand model in water channel pressure + force measurement	Steady-state surface penetration, angle of attack	Wave drag largely increases C_D of the hand
Matsuuchi et al[44]	Swimmers in water channel PIV	Unsteady front crawl swimming	Directional change of hand induces high momentum due to vortex shedding
Nakashima & Takahashi[11]	Robot arm in water channel force measurement	Unsteady 4 strokes + 2 variations front crawl	Formulation of the fluid force model, validity confirmed because model reproduced experimental results
Takagi et al[41]	Robot arm in water channel pressure measurement + PIV	Unsteady semicircles around shoulder joint, perpendicular to water surface	Vortex generation due to unsteady hand movement is essential for generating high hydrodynamic forces
Kudo et al[38]	Hand model in water channel force measurement	Unsteady acceleration, angular motion, general motion (imitate front crawl)	Hydrodynamic forces are in general bigger under accelerated conditions
Takagi et al[42]	Swimmer in water channel pressure measurement + PIV	Unsteady sculling motion	Vortex capturing induces high hydrodynamic forces
Takagi et al[43]	Robot arm in water channel force + pressure measurement + PIV	Unsteady front crawl (2 types)	I and S stroke have different mechanism to produce unsteady forces
Gourgoulis et al[37]	3D path reconstruction swimmer kinematic data	Unsteady front crawl	Acceleration is important determinant in generation of propulsive forces

Abbreviation: PIV = particle image velocimetry.

Note. An indication of the experimental method, research topics, and main results is given.

channels (or, in some cases, wind tunnels). To examine unsteady effects, the hand models were attached to a robotic arm or other mechanical device to generate accelerations, rotations, or complete underwater strokes. Some studies used real swimmers for mapping a complete stroke or swimming technique. The main advantage of using models instead of humans is that models can be more readily equipped with sensors and trials are more reproducible.

Forces can be measured with load cells and dynamometers attached to the model. Alternatively, pressure can be measured with sensors placed at strategic positions on the hand's surface. The obtained local information may help to estimate the propulsive forces acting on the hand when combined with other measurement techniques or simulations.

Using arm models to examine the optimal propulsion technique is helpful, especially when their motion resembles actual swimming dynamics. However, many studies are still limited in identifying drag and lift coefficients and/or forces. State-of-the-art experiments use PIV, a nonintrusive method for determining instantaneous local fluid velocities,[12] for visualizing the flow structures (including vortices) originating at, and shed from, the hand. In this way, fundamental insights can be gained into the creation of propulsive forces, which are currently lacking.

An alternative method involves the registration of a swimmer's hand and arm movements using 2 or more video cameras. Three-dimensional hand and arm trajectories and orientations can then be reconstructed from the markers visible in the video images. Using a database of drag and lift coefficients obtained at different velocities, accelerations, and orientations, the hydrodynamic forces acting on the hand can be estimated. A major limitation of this kinematic method is that the drag and lift forces/coefficients are not measured directly but estimated, while their magnitudes are known to depend strongly on the shape, orientation, and motion characteristics of the hand. Payton and Bartlett[13] estimated the hydrodynamic forces acting on the hand, using the force coefficients of Schleihauf[6] and found that the errors in estimating the lift and drag coefficients were 27% and 20%, respectively.

Numerical Studies

In CFD the hydrodynamic equations describing the flow, the (incompressible) Navier-Stokes equations, are solved numerically.[14] The increase in computational power over the last decades has led to the emergence of numerical approaches to study the hydrodynamics of the swimmer's hand and arm, starting with the pioneering work of Bixler and Schloder.[15] Table 2 provides an overview of related research since then.

The main advantage of using a numerical approach is that a more comprehensive dataset can be obtained than is feasible in real-life measurements. In general, velocities, velocity gradients, and pressure data (and thus forces) can be acquired in the complete computational domain and on the body's surface. However, careful attention should be paid to the numerical settings (temporal and spatial resolution, domain and grid sizes, and so on, in relation to the problem at hand). In choosing the spatial resolution one should decide whether to consider small-scale flow structures. If so, a sufficient number of nodes (ie, high enough spatial resolution) must be used to resolve them. Moreover, stability requirements impose the following time step condition, $\Delta t < h / v$, with Δt representing the time step, h being the smallest mesh element, and v the velocity.[14]

Most numerical studies on the topic[7,15–21] have been performed using a commercial code named Fluent, which involves a finite volume approach to solve the Navier-Stokes equations in which all turbulence is modeled (RANS). Most studies applied a (k-ε) turbulence model to model the small scales of the flow. In this way, computational time is saved compared with direct numerical simulation (DNS), which solves the Navier-Stokes equation exactly up to the smallest scales. The disadvantage of this model is the poor performance for flows that are unconfined or have large strains. Two studies[22,23] on this topic are based on an in-house code using the immersed boundary (IB) method,[24] which was developed to deal with complex moving bodies. The main advantage of IB is easier grid generation, since the grid does not necessarily have to conform to the mesh of the immersed body.

A recent study[25] used the smoothed particle hydrodynamics (SPH) method, which is mesh free and uses "sampling" particles following the hydrodynamic equations of motion to describe the flow. This method is suitable for modeling the flow around complex and deforming bodies and at the free surface of the flow. A major disadvantage is the limited accuracy at small scales compared with grid-based methods.

CFD is a very promising technique for studying the hydrodynamics of swimming, especially because current computational power allows simulations to better mimic human 3D movements, including determining optimal propulsion paths, hand and arm configurations, and speed and acceleration profiles of the arm during the stroke. However, in applying CFD, several challenges remain. For example, accurately solving boundary-layer effects at the scale of a complete swimmer or even a body part requires many computational cells (fine meshes) and takes (too) much computational time. Furthermore, the swimmer, moving at the air-water interface, is still too complex to be simulated, which is a considerable limitation, since free surface effects are important in swimming given the influence of wave drag.[26] Ultimately, theoretical models should be evaluated using real-world experimental data.

Findings

The empirical and numerical studies considered in this review focused on the hydrodynamic properties (typically drag and lift) for different hand orientations, sizes, shapes, and velocities under steady-state conditions, as well as on the effects of accelerations and unsteadiness. Some studies focused more fundamentally on vortex generation and their shedding during the arm stroke. First, the effects of hand shapes in steady-state approaches are discussed. Next, the influence of orientation is considered, followed by studies considering different velocities. Finally, investigations considering full stroke analyses and unsteady effects like accelerations are examined.

