Forces on the swimming hand[1]

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The purpose of this work was to determine which hand geometry is the most effective when swimming crawl, and to examine the relative contributions of lift and drag forces to forward propulsion. Three different hand geometries were used: flat hand with fingers slightly spread, flat hand with fingers together, and cupped hand. The forces on each were determined at six characteristic points in the stroke, which were established from examination of published photographs of an expert swimmer. The relative velocity between the hand and the water for each of these positions was determined. Wind tunnel tests were conducted under conditions of flow similarity and correct hand orientation, and the forces on full-scale hand models measured. It was established that there was no single best hand geometry. In hand positions where the backward component of hand velocity is dominant, the geometry with fingers slightly apart was best, and drag forces were the main contributor to forward propulsion. When the sideways component of hand velocity was dominant, the hand geometry with fingers together was best and when the main component of hand velocity was upward, the cupped hand was best, with lift forces being significant.

Introduction

Like in most sports, technique in swimming is all-important. A significant proportion of forward propulsion is generated as a result of lift and drag forces generated by the hand as it moves through the water. The motion of the hand and the position in which it is held greatly influences the magnitude of the forces. Each swimmer will hold his hand and move his arm in such a way that he feels he is generating the maximum possible propulsion for the amount of energy being expended. This may indeed not be the case and coaching is needed to modify the stroke in order to improve performance. With increasing levels of performance being achieved, experimentation and modelling can assist in determining specific features that could be helpful in determining optimum conditions. In the current study it was the particular way in which the fingers and thumb of the hand are positioned that was examined.

The first detailed analysis of the motion of the hand through the water was done by Counsilman,[1] who clearly defined the complex path that the hand takes. His analysis will be used in the current work in order to establish the appropriate relative velocities. He clearly recognised that both lift and drag forces contribute to the forward propulsion. The earliest quantitative study to estimate forces on a swimmer's hand when swimming crawl, was done by Schleihauf.[2] He measured forces on a model hand in a steady water flow and obtained two-dimensional data of lift and drag coefficients for a number of hand orientations, and then inferred the resultant force acting on a swimmer's hand during the pull. This work was subsequently combined with an analysis of hand motion through the water to obtain the propulsive force per stroke.[3] This technique will also be applied in the current study. Similar studies have been done more recently by Berger *et al.*[4] to include the adjacent effect of the arm.

The above investigations treat the flow as being quasi-steady, i.e. the force acting on the hand at any instant is considered to be the same as that experienced if it were held in a flow moving at constant velocity. They thus ignore the effects of relative acceleration and the forces arising therefrom, an influence sometimes referred to as the added-mass effect. Examination of swimmers actions indicates that there are likely to be such effects, and papers at recent international meetings[5] highlight the need for such studies. The issues are clearly complex as it is not simply the absolute acceleration of the hand that is important but also the induced velocity field resulting from the history of earlier motion of all parts the swimmer's body. Recent idealised studies have been conducted by Sanders[6] where a model hand is accelerated in a water flume in the direction of hand motion. This study indicated that the flow unsteadiness can result in force coefficients resulting from acceleration which can be some 6% of those due to velocity. Berger *et al.*[7] estimated that quasi-steady forces were some 17% lower than propulsive forces directly measured on a swimmer. The various studies unfortunately also show dramatic differences in the values of the maximum drag coefficient, being 0.59 for Sander's study, 1.4 for Schleihauf, to 1.2 for Berger.

This work examines the geometry in which the hand is held in order to determine which is most effective in producing forward propulsion when swimming front crawl. It compares three typical cases: the first has the hand held flat with the fingers slightly apart, the second has the hand held flat with the fingers together, and the third has the hand cupped with the fingers and thumb held together. The pattern of the crawl stroke itself is not investigated for its effectiveness and the most commonly used pull pattern, as used by expert swimmers, is assumed. Because of the differences in force coefficients obtained by previous workers, and the complexities of taking into account the true unsteady flow conditions, this work is done in a quasi-steady frame, and is strictly comparative, i.e. the forces

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for one particular hand geometry at a given position of the stroke are compared directly with the forces for a different hand geometry. Thus even if some of the other effects are excluded it is unlikely that the rank order of any particular hand position would be materially affected. Furthermore, if it were found that a particular hand geometry was optimum, then the second-order effects could be explored more rigorously. The current study must therefore be regarded as preliminary.

