HYDRODYNAMIC DRAG AND LIFT FORCES ON HUMAN HAND/ARM MODELS

Monique A. M. Berger, Gert de Groot and A. Peter Hollander
Faculty of Human Movement Sciences, Vrije Universiteit, Amsterdam, The Netherlands

Abstract—Forces acting on the forearm and hand during swimming can be decomposed into drag forces and lift forces. In this study drag and lift forces were measured on two models of a human hand and forearm when towed in a towing tank. To compare the results of models with different size at different velocities force data were normalized to drag and lift coefficients \( (C_d \text{ and } C_l) \). Influence of the orientation of the model with respect to the flow, velocity, size of the model and the relative contribution of the hand and forearm on \( C_d \) and \( C_l \) were studied. The orientation of the model with respect to the line of motion was varied by rotating the models around three axes, and quantified using the angle of pitch \( (AP) \), the angle between the hand plane and flow \( (AP) \), and the sweep-back angle \( (SB) \). The influence of propulsive forces produced by arm and hand on \( C_d \) and \( C_l \) was examined by varying the immersion depth of the model. In the experiments where only the hand was towed \( C_d \) was about the same as for the condition where hand and forearm together were towed. \( C_l \) reached the highest values in the experiments where only the hand was towed. The hands are the main contributors for the generation of lift force.

INTRODUCTION

Propulsion in freestyle swimming is mainly generated by movements of the arms (Adrian et al., 1966; Hollander et al., 1987). In particular, the hand and forearm move backward eliciting forces that tend to propel the body forward. Parts of the arm close to the shoulder move forward and encounter drag forces tending to resist the body’s forward motion (Hay and Thayer, 1989).

For many years the predominant theory for swimming was that propulsion is achieved by the drag force created by the hand moving backwards. The direction of the drag force is opposite to the line of motion of the hand. However, not only drag forces are induced by the arm movements; from hydrodynamic theories it is known that the hand and arm also have the capability of generating a force perpendicular to their line of motion. Although this force is known as lift force, it is not always directed vertically (Lighthill, 1986). Brown and Counsilman (1970) and Counsilman (1971) were the first to point out the importance of lift forces in generating propulsion in human swimming. Counsilman (1971) stated that propeller-like, diagonal sculling motions were used by skilled swimmers, acknowledging the importance of lift forces. In freestyle swimming, hands follow a curvilinear path, creating lift forces acting perpendicular to the direction of motion of the hand. From a theoretical point of view it has been shown that propulsive forces in human swimming can be more efficiently derived from these lift forces than from drag forces (de Groot and van Ingen Schenau, 1988). This idea originates from Lighthill (1986), who demonstrated that blade designs (such as propeller blades), capable of achieving very low ratios of drag to lift, may be successful in minimizing the energy loss to the water.

To elaborate the propulsive forces in freestyle swimming force measurements on a hand/arm model can be done in a laboratory situation. Schleihauf (1979) investigated lift and drag forces on hand models in an open-water channel. The force \( (i.e. \text{the drag coefficient } C_d \text{ and the lift coefficient } C_l) \) on a plastic resin model of an adult human hand was measured at certain steady-state flow conditions for different hand orientations. For estimating the magnitude of propulsive forces produced by arm and hand together during swimming, Schleihauf used preliminary data of drag and lift coefficients for the forearm (Schleihauf et al., 1983). However, these values of \( C_d \) and \( C_l \) for the forearm were never published. The assumption that the force on the total arm can be derived from the separate values for \( C_d \) and \( C_l \) for the hand and for the forearm may be incorrect, due to interaction effects.

The way Schleihauf measured the force vector on the hand is not completely described in the literature and it is possible that he did not use the correct method. To obtain the magnitude and direction of the drag and lift force it is necessary to measure the force components in three directions and decompose the resultant force into a lift and drag component. In this...
study force data were obtained with a six-component dynamometer. In addition to replicating (partially) the experiments of Schleihauf two models (different in size) of hand and forearm were towed in a towing tank at different velocities. To compare results of different models with different size at different velocities force data were normalized to $C_d$ and $C_l$.

