THE CONTRIBUTIONS OF LIFT AND DRAG FORCE COMPONENTS OF THE HAND/FOREARM TO A SWIMMER'S PROPULSION

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In swimming there has been a limited amount of research carried out investigating the degree to which the forces generated by the upper limb contribute to the total forward propulsion of a swimmer (Schleihauf, 1979; Wood, 1979). Two types of forces are generated, induced forces and parasitic forces. Drag is a force component that is made up of both induced and parasitic forces, whereas lift is a force component primarily made up of induced forces.

For years, it was believed that "drag" was the principle governing propulsion, and swimmers were encouraged to attempt to the best of their ability to maximize the factors which contribute to induced drag development. Coaches however, noticed that accomplished swimmers rarely adopted a straight pull path, but pulled in some type of a deviating pattern. It was this observation that led James Counsilman (1969) to propose that another form of induced force, hydrodynamic lift, contributed significantly to propulsion in swimming. Whereas drag is a force component acting normal to the hand and opposite to the direction of movement of the hand, lift is a force component that acts perpendicular to the direction of fluid flow past the hand.

The most recent research suggest that propulsion is gained from a combination of lift and drag components (Schleihauf, 1979; Wood, 1979). The relative contribution of each component to the total propulsive force continually varies as the swimming stroke progresses, and is influenced by variables such as hand velocity, handpitch, pull pattern, fluid characteristics, and to a certain extent, hand shape.

Opinions have differed concerning the roles played by these two force components. The purpose of this study was to try to determine the relative contributions of lift force components and drag force components to the total propulsive force in a front crawl swimming stroke. A second purpose was to attempt verification of the use of wind tunnel data collected on hand/forearm models for the prediction of the propulsive forces generated by the upper limb in an actual swimming situation.

Methods

Instantaneous measures of a swimmer's acceleration during the front crawl stroke were made while simultaneously filming the swimmer. An arrangement was designed where a linear accelerometer rated for ± 0.5g (Schaevitz, 1977) was suspended above the water surface and towed by the swimmer. The accelerometer was not water-proofed but was instead firmly fastened within a water-tight plexiglass box. This particular arrangement is shown in Figure 1.

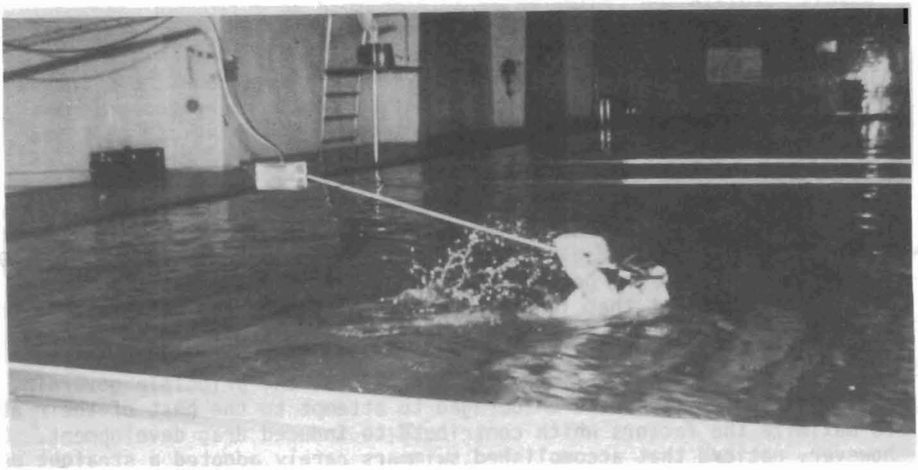

Figure 1. Suspension of accelerometer

Because the accelerometer which was used (model LSB Linear) had only one sensitive axis the arrangement chosen had to ensure that the forward, or propulsive component of the swimmer's acceleration and only the forward component was being measured. Four parallel wires were stretched across the pool. Eight low-friction nylon rollers were fitted on the sides of the plexiglass box, four on each side. These rollers sat on the wires, which guided the box in a straight line across the pool. The box was attached indirectly to the swimmer's head via an aluminum rod. Because all swimming trials were conducted without breathing, the movement of the head was primarily one dimensional. The rod was rigidly attached to the box through a universal joint, and to the swimmer's head through a head gear secured with velcroe.