The path followed by the hand of a swimmer when swimming crawl is a complex three-dimensional one. The perception by many that the hand follows an approximately circular path in a vertical plane is incorrect. The path followed by the hand is important in this work as it determines at what angles the hand model must be placed in the wind tunnel with respect to the flow. Counsilman[1] has done extensive research into the mechanics of swimming and the analysis presented by him was used as the basis for establishing the initial conditions for this study. Two of his studies are important, the first involved determining the pattern followed by the hand when swimming crawl and the second involved the velocity of the hand relative to the water. The swimmer used in both studies was Mark Spitz – winner of seven gold medals in seven world-record times at the 1972 Olympic Games. To determine the path Counsilman attached a flashing light to the end of one of the swimmer's fingers and with an open shutter camera recorded the trace of the light. Analysis of this data enabled him to plot the path of the hand. He used a set of three orthogonal axes, which he termed Sideways (S), Forward-Back (FB), and Up-Down (UD), to present the motion in three planes. His plots have been reworked to remove some inconsistencies in the relative scales of his diagrams along the different axes, and are given in Fig. 1 for the path of a right hand, relative to the water. The top view is the FB/S plane, the right side view the FB/UD plane, and the front view the S/UD plane. Following Counsilman, a number of specific points in the stroke are identified. Point I is where the hand enters the water, and it then swings slightly outward and down to point C. At C, the forward-most point of the stroke, where the FB velocity component changes direction, it is noted from the top view that the S velocity component also changes direction. The velocity at point C is therefore entirely downwards. At F, which is the deepest part of the stroke, and is therefore a position of zero vertical velocity, Counsilman's measurements showed that it also corresponds to a local maximum in horizontal velocity in the FB direction. At A he found that the sideways velocity is a maximum in a direction towards the centreline of the swimmer. This sideways velocity then slows down to become zero at D, and then increases again to become a maximum at B in the opposite direction. Between B and D when the hand is sweeping almost horizontally there is a second local maximum in FB velocity, at G, of a similar magnitude to that at F. Towards the end of the stroke, at E, when the hand is sweeping past the thigh, the rearmost point of the stroke is reached, with nearly zero FB velocity. Thereafter the hand moves forward again relative to the water to exit the surface at O. It is interesting to note that the hand leaves the water at a position in front of where it entered. Thus the net movement during one stroke of the hand through the water is forward, from I to O, and not backwards as is often thought.

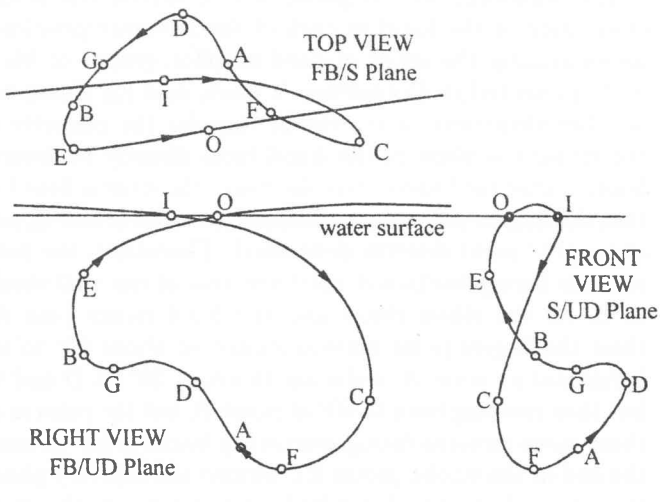


Fig. 1. Path of hand through the water

With the above path data, and the velocity data given by Counsilman, all the necessary initial information to undertake wind tunnel tests is available. Issues relating to the models used and test procedures are given below and the analyses required to establish the hand orientation in the wind tunnel are given under experimental conditions.