In this study attention is focused on the influence of (a) the orientation of the model with respect to the flow, (b) velocity, (c) size of the model and (d) relative contribution of hand and forearm to the coefficients of drag and lift.

**METHODS**

**Hand/arm models**

Models of hand and forearm were made of a rubber cover, normally used for the construction of prostheses, pulled over a rod and filled with wax. Two different models were used. Model 1 was more or less representative of a woman's hand/arm and Model 2 of a man's hand/arm. Hand width, defined as the distance across the back of the hand between metacarpophalangeal II and metacarpophalangeal V, was 9 and 11 cm, respectively. The distance from the tip of the third finger to the elbow joint was 51 cm for Model 1 and for Model 2 the length of forearm and hand was 26 cm. At equal length (38 cm) the surface area $S$ was 899 cm$^2$ for Model 1 and 964 cm$^2$ for Model 2. The surface $S$ was estimated by taking the circumference $y_i$ of the model every 2 cm along its length. According to the surface of a small trapeziform solid of revolution, the surface area was calculated by:

$$S = l \left[ \sum_{i=0}^{n} y_i - 0.5(y_0 + y_n) \right]$$

where $l = 2$ cm, $n$ is the number of trapeziform segments, $y_0$ and $y_n$ are the circumferences of the model at the extreme points and $y_i$ is the circumference of the model taken at every 2 cm along the length of the arm. The immersion depth determines the value of the number $n$ and equation (1) gives the wet surface area.

The shape of both models was about the same: the wrist was placed in a mid-position; the interphalangeal joints were extended and the metacarpophalangeal joints were slightly flexed.

**Force measurements**

The measurements were performed in a towing tank of the Delft University of Technology in the Netherlands. The tank consisted of a basin, 3 m wide, 85 m long and 1.2 m deep. The temperature of the water was 18°C. The basin was provided with an electrically driven carriage (5.5 x 3.5 m) running over the full length of the basin at controllable speed (see Fig. 1). On the carriage a dynamometer was mounted with accompanying equipment for force registration. Forces were measured in three directions (mutually perpendicular) by a six-component dynamometer provided with strain gauges (see Fig. 1): $F_x$ was registered by two force transducers, $F_y$ by one, and the vertical component $F_z$ by three. (This set-up also allows the determination of the moments of the force but this aspect was not elaborated in this study.) By applying known loads in the $x$-, $y$- and $z$-direction the dynamometer was calibrated. Each force transducer was reset to zero at the beginning of each run of the carriage. Sampling of the force signals (sample frequency 40 Hz) started after the towing carriage had reached a constant velocity, opposite to the positive $x$-direction of the dynamometer. The forces were sampled over a 20 s period and time-averaged. The registered force component in the $x$-direction, $F_x$, was opposite to the line of motion, and therefore equals the drag force, $F_d$. The lift force, $F_l$, perpendicular to the drag force, was defined as the vector sum of $F_x$ and $F_y$ (forces in a vertical plane). Therefore the magnitudes of these vectors are:

$$F_d = F_x,$$

$$F_l = \sqrt{F_y^2 + F_z^2}.$$  

Coefficients of drag ($C_d$) and lift ($C_l$) were calculated according to the following equations (Alexander, 1977):

$$C_d = \frac{F_d}{0.5 \rho v^2 A_w},$$

$$C_l = \frac{F_l}{0.5 \rho v^2 A_w},$$

where $F_d$ is the drag force (N), $F_l$ the lift force (N), $\rho$ the density of water ($= 998.6 \text{ kg m}^{-3}$ for 18°C), $v$ the velocity of the model/carriage (m s$^{-1}$), and $A_w$ the wet surface area (m$^2$), obtained with equation (1).