Finger Spacing

Several studies[6,16,17,27–29] investigated the effect of finger spacing on the hydrodynamic forces acting on the hand. Figure 3 summarizes the results on the effect of finger spacing on the propulsive capabilities of the hand. Using different C_D values, all studies, except for Schleihauf,[6] reported evidence for an optimal finger spacing. Due to a blockage effect of the flow between the fingers, the functional area of the hand is increased with a small finger spread.

Schleihauf[6] was the first to study the drag and lift coefficients of the hand of a swimmer. He conducted experiments with 3 different finger spacings (0, 6.35, and 12.7 mm) for different angles of attack, α (Figure 2); only the results for $\alpha = 90°$ are included in Figure 3. No advantage of finger spread was found. Closed fingers gave the highest drag coefficient. The highest lift coefficients were

Table 2 An overview of the numerical studies on the hydrodynamics of the swimmer's hand

Article	Software	Method	Grid	Topics	Results/Conclusions
Bixler & Schloder[15]	Fluent	Finite volume, k-ε, RNG and RSM turbulence model, 2D	Adaptive 5394	Hand represented by disk acceleration	Propulsive drag increases under accelerated conditions
Sato & Hino[31]	-	Finite volume	Unstructured, polyhedron steady: $1.8 \cdot 10^5$ unsteady: ~$5.9 \cdot 10^4$	Steady-state + unsteady angle of attack, velocity, acceleration, front crawl	Drag in accelerated conditions higher, unsteady approach is required.
Bixler & Riewald[7]	Fluent	Finite volume, k-ε turbulence model, 2nd order	Adaptive $2.15 \cdot 10^5$	Steady-state velocity, angle of attack, hand/forearm	Drag is dominant (max at $\alpha = 90°$), C_L max at α = 55,140°
Rouboa et al[18]	Fluent	Finite volume, k-ε turbulence model, 2D	Adaptive, trapezoidal $4 \cdot 10^5$	Steady-state velocity, angle of attack + acceleration	More propulsive force under accelerated conditions
Gardano & Dabnichki[21]	Fluent	Finite volume, k-ε turbulence model	-	Steady-state pitch angle, elbow angle	Drag profiles differ substantially with elbow angles
Marinho et al[19]	Fluent	Finite volume, k-ε turbulence model	Adaptive (high velocity + pressure), hybrid $2 \cdot 10^5$	Steady-state thumb position, angle of attack	Adduction is beneficial at high α, abduction when lift is important
Minetti et al[28]	Ansys CFX	SST turbulence model	Tetrahedral $6.5 \cdot 10^5$	Steady-state finger spacing, velocity	C_D max at finger spread of 12°, wake region bigger in optimal spacing
Marinho et al[16]	Fluent	Finite volume, k-ε turbulence model, 2nd order	Adaptive (high velocity + pressure), hybrid	Steady-state finger spread, angle of attack	Fingers slightly spread creates more force
Marinho et al[20]	Fluent	Finite volume, k-ε turbulence model	Adaptive (high velocity + pressure), hybrid $9 \cdot 10^5$	Steady-state velocity, angle of attack, sweepback angle	C_D max at $\alpha = 90°$, C_L max at $\alpha = 45°$, drag always higher
von Loebbecke & Mittal[23]	In-house IB solver Mittal & Iaccarino (2005)	Finite difference, immersed boundary	Nonuniform, Cartesian ~$4.2 \cdot 10^6$	Unsteady arm pull styles front crawl and backstroke	Lift is a major contributor to thrust, also in a "drag-based" technique
Lorente et al[29]	-	2D	-	Steady-state cylinder (finger) spread	An optimal finger spacing exists (twice boundary layer)
Bilinauskaite et al[17]	Fluent	Finite volume, k-ε turbulence model, 2nd order, PISO coupling	Adaptive (high velocity + pressure) ~$8.4 \cdot 10^5$	Steady-state thumb position, finger spread, orientation crawl	Drag force affected by velocity, hand shape, orientation
van Houwelingen[22]	In-house IB solver Verzicco	Fractional step, immersed boundary, SGS turbulence model	Cartesian ~$8.1 \cdot 10^6$	Steady-state angle of attack, velocity + acceleration	Drag is dominant (max at $\alpha = 90°$), C_L max at α = 60°
Cohen et al[25]	-	Lagranian mesh free approach (SPH), fluid acceleration included	$5 \cdot 10^6$ SPH particles spaced 20 mm	Unsteady, complete swimmer, freestyle, free surface included	Propulsion based on drag and lift; largest propulsion during push and pull

Abbreviations: IB = immersed boundary; RNG = renormalization group; RSM = Reynolds stress model; SST = shear stress transport; PISO = Pressure-Implicit with Splitting of Operators; SGS = subgrid-scale; SPH = smoothed particle hydrodynamics.

Note. An indication of the numerical methods, grid, studied topics, and main results is given.

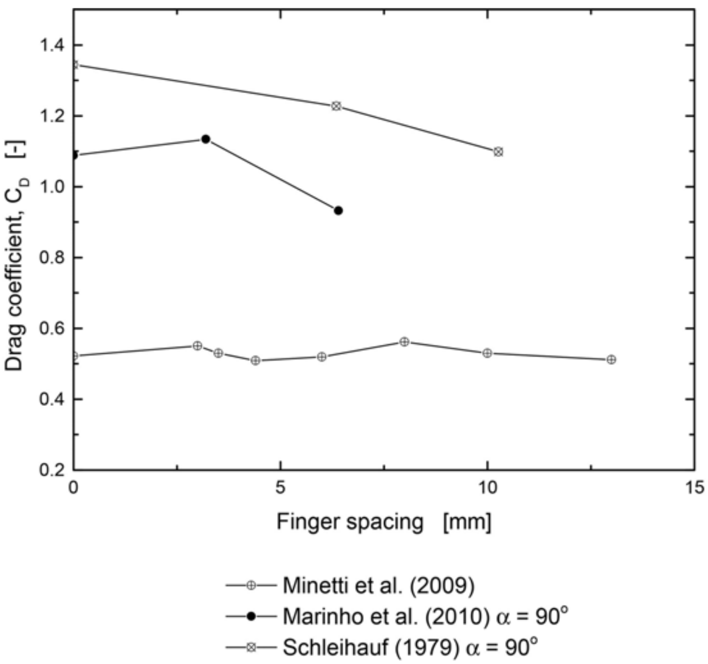

Figure 3 — Drag coefficient (see Equation 1: $c_D = \frac{2F_D}{\rho A v^2}$) as a function of finger spacing. Notes: Schleihauf[6] C_D based on projected area hand, definition finger spacing not known. Minetti et al[28] C_D based on paddling surface, interdigit distance at midfinger horizontally measured from the middle point of the shorter of adjacent fingers. Marinho et al[16] C_D based on projection area of the model for different orientations, intrafinger distance from fingertip to fingertip.

also obtained with fingers closed, although values of the lift coefficient became similar around $\alpha = 80°$.