Materials and methods

Hand models

Three model hands were used. They are full-size casts of an actual hand. The first hand was held with the palm flat and the fingers slightly apart, with the thumb slightly extended. The second hand was held with the palm flat and the fingers together, with the thumb slightly extended. The third hand was held in the cupped position with the fingers and thumb held together. The model hands are hereafter referred to as Apart (A), Together (T), and Cupped (C), and are shown in Fig. 2.

The models were manufactured from a urethane plastic cast in Plaster of Paris moulds. The moulds were made from imprints of the left hand of one of the authors (AS) using techniques for making copies of fossils. The hands, which terminated at the wrist, could be attached to a steel support sting for mounting in the wind tunnel. The sting was fitted with pivots so that it could be manipulated about three axes, in order to be able to position the hand correctly. In order to avoid having the aerodynamic loads (acting on the sting) influencing the readings, it was surrounded by a hollow windshield manufactured in the shape of a forearm, so that the correct induced flows in the vicinity of the hand were also modelled. There was no direct contact between the windshield, which was attached to the tunnel wall, and the model and sting, a small gap being ar-

ranged between them. The sting passed through a hole in the tunnel wall where it was attached to a six-component external force balance.

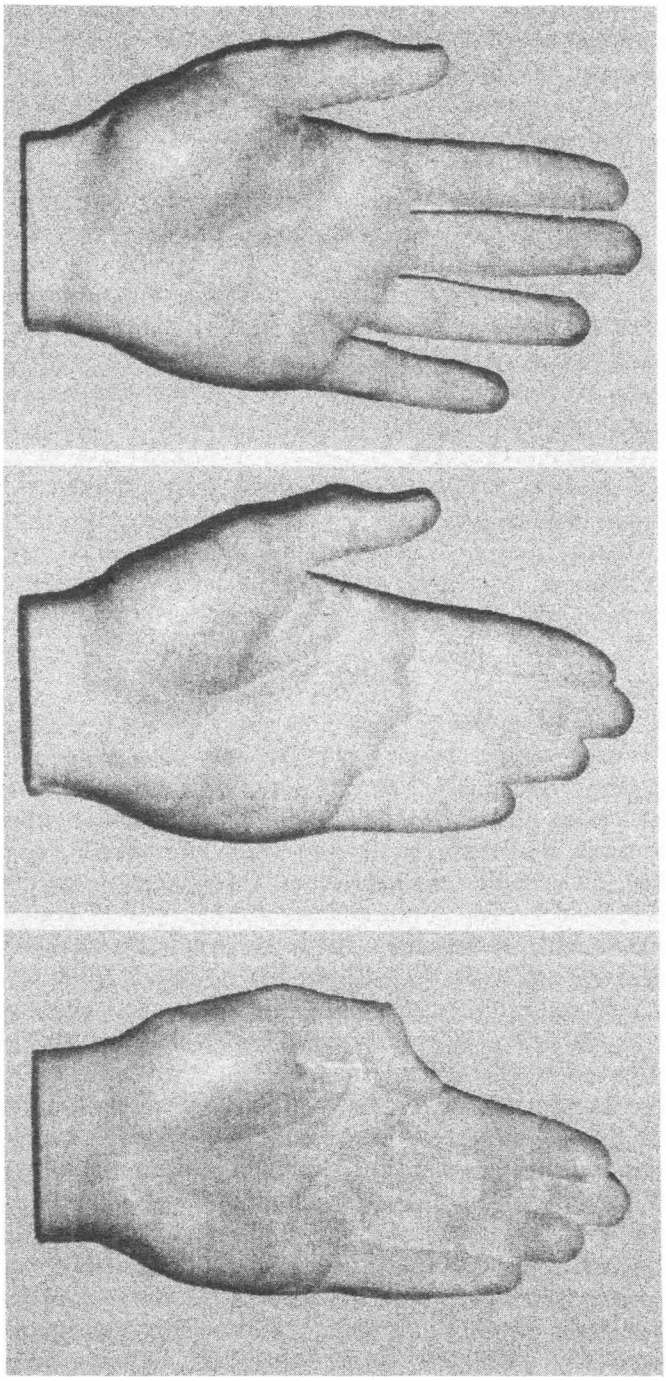


Fig. 2. Wind tunnel model hands. From top: Apart, Together, and Cupped

Wind tunnel facilities

The wind tunnel used is a closed circuit continuous flow tunnel with a 900 mm × 600 mm elliptical cross-section test section. It is driven by a variable speed electric motor so that various flow speeds can be set. A pitot-static tube connected to an electronic micro-manometer measures flow velocity. Test section pressure and temperature readings were taken in order to establish the air density.

The pyramidal force balance is arranged to measure the three orthogonal forces of lift, drag, and side force, and the three moments about the resolving centre of the balance. Only the three forces were recorded since the position of the line of action of the forces through the hand is not relevant for this work, the muscles in the arm and wrist counteracting these moments.

Experimental conditions