**Experiments**

The models were attached to the dynamometer with a special calibrated device allowing rotation of the model (a) around the vertical axis over an angle $\psi$, (b) around the sagittal axis (perpendicular to the vertical axis) over an angle $\varphi$, and (c) around the longitudinal axis of the forearm over an angle $\theta$ (see Fig. 1). Rotation around this longitudinal axis was done with well-defined angles $\theta$, ranging from 0 to 180° at increments of 5 or 10° at relevant angles $\psi$ and $\varphi$ of $-30, 0$ and $30°$; only combinations at which the palmar side of the hand faced more or less the direction of the flow were measured. At these orientations the models were towed in the tank at a velocity of 1 m s$^{-1}$. The maximal immersion depth used was 4 cm less than the lengths of the models.

In order to investigate the influence of speed, Model 1 was towed at different velocities ranging from 0.3 to 3.0 m s$^{-1}$ (with increments of 0.1 or 0.3 m s$^{-1}$). This was done at an arbitrarily chosen orientation of the model: $\psi = 0°$, $\varphi = -30°$ and $\theta = 160°$.

The relative contribution of hand and forearm of Model 2 was investigated by varying the immersion depth (by changing the water level in the tank) at orientations $\psi = \varphi = 0°$ and $\theta$ ranged from 0 to 180°. Three immersion depths were studied: an immersion
depth of 51 cm, an immersion depth of 41 cm and an immersion depth of 22 cm, where only the hand was immersed.

Flow direction

The angles $\psi$, $\varphi$ and $\theta$ determine the orientation of the model with respect to the towing direction. In order to describe the orientation in a more general way, the direction of the water flow vector (opposite to the towing direction) was calculated in a local co-ordinate system on the hand. According to the literature (e.g. Schleihauf, 1979), this direction is expressed by two angles: AP (angle of pitch) and SB (sweep-back angle).

A local (right handed) Cartesian co-ordinate system on the left hand of the model was defined in the following way (see Fig. 2(a)):

- $x'$-axis: positive direction pointing from styloid process of ulna to metacarpophalangeal V. The plane of the hand was then defined by the $x'$-axis and the distal end of the middle finger.
**Fig. 2.** (a) Local co-ordinate system on the hand (x'-, y'- and z'-axis). The definition of SB angles is indicated, with the arrows representing the direction of the water flow. (b) Calculation of angle of pitch (AP) and sweep-back angle (SB) in a local co-ordinate system on the hand.

z'-axis: perpendicular to the plane of the hand, positive direction pointing from dorsal to palmar side of the hand.

y'-axis: perpendicular to the x'- and z'-axis, positive direction pointing from the ulnar to the radial side of the hand.

In this local co-ordinate system the direction of the velocity vector v of the water flow is determined. The angle of pitch (AP) is the angle between the flow vector v and its projection v_{xy} on the x'y'-plane. The sweep-back angle SB is the angle between v_x and the negative y'-axis. Thus, these angles are calculated from [see Fig. 2(b)]

\[
AP = -\sin^{-1} \frac{v_x}{|v|} \quad \text{and} \quad SB = \cos^{-1} \frac{v_y}{v_{xy}} \quad (6)
\]

where \(v_x\) and \(v_z\) are the y'- and z'-component of the velocity vector of the water flow. AP is defined positive when the palm of the hand is facing the line of motion, and negative when the dorsal side of the hand is facing the line of motion. Characteristic values of SB are indicated in Fig. 2(a).

The orientation of the local hand co-ordinate system with respect to the coordinate system of the towing carriage (i.e. the direction of flow) was obtained as follows. At \(\psi = \phi = \theta = 0\) the orientation of x'y'z' was determined. For any value of \(\psi, \phi\), and \(\theta\) the orientation of the local co-ordinate system with respect to the flow was calculated by applying the appropriate rotation matrices. The local co-ordinate system was not aligned with the rotation axes of the device on which the model was attached: at \(\psi = \phi = \theta = 0\) AP = -20° and SB = 10°.