While the acceleration was being measured, the swimmers were filmed underwater simultaneously from two orthogonal directions; one camera filmed from directly underneath and one camera filmed from the left side. Spring wound 16mm Bolex cameras, enclosed in underwater housings, were used for the filming. Both films records and accelerometer output were synchronized. Four different subjects were analyzed, and four trials were filmed for each subject, two each at a fast speed and at a slow speed.

All trials were conducted with the legs together and supported by a pull-buoy. Thus any propulsion that may have been due to the leg kick was eliminated and propulsion was solely due to the forces generated by the hand, forearm, and arm.

Results and Discussion

The results presented here are of one slow trial by one swimmer, but are representative of all trials of all swimmers. Figure 2a shows the pullpath of both hands as viewed from the side. As the swimmer moves from right to left, the left hand moves forward from point (a) to point (b), and the right hand moves backward from point (a) to point (b). Shortly after passing point (b) the right hand leaves the water, recovers above the water surface, and then re-enters the water at point (c). At this instant the left hand is at point (c). When the left hand exits the water at point (d), the right hand is at point (d).

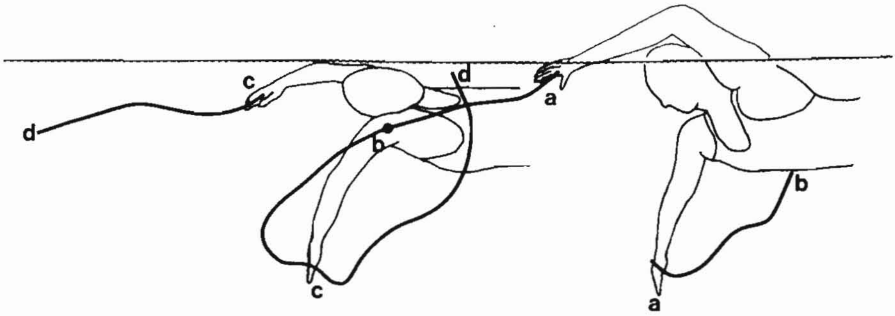

Figure 2a. Side view pull paths of both hands during slow front crawl swimming.

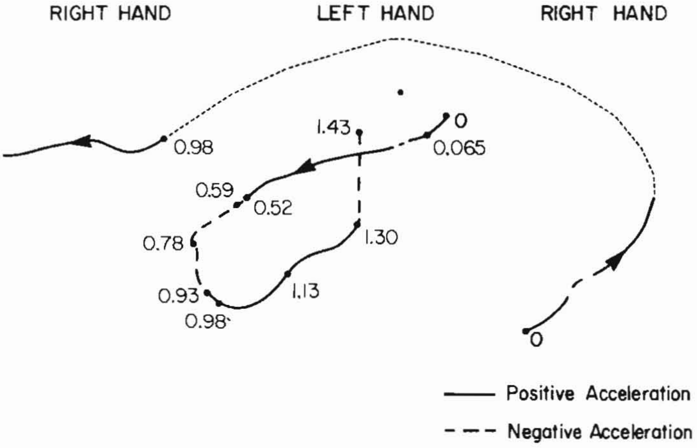

Figure 2b. Side view hand paths related to positive and negative phases of accelerometer output.

Figure 2b shows the same paths as in Figure 2a. The numbers refer to time in seconds from left hand entry into the water. The solid line refers to those intervals in time when accelerometer output is positive, and the broken line refers to those intervals in time when accelerometer output is negative. There are two primary intervals in which the swimmer's forward acceleration is positive, from 0 to 0.52 seconds and from 0.93 to 1.30 seconds.

Figure 3 is a vector analysis of the generation of forces at the hands for time 0.065 seconds. The left hand is at the point marked (x) in its hand path and the right hand is at the point marked (x) in its respective hand path.

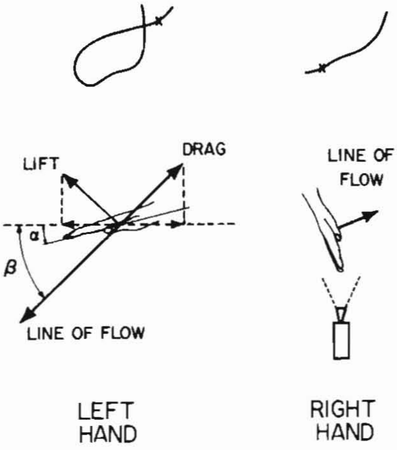

Figure 3. Generated force vectors for the left hand at 0.065 seconds into the stroke.