In order to correctly model the forces on the hand it is necessary that the hand be in the correct orientation with respect to the flow direction in the wind tunnel in order to mimic the same orientation of the hand with respect to its relative velocity through the water at the various points of the stroke. The first step is to determine the velocity and position of the hand relative to the water for each selected hand position throughout the stroke. This step also includes calculating the corresponding velocity at which the testing is to be conducted in the tunnel. The second step is to process the lift, drag, and side force results obtained from the tests and place them in the correct orientation in the swimmer's frame of reference, and then to extract the components acting in the FB (propulsive) direction.

The hand velocities are readily obtained, at the points given in Fig. 1, from the graphs presented by Counsilman.[1] The results are presented in Table I. From these component velocities both the velocity of the hand through the water and its direction can be established. These velocity components are given in Fig. 3, where the directions are seen to correlate well with the path of the hand.

The remaining step required is to establish the actual orientation of the hand at each of the reference positions. By examining the series of head-on photographs of Mark Spitz presented in Counsilman's book, and his discussion of other swimmers, it is evident that for the majority of the stroke the palm of the hand faces directly backward. Shortly after the hand enters the water the wrist is flexed so that the fingers point along the path between O and C, and at point C point directly downward. Thereafter, the palm remains facing backward until the end of the pull stroke at B. As the elbow flexes and the hand moves past the chest the fingers point more sideways, at about 60° to the horizontal at point A, reducing to about 30° at D and G, but then rotating back to 60° at point B, but the palm in all these cases remains facing essentially backwards. Towards the end of the stroke (point E), termed the recovery phase, the palm of the hand is tilted inward towards the thigh and the fingers point more directly backward. The hand is then moving forward through the water and the flow

TABLE I
MAGNITUDE AND DIRECTION OF VELOCITY VECTORS

Hand position	Direction	Velocity components (m/s)	Velocity (m/s)
	S	0.00	
C	FB	0.00	2.74
	UD	2.74	
	S	−1.52	
F	FB	2.90	3.27
	UD	0.00	
	S	−3.05	
A	FB	1.22	3.62
	UD	−1.52	
	S	0.00	
D	FB	2.13	3.85
	UD	−3.20	
	S	1.52	
G	FB	2.90	3.27
	UD	0.00	
	S	2.74	
B	FB	1.22	3.37
	UD	−1.52	
	S	1.22	
E	FB	0.00	3.71
	UD	−3.51	