A number of results were obtained at \(\psi - \phi - 0\) and varying values of \(\theta\). This can be interpreted roughly as a variation in AP at SB = 0° if 0 < \(\theta < 90\)° (thumb-leading situation) and at SB = 180° if 90 < \(\theta < 180\)° (little finger-leading situation). For simplicity most of the results are presented as a function of \(\theta\).

**RESULTS**

Reproducibility of the force measurements was examined by measuring the force components \(F_x, F_y,\) and \(F_z\) for Model 1 on two different days. The absolute difference averaged over the measured angles was calculated. The absolute mean difference for \(F_x\) was 0.13 ± 0.09 N, 0.05 ± 0.06 N for \(F_y\) and 0.28 ± 0.25 N for \(F_z\). This results in a possible error less than 10% of the mean values of \(F_x\) and \(F_y\) and consequently also for \(C_d\) and \(C_t\).

Typical curves of recorded force components \(F_x, F_y,\) and \(F_z\) of Model 1 are presented in Fig. 3. The forces are given in relation to the angle \(\theta\) at a velocity of 1 m s\(^{-1}\). In the left part of Fig. 3 forces are presented for thumb-leading orientations, and in the right part for little finger-leading orientations. From these figures it can be seen that the drag force \(F_d\) (= \(F_x\)) increases until the palm of the hand is faced almost perpendicular to the line of motion (\(\theta = 90\)°, corresponding to \(AP = 64.5\)°, \(SB = 342\)°). The \(F_c\)-component of the lift force shows a sine-wave behaviour, with extreme values at an angle \(\theta\) of 55 and 155° (corresponding to \(AP = 31\)°, \(SB = 328\)° and \(AP = 48\)°, \(SB = 193\)°, respectively). Variations in \(F_z\) are very small in these observations. In this paper, the direction of the lift force will not be elaborated further. Attention will only be paid to the magnitude of the force.

Figure 4 shows values of \(C_d\) and \(C_t\) calculated, with the forces presented in Fig. 3, according to equations (4) and (5), versus rotation angles \(\theta\). From these curves it can be noticed that according to the \(F_x\) curve (Fig. 3), \(C_d\) increases until the palm of the hand is faced perpendicular to the line of motion (\(\theta = 90\)°). In the thumb- and little finger-leading situation, at equal angle \(\theta\), the values of \(C_d\) are approximately the same. The \(C_t\) curve shows the highest values at \(\theta = 55\)° and 155° approximately, corresponding to \(AP = 31\)°, \(SB = 358\)° (thumb-leading) and \(AP = 48\)°, \(SB = 193\)° (little finger-leading), respectively.
Drag and lift forces

For the hand/arm models, changes in $C_d$ and $C_l$ due to the orientation of the models were determined. In Fig. 5 the results obtained from both models are combined since no influence of the models on $C_d$ and $C_l$ could be demonstrated (see below). By changing $\psi$, $\phi$ and $\theta$, 145 relevant combinations of AP and SB were tested. Only those combinations of AP and SB which seem relevant in swimming were measured. With the help of a biharmonic spline interpolation method (Sandwell, 1987) values for $C_d$ and $C_l$ could be obtained for a wide range of AP and SB angles. The rectangle in Fig. 5 shows the combinations of AP and SB where the measurements were done. The values of $C_d$ and $C_l$ are presented in Fig. 5(a) and (b), respectively. It shows that at all values of SB $C_d$ increases at increasing AP. $C_l$ increases until AP is approximately 50°; then it decreases again.

For an arbitrary chosen orientation of the model ($\psi = 0°$, $\phi = -30°$ and $\theta = 160°$ which yields AP = 43°, SR = 150°) a series of measurements with Model 1 was carried out at velocities ranging from 0.3 to 3 m s$^{-1}$. The results of these measurements are presented in Fig. 6. For velocities higher than 0.7 m s$^{-1}$ the values of $C_d$ and $C_l$ seem only slightly dependent on velocity. This result was confirmed by a number of experiments at velocities of 0.7, 1.0 and 1.5 m s$^{-1}$ ($\psi = \phi = 0°$ and $\theta$ varies from 0 to 180° with increments of 10°). At lower velocities $C_d$ and $C_l$ seem to be strongly dependent on velocity.