Several steady-state simulations have been conducted on hands with different finger spacings.[16,28] Minetti et al[28] performed simulations at 4 different velocities (1.5–3 m/s) but found no significant dependence on velocity and therefore averaged all results over all 4 velocities. Marinho et al[16] performed simulations for 3 finger spacings at different angles of attack at a velocity of 2 m/s. Both studies showed an increase in drag coefficient for a small finger spread, with an interdigit spacing of circa 8 mm and 3.2 mm, respectively. Moreover, the wake region (ie, the region of disturbed flow behind a body) with optimal finger spacing increased up to 20% in Minetti et al.[28] Jets were produced between the fingers preventing the formation of vortical structures in the wake, which reduces the flow separation.[28] Usually, flow separation (ie, fluid flow detaching of an object) results in an increased pressure differential between the back and front of an object and thus an increased drag force. Marinho et al[16] suggested that the water cannot flow freely through the fingers due to a turbulent flow forming a barrier. The beneficial effects seemed to be minor; increases of 4%[16] and 9%,[28] respectively, were found relative to the C_D of closed or wide open fingers, without taking the uncertainties (the standard deviation in Minetti et al[28] was ~3%) into account. Possible discrepancies among studies could be related to differences in finger spacing definition.

Bilinauskaite et al[17] performed steady-state simulations with 4 different hand models (spread/closed fingers and thumb abduction/adduction) in 9 orientations and flow velocities corresponding to different phases of the front crawl. Although the accuracy of the resulting drag force/coefficients and pressure measurements appear to have been limited, they concluded from the results obtained that spread fingers lead to the highest pressure forces and generate the highest drag force, in accordance with experimental results.[16,28]

Lorente et al[29] performed 2D simulations around cylinders (ie, simplified fingers). Simulations in this study were performed with Reynolds numbers between ~20 to 100, whereas in actual swimming, Reynolds numbers of ~10^4 are obtained around the fingers. The total force was found to be 50% larger for optimally-spaced fingers compared with fingers closed. Optimal spacing was found to correspond to twice the boundary layer thickness.

In studying the effect of finger spread, the small flow structures around the fingers are important. Therefore, the adopted numerical approach to this problem is critical. At regular swimming velocities, the boundary layer thickness around the fingers could become rather small, ~0.5 mm. To solve the boundary layer at least 5–10 nodes are required across the boundary layer, a fact that must be considered in choosing proper spatial resolution and time steps in the simulation. Also, the numerical method of choice can have an influence in solving near-wall effects (ie, close to the body) and turbulence, like the RANS modeling in Fluent simulations and the applied turbulence models.

In another study, based on an unsteady approach, an arm model with closed fingers and 10° finger spacing was towed through a water tank.[27] The arm model was connected to a motor, which generated sculling motions at a (hand) slip speed of 0.5 m/s. The total force during a cycle was measured for both models, resulting in a higher force for the model with small finger spread.

Most studies concluded that a small finger spread leads to increased propulsive forces. Whether this is related to a blockage effect of the boundary layer (unlikely due to small thickness) or to vortical structures emerging between the fingers or in the wake of the hand is unclear and should be studied more closely.

Thumb Position

Several studies[6,17,19,30] examined the effect of thumb position. Thumb position appears to have a marked influence on the drag and lift characteristics of the hand, which changes with hand orientation, implying that the position of the thumb should be altered during the stroke to optimize propulsion. It has been suggested that thumb abduction could enhance lift forces by delaying the boundary layer separation.[7]

Schleihauf[6] performed experiments with different thumb positions (50, 75, and 100% abducted) at a range of angles of attack (and $\gamma = 0°$). For small angles of attack, the lift coefficient was significantly larger for a fully abducted thumb. For larger angles of attack, a partially-abducted thumb was beneficial. Takagi et al[30] performed experiments with 2 hand models, 1 with an abducted thumb and 1 with an adducted thumb (held against the hand) at the full range of angles of attack (and $\gamma = 0°$). Thumb abduction proved advantageous in generating lift forces for angles of attack in which the thumb is leading. With a little finger leading orientation, thumb adduction was found to be more favorable in generating lift and drag forces. The increase in lift force was explained by a pressure increase on the palm side and a pressure decrease on the back of the hand. Marinho et al[19] studied 3 different thumb positions (fully abducted, partially abducted, and adducted) at 3 angles of attack and a range of velocities. They found a minor increase of the drag coefficients for thumb adduction. Lift coefficients were increased with the thumb abducted at angles of attack of 0° and 45°. Although the outcome varied for different hand shapes, velocities, and stroke phases, Bilinauskaite et al[17] found the highest drag coefficient during the pull phase for a hand orientation with the thumb adducted.

From these findings it may be concluded that the thumb should be abducted in those parts of the stroke in which lift force plays an important role (eg, entry/catch and upsweep in front crawl) in generating forward propulsion. Conversely, the thumb should be adducted in those parts of the stroke in which drag force prevails (pull phase in front crawl).