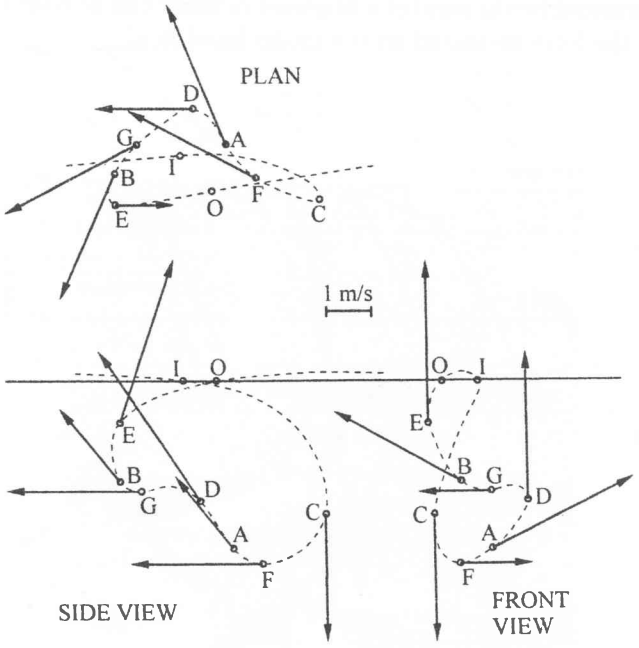


Fig. 3. Three orthogonal scale views of velocity vectors

over the hand is from the wrist towards the fingers. This part of the stroke does not contribute to forward propulsion and the hand orientation is such as to minimize the drag opposing forward motion of the swimmer. Since this is not part of the forward pull, which occurs between C and B, it was not tested in the wind tunnel. The hand orientations at the various parts of the stroke as discussed above are shown in Fig. 4.

With the hand orientation and the direction and magnitude of the velocity established, the position of the hand relative to the flow is thus determined, and can be set up in the wind tunnel. The lift, drag, and side force measured in the wind tunnel are measured with respect to the wind direction. The drag force is the force measured in the direction of the velocity vector. In aerodynamic applications the lift force is generally taken to be normal to the mean plane of the aircraft wings and the side force as the force orthogonal to the lift and drag force. In the present case the definition of the lift and side force directions are arbitrary since there is no obvious symmetry of the position of the hand relative to the fluid flow in all cases. Therefore, for evaluation and discussion purposes, the lift and side forces as measured by the wind tunnel balance are combined vectorially into a single transverse force normal to the flow direction, and which will subsequently be referred to as the lift force. The contributions to the propulsive force of the swimmer will be distinguished as those that arise from this transverse lift force and from the drag force.

The velocity used for the wind tunnel testing uses the principle of Reynolds number similarity, with the ratio of viscous forces to inertia forces being set to be the same for the hand moving in water and in air. This principle ensures that the flow fields are similar if geometrical similarity is satisfied, and therefore the forces measured in air can be simply converted to the forces that would be acting in water, since the force coefficients will also be the sames. The Reynolds number is $\mathrm{Re} = LV\rho/\mu$, with L being the characteristic length of the hand, and is the same for both the tests in air and the actual situation in water, ρ is the fluid density, and μ the fluid viscosity. The values of ρ and μ for water were taken to be 996.34 kg/m^3 and 8.84×10^{-4} kg/ms, respectively, corresponding to a water temperature of 26°C, which is the standard water temperature for competitive swimming as required by F.I.N.A. (the world governing body for swimming). The hand Reynolds number is therefore about 900 000. Air density and viscosity were determined during experimentation from the temperature and pressure measured in the wind tunnel, and thermodynamic property tables.[9] Force coefficients, which will be the same in air tests and for water, are given by C_F=F/$0.5\rho V^2 A$, where F is the force (drag, lift, or side force), $0.5\rho V^2$ is the dynamic pressure, and A is a characteristic area which is the same for both air and water flows because of the full-scale hand models being used.

For normal operating conditions and the range of water speeds to be simulated, the tunnel speed should have been about 50 m/s in order to achieve exact similarity. Unfortunately due to some limitations with the hardware, tunnel speeds of only some 60% of this were achievable. This is not a serious limitation, as in the Reynolds number region of interest it can be expected that force coefficients, such as the drag and lift coefficients, would be essentially independent of Reynolds number.[10] Because of the equality in

force coefficients for any particular geometry, the force experienced by the hand of a swimmer in water can be related to the force measured on the model hand in air by