In order to make a comparison between the two models they were towed at the same immersion depth (50 cm). The resulting difference in wet surface area was found to agree with the observed difference in force values: almost equal values of $C_d$ and $C_l$ were observed (Fig. 7). A difference in $C_l$ could only be observed at very low (0–20°) or very high (160–170°) values of $\theta$.

The contribution of the forearm and hand to the lift and drag coefficients was investigated by varying the immersion depth of the model. Changing depth, the relative contribution of the forearm to the shape of the whole model changes. As can be seen in Fig. 8 a smaller immersion depth appears to make the drag coefficient more sensitive to direction. For the lift coefficient the influence is even more pronounced. $C_l$ was higher for the condition where only the hand was
DISCUSSION

The measured forces on the hand/arm model are decomposed into drag and lift forces. The magnitude of lift and drag force is dependent on the orientation of the model. In Fig. 3 it can be seen that the drag force $F_d$ increases to a maximum at an orientation of the model where the hand plane is almost perpendicular to the direction of the flow ($\theta = 90^\circ$, $AP = 64.5^\circ$, $SB = 342^\circ$). That maximum is a result of the maximal value of the frontal surface area of the hand at that orientation. Because of the choice to normalize the forces taking into account the wet surface area, such orientation effects will become apparent in the drag coefficient $C_d$ and lift coefficient $C_l$. Figure 5, derived through a biharmonic spline interpolation, illustrates how $C_d$ and $C_l$ depend on the angle of pitch ($AP$) and the sweep-back angle ($SB$). It should be noted that the interpolated values of $C_d$ and $C_l$ are not always reliable in the areas where no measurements were done (for example, negative values of $C_d$ and $C_l$ sometimes found by means of this interpolation technique are even impossible). However, as stated earlier only the combinations of $AP$ and $SB$ which seem relevant in swimming were measured and therefore $C_d$ and $C_l$ values obtained in these regions are realistic. In general, it can be stated that at the various values of $SB$, the dependency of the coefficients on $AP$ emerges as Fig. 4 shows: $C_d$ has its maximum values, if the flow vector is at right angles to the hand plane, whereas $C_l$ has its maximum values, if the hand plane makes an angle with the flow vector.

In Fig. 4 the $C_l$ curve shows two peaks. The orientation of the hand in which the highest values of $C_l$ are observed is at $\theta = 55^\circ$ ($AP = 31^\circ$, $SB = 358^\circ$) and immersed. This was mainly caused by a decreased value of $A_w$, while $F_l$ and $F_z$ remained the same.
at $\theta = 155^\circ$ (AP = 48°, SB = 193°) approximately. Obviously the model does not have the rotation symmetry of a cylinder and therefore the model will generate a lift force, dependent on the angle of pitch. This dependency is even more pronounced for the single hand than for the total hand/arm model (Fig. 8). The hand seems to be the main contributor for generating lift force. It is tempting to compare the hand with a wing-shaped hydrofoil. For such profiles it is known that the value of $C_f$ is dependent on the angle of pitch (Lighthill, 1986). A so-called 'Joukowsky' profile (cambered wing-shaped foils) shows that $C_f = 0$ at $\alpha = -7^\circ$, $C_f = 1.5$ (maximum) at $\alpha = 11^\circ$ and $C_f$ decreases at increasing $\alpha$, possibly due to so-called stalling (separation at the leading edge) (Alexander, 1977; Lighthill, 1986; Rouse, 1946). One cannot expect that hands have the full characteristics of such lift force generators. But certainly, hands can generate
some lift force, dependent on the hand orientation with respect to the flow.