Hand Orientation

Establishing changes in drag and lift coefficients in steady-state conditions with orientation, especially angle of attack (at $\alpha = 0°$), is a common research theme. Figures 4A and 4B show the results of numerical studies,[7,22,31] while Figures 4C and 4D show the results of experimental studies.[5,6,30–32]

As expected, all studies obtained the highest drag coefficients around $\alpha = 90°$, with the hand palm almost perpendicular to the line of motion. When the little finger or thumb was facing the flow, the drag coefficient was lowest. Extremes in the lift coefficient were found around $\alpha = 50°$ (thumb leading) and around $\alpha = 130°$ (little finger leading). Most studies did not report a marked difference between those extremes; some studies[5,7,30] reported larger extremes in the lift force when the little finger was leading. In general, the values of the drag coefficient were found to be (much) larger than the lift coefficient for almost all angles of attack. Other studies

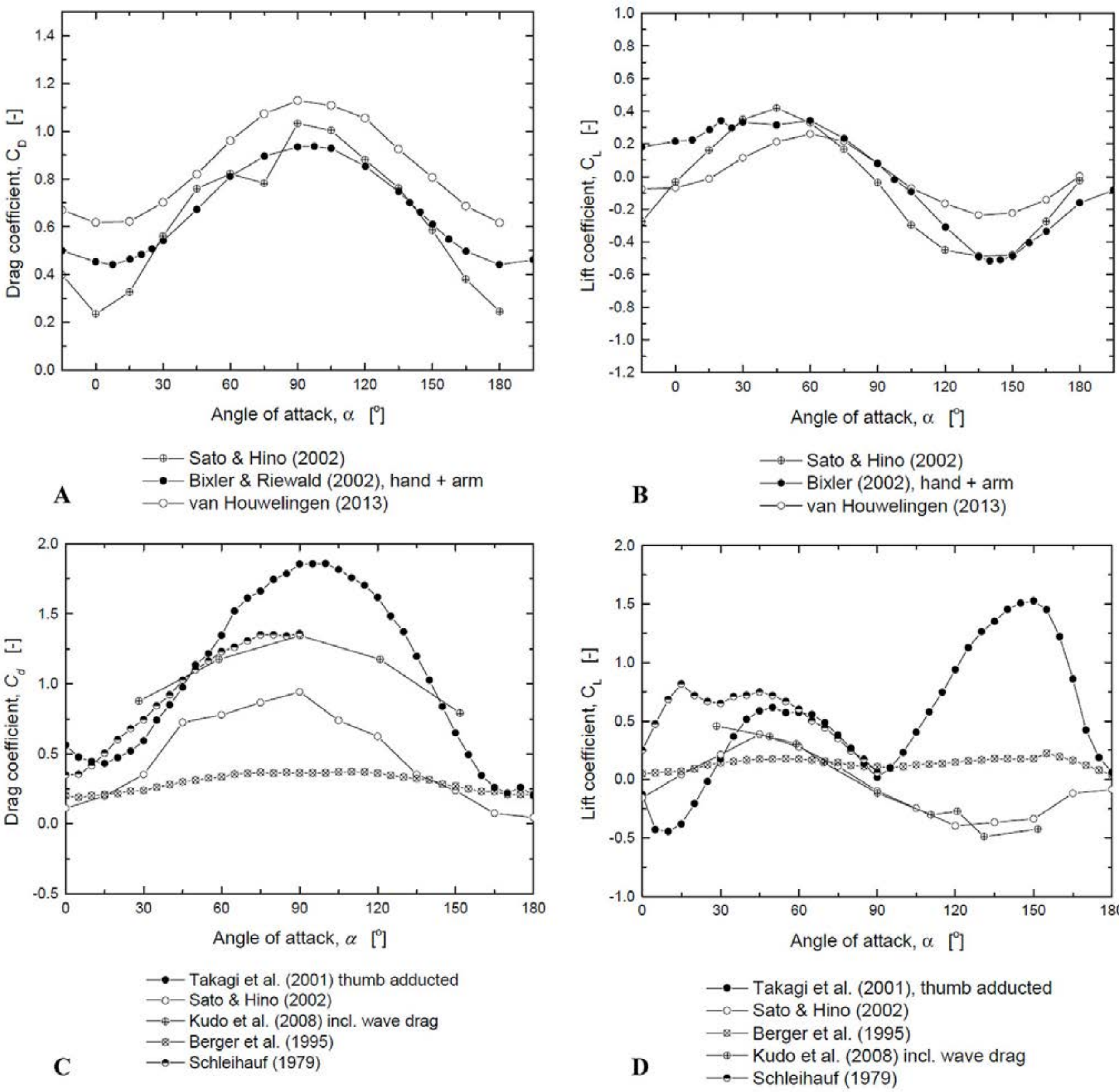

Figure 4 — Drag and lift coefficients as a function of angle of attack (at $\gamma = 0°$). Lift coefficients are calculated with 2D lift force unless otherwise indicated. (A) Drag coefficient, numerical studies. (B) Lift coefficient, numerical studies. (C) Drag coefficient, experimental studies. (D) Lift coefficient, experimental studies. Notes: Schleihauf[6] C_D based on projected area. Berger et al[5] C_D based on wet surface area at 1 m/s, 3D lift. Takagi et al[30] C_D based on total hand plane area at 12 m/s in air (equals 0.8 m/s in water). Sato and Hino[31] C_D based on maximum projected area at 1 m/s. Bixler and Riewald[7] C_D based on maximum projected area at 2 m/s. Kudo et al[32] C_D based on area of the hand part of the model at 1.5 m/s. Van Houwelingen[22] C_D based on maximum projected area at 1.83 m/s.

considering the angle of attack reported similar findings.[16,18–20] Marked discrepancies exist in the data reported, particularly in Figure 4D. Besides differences in measurement and data analysis, these discrepancies seem to be caused by differences in the lift definition used. For example, Berger et al[5] calculated force coefficients based on the total wet surface area instead of the (maximum) projected area and used the so-called 3D lift, while others used the 2D lift.

Other orientation parameters of interest are the pitch and sweepback angle. Schleihauf[6] studied 8 sweepback angles ($0° \leq \gamma \leq 315°$) at a range of pitch angles ($0° \leq \theta \leq 90°$). The general trend was that lift coefficients increased up to $\theta \approx 40°$, with the peak heights varying for sweepback angle. Drag coefficients increased with increasing pitch angle. Berger et al[5] studied 145 relevant combinations of pitch and sweepback angle ($-20° \leq \theta \leq 80°$, $0° \leq \gamma \leq 360°$) and obtained similar findings. They also found that the lift coefficient roughly increased with increasing pitch angle up to θ ~50°.