The orientation of the left hand with respect to flow is shown; (α) defines the angle of hand pitch with respect to the horizontal and (β) defines the angle that the line of flow makes with the horizontal. The direction of the lift and drag vectors are determined by the line of flow. These vectors are presented in this figure to express direction only and their magnitudes for the time being, are arbitrary. In this study, wind tunnel data was also applied to these swimming trials in an attempt to make estimates of the magnitudes of these lift and drag vectors. The results of this endeavour will be presented in the second part of the paper.

From Figure 2b, it can be seen that the left hand is moving forward in the interval 0 to 0.78 seconds, and so the flow of water over the hand will be primarily over the fingertips or the distal border. This has been defined as distal flow. Reports in the literature (Wood, 1977) have suggested that this distal flow is conducive to positive force generation, with the suggestion that swimmers should be encouraged to adopt a stroke technique that devotes considerable attention to distal flow orientation. However it must not be forgotten that for the first part of this interval both hands are in the water and it is impossible to separate the effects of each as the accelerometer is measuring only the total horizontal propulsive force. It is necessary to also examine the orientation of the right hand at this same point in time and examine its potential for generating a forward propulsive force.

The right hand is clearly moving backwards in this interval, but it also has a medial component relative to the body which cannot be shown in this two-dimensional view. Imagine then looking up at the swimmer and the right hand from a camera located on the bottom of the pool. The view would look something like that shown in Figure 4.

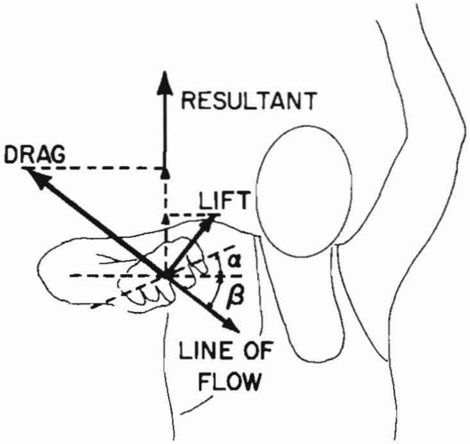

Figure 4. Determination of the propulsive force component for the right hand at time 0.065 seconds.

The swimmer is moving in this Figure from bottom to top and the right hand shows a backward and medial movement. The generated drag force component is opposite to the direction of the line of flow and the generated lift component is perpendicular. Both of these force components can be resolved into vectors which are in the direction of the horizontal movement of the swimmer and both have the potential for making positive contributions. Again, magnitudes of vectors are represented arbitrarily.

Thus it can be seen how forces are potentially created at both right and left hands at one instant. At this point in time, namely at 0.065 seconds, the two hands have different orientations with respect to flow and the way that propulsive forces are created are different at the two hands. As will be demonstrated later in this paper, the relative contributions made by each hand to the total propulsive force cannot be determined. Returning again to Figure 3 and considering the left hand at time 0.59 seconds, with regard to the combinations of (α) and (β), the hand pitch and line of flow respectively. In addition, the left hand velocities are relatively close for both instances, 3.03 and 3.34 m/sec at times 0.065 and 0.59 seconds respectively. Thus, the potential propulsive forces created by the left hand at these two different points in time should be quite similar. The right hand at time 0.59 seconds is out of the water and engaged in arm recovery, so it is no longer contributing to forward force propulsion. Any forward propulsive force generated at time 0.59 seconds is due solely to the left hand. It can be seen that at this time the accelerometer output shows a negative value. Figure 5 shows the output of the accelerometer over the complete interval from left hand entry at time 0 to left hand exit at time 1.43 seconds.

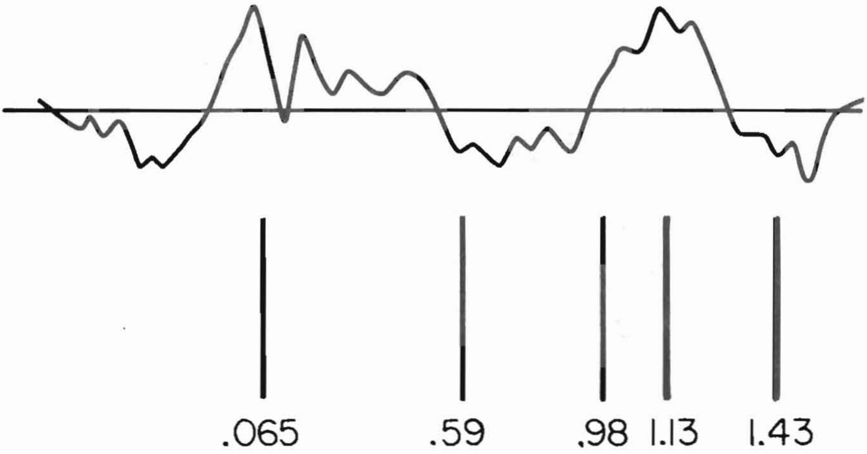

Figure 5. Accelerometer output during slow front crawl swimming.