Values of drag and lift coefficients for a hand model were reported earlier (Schleihauf, 1979). In order to compare Schleihauf's data with the present results, $C_d$ and $C_l$ were recalculated per hand plane area (obtained by scanning photographs of the model). In Fig. 9 $C_d$ and $C_l$ are plotted versus the angle of pitch (AP) at $SB=0^\circ$ for the left part of the figure, and at $SB=180^\circ$ for the right part. The shape of the curves is approximately the same. Peak values arise at the same orientation of the hand, which indicates that the hydrodynamic characteristics of the model of Schleihauf and the present ones are about the same. However, the variation of $C_d$ and $C_l$ with the angle of pitch is slightly different. In Schleihauf's data, peak values for $C_d$ are higher, whereas peak values for $C_l$ are lower than in the present study. The lower values of $C_l$ obtained by Schleihauf might be due to the fact that he probably measured the (component of the) lift forces in a predetermined direction of the force transducer (Schleihauf did not provide clear information concerning its measurement technique in the literature). This would result in an underestimation of the lift force. Differences in material, hand size and shape of the model might also account for the observed differences in $C_d$ and $C_l$. Our two models, approximately equal in shape but different in size, show only substantial differences in $C_l$ at small angles of pitch (Fig. 7). Perhaps small differences in shape, for example position of the thumb, flexion of the wrist, are the reason for these differences suggesting that values of $C_l$ are very sensitive to shape.

The influence of velocity on $C_d$ and $C_l$ was studied for one orientation of the model ($\varphi=0^\circ$, $\phi=-30^\circ$ and $\theta=180^\circ$). The results (Fig. 6) showed that values of $C_d$ and $C_l$, within the velocity range from 0.7 to 3.0 m s$^{-1}$, change very little. At velocities lower than 0.7 m s$^{-1}$, $C_d$ and $C_l$ seem to be strongly dependent on velocity. During freestyle swimming the velocity of the fingertip varies from 1.5 m s$^{-1}$ to about 3.5 m s$^{-1}$ (Schleihauf et al., 1983). The velocity at the fingertip will be higher than at other parts of the hand or forearm; therefore, during sub-maximal swimming the mean velocity of the hand and forearm is expected to be lower than 3.5 m s$^{-1}$ and higher than 0.7 m s$^{-1}$. It can be concluded that $C_d$ and $C_l$ are more or less independent of velocities during sub-maximal, human swimming.

As stated earlier, it has been shown from a theoretical point of view that propulsive forces during human swimming can be more efficiently derived from lift forces than from drag forces. At high lift forces the loss of energy will be minimal (de Groot and van Ingen Schenau, 1988). Consequently, a proper technique should generate as much lift force as possible. The implication of the results from this study to the actual swimming practice is that positioning of the hand and
forearm during the downsweep, insweep and upsweep phase of the stroke (Maglischo, 1982) appears to be rather critical for generating lift forces and thus for an efficient stroke technique. The present data indicate that the optimal orientation of the hand with respect to the direction of motion of the hand would be about 55° for a thumb-leading orientation and 25° for a little finger-leading orientation. The lift force will be as high as possible at these orientations of the hand. Further research during actual swimming is necessary to establish the orientation and movement of the hand in which the forward component of the sum of drag and lift force is maximal.

It is shown that the hand is the main contributor for generating lift force. The generated lift force is dependent on \( C_l \) and the size and velocity of the hand. The shape of the hand seems to be more suitable in generating lift forces than the shape of the forearm. An optimal use of the shape of the hand demands high hand velocities. Swimming with a sculling motion in which the hand velocity is always higher than the velocity of the forearm might be much more efficient than swimming with a 'pull—push' stroke, in which the hand and forearm velocity are much more similar.

In conclusion, the orientation of the model is the predominant factor for the amount of lift force. Influence of velocity and size of the model on values of \( C_d \) and \( C_l \) seems to be small.

In the future, it should be possible to estimate the contribution of drag and lift forces from a kinematic analysis of arm strokes during swimming, taking into account the direction of the forces and the obtained lift and drag coefficients. Perhaps it will also be possible to verify the hypothesis that an increased contribution of lift forces will result in more efficient swimming, as proposed by Toussaint et al. (1991).

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