Sanders[33] examined angles between –90° and 90° and sweepback angles between 0° and 360° and, in accordance with the aforementioned studies, found that the force magnitudes were considerably larger for pitch angles $\theta = 90°$ or $-90°$. For $\theta = 45°$, large lift forces resulted for sweepback angles of $\gamma = 45°$ and 135°, which is likely to occur during the insweep of breaststroke and butterfly and the outsweep of the backstroke.

Gardano and Dabnichki[21] determined the effect of elbow angles and pitch angles on the force coefficients for steady-state flow conditions in both experiments and simulations. The highest drag coefficients were obtained for pitch angles of roughly 90° for all elbow angles, while the lift coefficients peaked at angles around 40°. Higher drag coefficients were found with an elbow angle of 160° at the complete range of pitch angles compared with elbow angles of 135° and 180°. This suggests that a slightly bent elbow within the arm stroke might be beneficial, although further research is required to substantiate this suggestion. In general, it can be safely concluded that elbow bending changes the hydrodynamic properties of the hand and arm; therefore, elbow bending should be taken into account in studying the (undoubtedly stroke dependent) optimal arm propulsion in swimming.

Lift seems to have lower values than drag for most orientations. However, the hands have been shown to contribute more to the generation of lift forces than the forearm[5,7] and can therefore certainly contribute to propulsion by means other than just a “simple” pull–push stroke. An important parameter to consider in this context is the resultant force in the propulsion direction (ie, a vector addition of lift and drag), but unfortunately none of the studies cited have calculated this resultant force.

Although the results indicate that drag force is the most important propulsion component, some authors recommended sculling motions (S-stroke) to generate as much lift force as possible.[5,33] Swimming with sculling motions would be more efficient than swimming with a straight pull stroke: with higher lift forces, the loss of energy would be minimal.[5] In a similar vein, it has been suggested that swimming with large pitch angles may be inefficient.[34]

In contrast, Wei et al[1] argued that an S-stroke is unlikely to be more effective than a straight pull. Although assuming equal values for lift and drag and equal arm speeds in the 2 strokes, the lift generated by the transverse motion of the hand cannot compensate for the thrust loss by the decrease of arm speed in the swimming direction. However, no definite conclusions regarding drag-based or lift-based propulsion can be drawn from these steady-state results.

Velocity

Several studies[5,7,18,19,22,31] examined drag and lift coefficients as a function of velocity (with *Re* ranging between ~$2 \cdot 10^4$ and $4 \cdot 10^5$ based on a typical hand palm width of 0.08 m). Figure 5 shows some

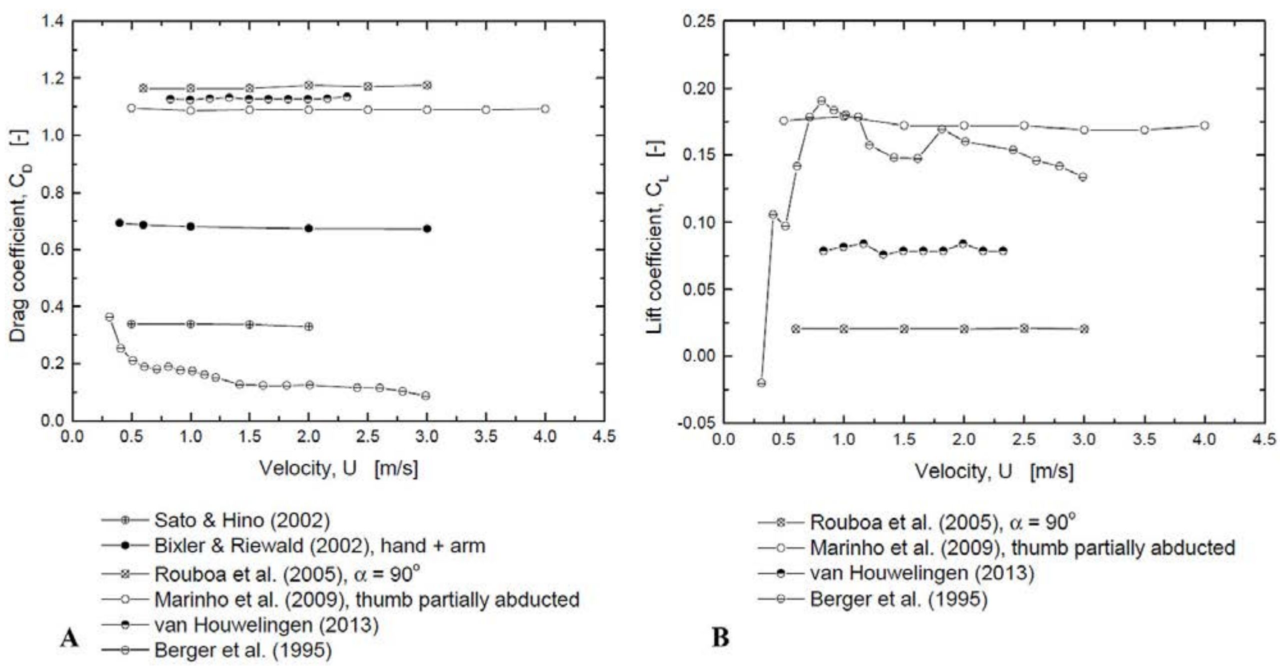

Figure 5 — The drag (A) and lift (B) coefficient as a function of velocity. In most of these studies, the hand palm was facing the flow ($\alpha = 90°$). Notes: Berger et al[5] $C_{D,L}$ based on total wet surface area. Sato and Hino[31] different hand model than for angle of attack simulations, $C_{D,L}$ based on maximum projected area. Bixler and Riewald[7] simulations performed at $\alpha = 45°$ and $\gamma = 0°$, $C_{D,L}$ based on maximum projected area. Rouboa et al[18] 2D model. Marinho et al[19] $C_{D,L}$ based on projection area of the model for different angles. Van Houwelingen[22] C_D based on maximum projected area.

of the drag coefficients obtained. None of the numerical studies found a clear dependence on velocity, irrespective of orientation and hand shape.[7,18,19,22,31] A minor decrease of the drag coefficient with increasing velocity was reported,[7,31] but this effect was deemed unimportant.[7] The only experimental study[3] showed that C_D and C_L changed little within the velocity range from 0.7 m/s to 3.0 m/s (*Re* ~$5.6 \cdot 10^4$–$2.4 \cdot 10^5$). At velocities below 0.7 m/s, C_D and C_L strongly depended on velocity.