Values above baseline are positive. Acceleration at time 0.59 seconds is a negative value indicating the swimmer is slowing down, and the left hand is incapable of generating enough force to accelerate the swimmer. Therefore, because the potential of the left hand for generating force is very similar at times 0.065 and 0.59 seconds, the high positive force seen at 0.065 seconds is probably due to the forces generated by the right hand. This suggests that the hand is probably not capable of creating sufficient propulsive forces when in a distal flow orientation.

Consider now the interval of positive acceleration which occurs from time 0.98 seconds to 1.30 seconds, as represented in Figure 2b. This second interval is essentially the same as the first interval except that the roles the two hands play have been reversed. The right hand is now engaged in distal flow and the left hand is moving backwards. Looking at the left hand path, it can be seen that at time 1.13 seconds, this hand is at about the same point in its path as was the right hand at time 0.065 seconds, and the accelerometer output at 1.13 seconds is positive, therefore suggesting that the major forward propulsive forces occur at this point in the stroke where there is considerable backward movement.

In this study, accurate measurements of hand pitch were difficult to determine, primarily because bubbles were present about the hand. However, within the limitations of the analysis of the films, it appeared that during the conditions of pulling backward in a deviating pull pattern, the swimmers by and large chose to adopt an angle of incidence of the hand to flow that was quite steep. This is demonstrated in Figure 4. The orientation of the hand to flow, which equals $(\alpha) + (\beta)$ is relatively high. At this orientation the critical angle for coefficient to lift (C_L) has been passed, and the potential for creating lift force components is not optimum. On the other hand, the potential for creating drag force components is better, because coefficient of drag (C_D)increases as angle of incidence approaches 90°.

Referring now to Figure 6, which is taken from the bottom view film, the difficulty in determining accurately the hand pitch is clearly evident due to the presence of the bubbles about the left hand, which is the lowermost hand in the photograph. However, hidden within the bubbles is a clue. The bubbles and the turbulent wake about the hand suggests there is very little opportunity for attached flow, meaning a low potential for creating a lift force component.

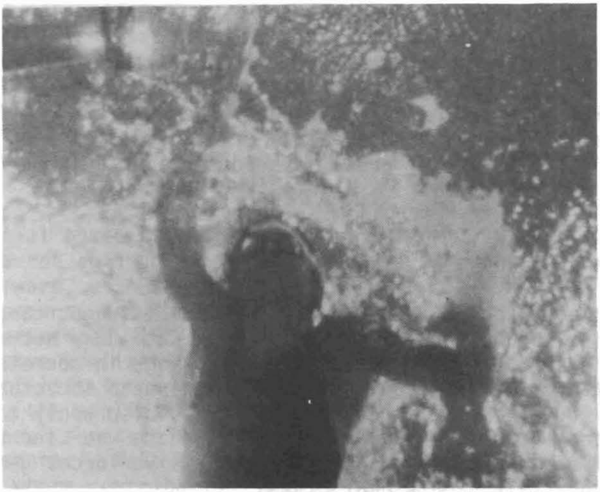

Figure 6. Bottom view at 0.35 seconds after left hand entry.

PREDICTION OF PROPULSIVE FORCES

Methods

The wind tunnel data used in this study was taken from Wood (1977). Lifesized hand/forearm models of differing shapes had been subjected to wind tunnel testing and direct measurements of lift force components and drag force components were made. The models were tested at different hand pitches ranging from 0 - 90° at 15° increments. Data was collected for differing flow velocities, and three different orientations were tested; flow activity over the distal border of the hand model, flow over the radial border, and flow over the ulnar border of the model. Thus coefficients of both lift and drag were determined for several combinations of these three independent variables.

Of the four swimmers filmed in the present study, two (one male, one female) were swimmers from whom plaster cast models of the hand /forearm had been made and subjected to the wind tunnel testing so that Wood's data for lift and drag force components could be used. The other two swimmers were matched to the first two approximating swimming ability and hand size. Because the data for the four different hand shapes used in Wood's study (1977) were "broadly similar", a mean value, for each hand velocity and hand pitch, of lift and drag was used for these two swimmers. Of the two females, one was a successful Olympian, the other a provincial level club swimmer. The male swimmers presently competing as Masters had extensive competitive experience at the interscholastic and intercollegiate levels.

For each frame of film analysed a specific combination of hand velocity, hand pitch, and hand orientation was determined for which a value for C_L and a value for C_D could be extracted from Wood's wind tunnel data. Figure 4 shows an example of how these coefficients were used in conjunction with the kinematic data to determine a propulsive force component for one hand at one point in time. These propulsive force components were then summed for both hands and the total represented the force generated that potentially could be used to propel the swimmer forward.

Instantaneous values of acceleration were taken from the analog record of accelerometer output at times corresponding to the analyzed frames of the synchronous film records for the portion of the stroke cycle from hand entry to exit of that same hand. These values of acceleration were correlated to the values of total potential propulsive force using Pearson Product Moment Correlation.

Results and Discussion

A wide range in correlation coefficients were found, ranging from -0.55 to +0.77. This indicates that the wind tunnel data does not sufficiently account for the swimmer's acceleration. This range in correlations indicates that several limitations in applying wind tunnel data to actual swimming situations exist. These limitations are felt to also apply to other studies presented in the literature which have attempted to use wind tunnel or other similarily collected data to predict the propulsive forces generated by the upper limb (Wood, 1977; Schleihauf, 1979).

Firstly, the models used by Wood in the wind tunnel only contained a portion of the forearm, and did not contain any part of the arm. In addition, the models were fixed with the wrist in a neutral position. For these reasons, the wind tunnel data was not totally representative of the actual swimming situation. Differences in hand shape due to movements occuring with the joints of the hand and wrist and the addition of a greater cross-sectional area of the arm and remaining part of the forearm that is present in the actual swimming situation means differences will exist in the production of lift and drag force components compared to those measured by Wood in the limited enviromnent of the wind tunnel.

Secondly, whereas flow across the hand in the real swimming situation occured at a great many hand orientations with respect to flow, Wood's data was collected only for flow at right angles to three borders of the hand, distal, radial, and ulnar. It was necessary therefore, in the analysis carried out in this study, to determine to which of the above three orientations the actual flow condition was closest, for each of the analysed frames. The choice obviously led to approximations of the actual production of lift and drag force components.

Although the best attempt possible was made to get accurate hand velocities, the movement of the hand was not confined to planes parallel to either camera lens. This study was able to contain two two-dimensional records of the position of the hands from which linear velocities of the hands were calculated, but with the deviating pull pattern exhibited by the hands, a three-dimensional cinematographical technique was needed to accurately define the position of the hands in space and subsequently calculate accurate linear velocities during all stages of the stroke. This is an important consideration because velocity plays a major role in the development of lift and drag force components. Three-dimensional cinematography could also give a more accurate definition of line of flow, as well as orientation of the hand with respect to flow. An accurate knowledge of flow line is not only required for determination of the angle of incidence the hand makes with the flow, but is also required when making a calculation of the horizontal components of the lift and drag force components.

Finally, a measure of the resistance by which the water is impeding the forward movement of the swimmer would add considerably to an analysis because some of the propulsive potential generated by the upper limbs is used to overcome this resistive drag, with the remainder of the propulsive potential being available for accelerating the body forward.

CONCLUSIONS

During the initial phase of the stroke (i.e. the distal flow condition), the hand/forearm is not able to create sufficient propulsive force to accelerate the swimmer forward, even though it is during this phase of the stroke that lift force components can potentially contribute their greatest positive propulsive effect (Wood, 1977). The swimmers in this study seemed to demonstrate a selective utilization of the potential of drag force components over the potential of lift force components during all phases of the deviative pull path. Finally, the application of wind tunnel data to actual swimming situations has not been shown to sufficiently account for a swimmer's acceleration. It is generally felt that knowledge concerning swimming propulsion is not at a level where contributions due to lift and drag can be quantified although it is felt that information is available concerning interaction of lift and drag with swimming propulsion. Any interpretation of results presented in the literature to date must be viewed with this in mind.

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