Across these studies, different hand models and definitions of surface area (Equation 1) were used (see Figure 5), which could account for the discrepancies in the values of C_D and C_L reported. C_D and C_L also depend on the Reynolds number. In similar experiments for steady spheres and cylinders, the drag coefficient decreases asymptotically with increasing *Re*.[35] At low *Re* the drag is mainly due to skin friction, whereas at high *Re* the contribution of skin friction is almost negligible. At a critical *Re* (~$3 - 4^2\ 10^5$) the boundary layer around the object starts to separate and becomes turbulent, resulting in a dip of the drag coefficient (a phenomenon called drag crisis[35,36]).

Similar phenomena could arise around the hand, although difficult to interpret due to its geometry. In the cited studies, the value of *Re* roughly varied from $2^2\ 10^4$ to $4^2\ 10^5$ (based on velocities ranging from 0.3 to 5 m/s). Applying accurate simulations (including resolving the eventual drag crisis) at these *Re* requires fine meshes around the hands, accurate time stepping, and a right choice of turbulence modeling to solve the very small flow scales and boundary layers. Confirmation of the trend observed by Berger et al[5] would be useful. Maybe the resolutions in the simulations were too coarse and the turbulence was not solved neatly due to the turbulence modeling, resulting in a constant C_D rather than a trend.[7,18,19,22,31] No dependence on velocity would imply there would be no benefit in terms of drag to move the hands at certain velocities.

Acceleration

As mentioned, deviations from uniform motion could induce additional effects on the force (coefficients). Several studies[15,18,31] examined the effect of linear acceleration on the drag force using CFD and reported higher drag forces in the accelerated conditions compared with constant velocity without reporting the accompanying lift force.

Bixler and Schloder[15] represented the hand as a disk and applied a linear motion using different (uniform and sinusoidal) acceleration patterns with similar magnitudes of acceleration as those generated by front crawl swimmers. The propulsive drag (averaged over the propulsive phase of the stroke) increased by as much as 40% compared with the quasi-steady condition. A sinusoidal increasing acceleration pattern showed the highest relative increase.

Sato and Hino[31] used accelerations ranging between 0 and 5 m/s^2 in their simulations. Drag force and drag coefficient increased with increasing acceleration, which was explained as an added mass effect. Rouboa et al[18] ran simulations at an acceleration of 6 m/s^2 at 3 angles of attack (0°, 90°, and 180°) and reported a circa 22.5% higher propulsive force in the accelerated condition compared with the steady-state condition (at 2 m/s). Table 3 summarizes the numerical studies that considered accelerated and steady-state conditions.

Sanders[33] established the effect of orientation and linear acceleration on the drag and lift forces acting on the hand in experiments (velocities ranging from 0.45 to 0.6 m/s and accelerations between –3 and 7 m/s^2, far below actual swimming velocities). A least squares fitting procedure was used to determine a drag/lift and added mass coefficient similar to Equation 2. Sanders[33] concluded that added mass coefficients should be incorporated in models to accurately predict hand forces from kinematic data. The methods and results of Sanders[33] have been implemented in a kinematic study to examine the influence of acceleration on the relative contributions of drag and lift to propulsion (resultant force) in various phases of front crawl swimming (downsweep, insweep and upsweep).[37] The effects of acceleration were highly dependent on the phase of the stroke and were different for drag and lift; also, negative contributions were found. For example, the drag force during the downsweep was significantly smaller.

Kudo et al[38] studied the effect of hand acceleration in general motion (combination of angular arm motion with uniform flume velocity to mimic front crawl) on the hydrodynamic forces acting on the hand. The drag and lift forces during the stroke were, in general, larger for acceleration. According to the authors, the unsteady flow in the accelerating condition caused an additional inertial force (also during deceleration stages) due to vortex generation. They further suggested that changes in hand orientation throughout an accelerated underwater stroke might lead to the generation of additional vortices behind the hand and/or an added mass effect. The shedding of these vortices could lower the pressure on the dorsal side, which would lead to an increase of the pressure difference over the hand.

All results indicated that accelerating the hand might enhance the propulsive force compared with using a constant hand speed and that acceleration should be included in models to accurately study propulsive forces. Conclusions concerning practical applications should be drawn with caution. Although acceleration produces higher drag forces, it could also lead to a shorter duration of force application and thus a lower net power generation. Also, the effect of acceleration and induced added mass effects on the entire body of the swimmer[39] should be taken into account when drawing conclusions.

Full Stroke Analysis and Unsteady Effects

The flow field around a swimmer is highly unsteady because the directional changes of the hand produce vortex motions. For an adequate interpretation of the propulsion force, these unsteady properties should be taken into account.

Takagi and Sanders[40] were among the first to quantitatively evaluate the propelling characteristics of a full stroke. They measured the pressure at the hand's surface in 4 swimming strokes to estimate the force output and found that the peak force generation was dependent on the swimmer's skill level. This method may help to describe stroke techniques in terms of force generation, but it does not allow quantifying the forces along the entire axis of the hand.

Kinematic analysis of the front crawl provided no clear statements regarding the predominance of drag versus lift forces during a full stroke.[37] Drag forces were dominant in the middle part of the stroke, whereas lift forces prevailed during the entry and the final part.[37] Sato and Hino[31] carried out a fully unsteady simulation of a swimming stroke. Stroke trajectories of the hand were measured in 3D and simulated in the hand model. Based on these simulations, the hydrodynamics forces and thrust efficiency (defined as time averaged thrust force/time averaged total force) were calculated. A swimmer with an elongated accelerated motion pattern showed better efficiency and higher time averaged forces.

In swimming science (as well as practice) there has been a longstanding debate whether the arms should be pulled backward on a more or less straight line (I-stroke) to obtain drag-based propulsion, or should involve "sculling" motions (S-stroke) to generate more lift-based propulsion. In the S-stroke, the hand sweeps inward toward the center line of the body, followed by an outsweep during

Table 3 Overview of the studies comparing linear accelerated and steady-state conditions

		v Initial (m/s)	*v Final* (m/s)	*a* (m/s²)	Pattern	*(Averaged) FD* (N)	*Increase* (%)
Bixler & Schloder[15]	Forces are time averaged over duration pull, compared with interpolated quasi-steady condition	1.7	2.2	1.66	Uniform (constant stroke length: 0.58 m)	46	**15**
		1.7	2.94	4.96		74	**27**
		2.43	3.6	6.2		113	**16**
		1.7	3.6	8.6		105	**36**
		2.43	4.87	15.25		150	**31**
		1.7	4.87	17.91		178	**43**
Sato & Hino[31]		2.84	5.84	7.5 (0.4 s)	Uniform	215	**4**
				11.25 (0.266 s)		230	**12**
				15 (0.2 s)		242	**17**
				~23.5–0 (0.2 s)	Sinusoidal decreasing	283	**37**
				~0–23.5 (0.2 s)	Sinusoidal increasing	282	**38**
Rouboa et al[18], α = 90°	Compared at 2 m/s with nonaccelerated condition	0	2	1	Uniform	70.9	**6.1**
				2		77.6	**16.1**
				3		83.6	**25.1**
		0.5		4		87.9	**31.6**
				5		94.4	**41.2**
				6		54.4	**22.5**

Note. The results from Sato and Hino[31] were digitized. The relative increase of the drag force compared with the steady-state condition is reported in the last column and printed in bold face.

the last phase of the stroke. It is assumed that this diagonal motion combines the effect of drag-based propulsion and propulsive lift forces related to the transverse motion of the hand.

Von Loebbecke and Mittal[23] analyzed 2 pull styles in both front crawl and backstroke. A front crawl and a backstroke technique were designed to produce drag-based thrust forces. The other techniques aimed to create lift forces for propulsion. It was found that lift forces played a prominent role in producing thrust in all techniques (the lift/drag-ratio ranged from 1.1 to 3.3). Nevertheless, the strokes designed to produce "drag-based" propulsion showed markedly higher thrust. The "lift-based" propulsion techniques resulted in a reduction of drag contribution and total thrust. In other words, pronounced sculling motion reduced the thrust production of the arm stroke.

Flow visualization based on PIV allows measurement and analysis of the unsteady effects (including vortex shedding) originating around the hand and other body parts, and could help unravel the origin of (unsteady) forces. Several attempts have been made in this direction.

Takagi et al[41] investigated the unsteady forces using a robotic arm preprogrammed to perform simple 2D motions in a water channel. The elbow angle was fixed at 90° and the hand moved in semicircles perpendicular to the water surface. At a certain stage a rapid increase in the drag/lift force was found, resulting from vortices produced at the hand (see Figure 6). First, a counter-clockwise vortex at the little finger side and a clockwise vortex at the thumb side were observed (t_1). The leading edge vortex on the little finger side was then shed and in between the pair of vortices a jet flow was induced (t_2), resulting in momentum (contribution to lift). Simultaneously, a marked pressure decrease at the dorsal side of the hand occurred, resulting in an increased pressure differential (contribution to drag).

Takagi et al[42] also analyzed the sculling motion of real swimmers to unveil the propulsion mechanism behind this technique. The highest contributions were found during the in-scull (see Figure 7). When the hand started to move toward the center line of the body, it encountered a pair of vortices (t_1) generated during the out-scull motion. During the in-scull (t_2), a counter-clockwise leading edge vortex occurred at the dorsal side of the hand. The pressure at the dorsal side of the hand dropped, resulting in an increased pressure differential between the palm and dorsal side of the hand, leading to greater fluid forces. Moreover, wake capturing (ie, interaction with a preceding wake) occurred simultaneously, which also might explain the increase in fluid forces.

Takagi et al[43] examined the differences in hydrodynamic force generation between the I- and S-stroke technique using a preprogrammed robotic arm. A different mechanism for generating unsteady forces was found for both strokes (see Figure 8). In the I-stroke a so-called Karman vortex street was created, implying that vortices were shed alternately from the thumb and little finger side. A large pressure differential was found between the hand palm and dorsal side of the hand acting as a drag (propulsive) force. The peak force occurred around maximum hand velocity, and might be explained by the fact that drag force increases with the velocity squared. In the S-stroke, lift force was generated when the hand changed direction from insweep toward outsweep. At the moment of directional change of the hand a clockwise vortex was shed from the thumb side of the hand. A new counter-rotating vortex was formed near the hand, resulting in a pressure decrease, which generated a lift force contributing to propulsion.

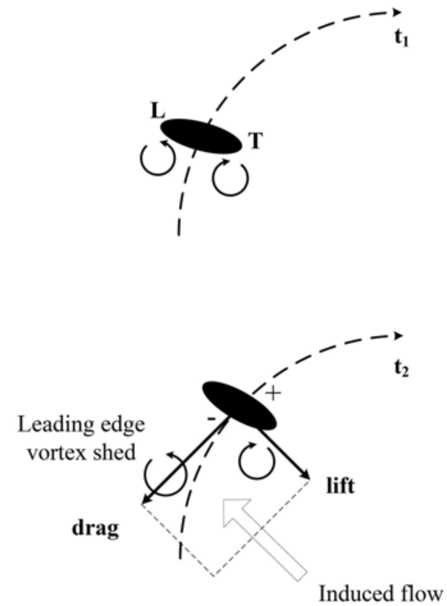

Figure 6 — Schematic of the findings of Takagi et al.[41] L indicates the little finger side, T the thumb side of the hand. + and – indicate high and low pressure areas at the hand, respectively.

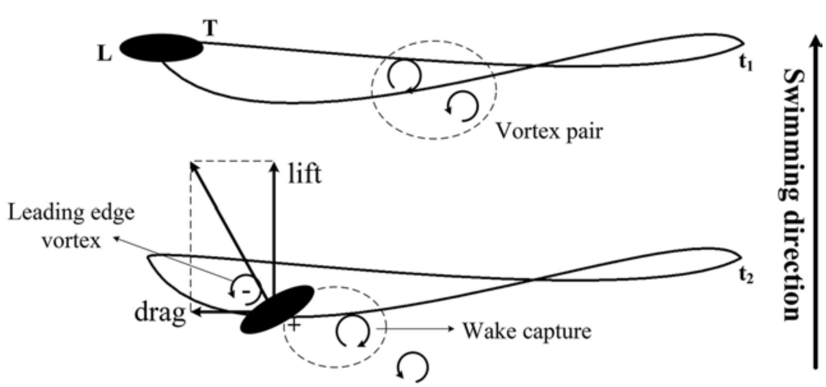

Figure 7 — Schematic of the findings of Takagi et al.[42] L indicates the little finger side, T the thumb side of the hand.

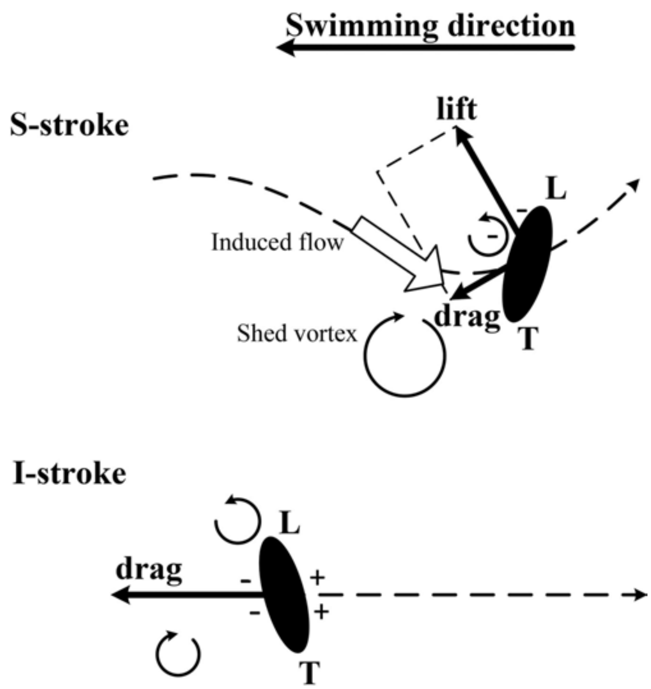

Figure 8 — Schematic of the findings of Matsuuchi et al[44] and Takagi et al.[43] L indicates the little finger side, T the thumb side of the hand.

Matsuuchi et al[44] obtained a similar result using PIV measurements on front crawl swimmers to capture the flow around the hands. Strong momentum was generated from the transition of insweep to outsweep. During this transition a large vortex was generated near the hand and subsequently shed by a directional change of the hand. At the instance of shedding, a counter-rotating vortex was created around the hand. Between the 2 vortices a jet flow was generated, resulting in a force in the swimming direction (since jet velocity is directed opposite to swimming direction). This resembles the situation of the S-stroke in Figure 8, but with a different explanation.

It can be concluded that vortices generated by the unsteady hand movements (like directional changes) play an essential role in generating high hydrodynamic forces. Therefore, it is likely that swimmers exploit these unsteady forces. Without the use of advanced measurement techniques, such as PIV, the origin and understanding of these unsteady hydrodynamic forces could not have been revealed.

Conclusions

The preceding discussion of the full stroke analysis and unsteady effects sets both the standard and the agenda for future research. Advances in understanding the hydrodynamics of swimming are closely related to the improvements in (and introduction of new) measurement techniques and simulations. Steady-state studies found that drag contributions were generally higher for most orientations, implying that a more "drag-based" technique would be recommendable. However, it has also been found that vortex generation, shedding, and capturing can lead to increased pressure differentials, increased momenta, and thus higher hydrodynamic forces. Therefore, unsteady effects must be considered when seeking to identify optimal propulsion techniques. A similar conclusion was reached by Toussaint and Truijens.[45]

Both in physical and computational arm models, significant strides forward have been made. Nowadays, the complex hydrodynamics of swimming can be adequately captured in models, rendering these techniques suitable to answer questions about swimming propulsion in a more valid and conclusive manner. Combining studies using CFD and experimental investigations using flow visualization techniques and force/pressure measurements provides a complete picture of the result (propulsive force) and the source of propulsion (vertical structures in the unsteady flow), and seems optimal to study the generation and optimization of propulsion in swimming.

Due to the increase of computational power, camera resolutions, and improvements in data transfer, both (PIV) experiments and simulations can be performed at larger scales and/or in greater detail than before. The time at which the flow around a full (moving) swimmer can be simulated is approaching. The same holds for a fully-resolved flow field around the swimmer in experiments using PIV.

The challenge for training and coaches is to determine the optimal technique for an individual swimmer. Developing specific guidelines regarding the optimal technique for an individual swimmer will remain difficult, since there are so many aspects that should be taken into account in such an optimization problem. However, only science can deliver evidence-based knowledge for improving propulsion. Which practical and general guidelines can be gleaned from the present literature review that may assist coaches in making their swimmers swim faster? There seems to be sufficiently firm evidence for the following guidelines, keeping in mind that most studies to date focused on front crawl swimming. Swimmers should not make excessive sculling motions, as these may impede drag generation. Although the current evidence is still inconclusive, it appears that with a small finger spread, higher propulsive forces can be obtained. Furthermore, some evidence exists for 2 additional guidelines. Swimmers should not move their hands at a constant speed through the water, but rather try to accelerate their arms throughout the stroke, because acceleration plays an important role in generating propulsive forces. All studies considering acceleration found an increase in force generation, suggesting that accelerating the hand may be beneficial. However, acceleration may have negative effects on lift and drag as well. Moreover, thumb position seems to have a marked effect on the hydrodynamic characteristics of the hand. Since these characteristics change with hand orientation, the thumb position should presumably alter orientation during the stroke.

In principle, the conclusions are not different for sprinters or distance swimmers. For example, when a swimmer (who could supply a certain amount of force to the water) is able to increase the drag on the hand/arm, the slip velocity of the hand must decrease. This lowers the power loss related to the propulsive phase and therefore more power is left to generate forward speed, which is beneficial for a sprinter and distance swimmer alike. Of course, a distance swimmer should spread the energy over a longer time span and a sprinter could apply higher forces during the strokes.

Future studies should help to answer questions such as: What should be the path and velocity profile of the hand? How should hand shape (thumb position, finger spread) vary throughout the stroke, but also elbow bending since it affects the hydrodynamic properties of the arm? Future studies should also determine the role of the entire swimmer in producing propulsive force. After all, when the whole body is accelerating, unsteady effects may also occur at the body. Will these effects be beneficial or disadvantageous? Also, the interaction of the hand with vortices generated at other body parts and vice versa[25] is of interest to swimming scientists and practitioners, since pertinent studies have shown that vortex interaction could produce large hydrodynamic forces.[46]

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