$$F_w = (\rho_w/\rho_a)\,(V_w/V_a)^2\,F_a$$

where, in the present case, the density ratio, ρ_w/ρ_a, is approximately 1 000 and the velocity squared ratio about 0.012. In the data presented subsequently, the forces specified are those that would be experienced by the swimmer, the above equation having been applied for the specific values of tunnel air density and velocity pertaining to each test. It should be emphasised, however, that for the purpose of the current study, the actual value of the forces are not of major importance, but rather the comparative ranking of the three hand geometries tested. Thus even if there is some slight variation in Force coefficient with Reynolds number, owing to having to test at a slightly lower velocity than desirable, this could be expected to be similar for the three hands tested, and therefore their relative performance would not be affected.

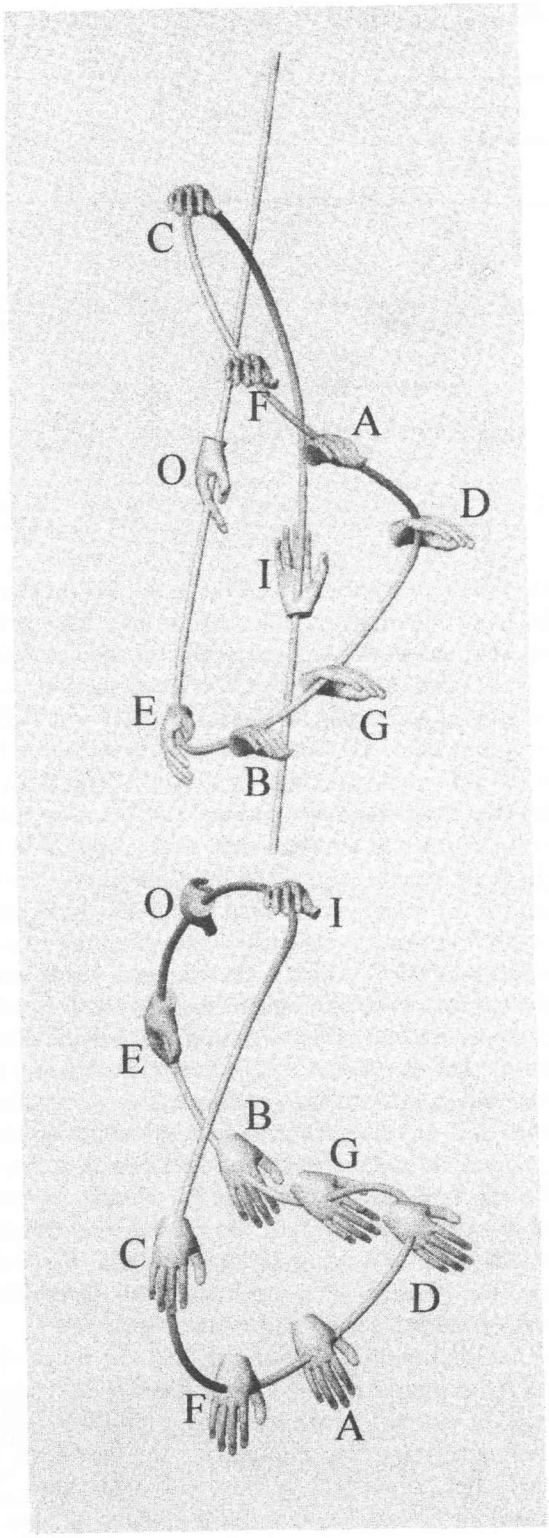


Fig. 4. Bottom and frontal views of hand orientation

Results and discussion

The drag and transverse force measurements obtained from the wind tunnel for each of the hand positions relative to the local direction of the velocity vector were resolved into the corresponding reference position of the swimmer, and the components of these forces acting in the direction of propulsion of the swimmer extracted. The results are presented in Fig. 5.

Swimming propulsion results from a combination of lift and drag forces. The lift forces are those that are generated perpendicular to the instantaneous hand motion, and the drag forces are along the line of the hand motion. (These are not the same as the same forces as measured in the wind tunnel because the positioning of the hands in the tunnel was done to obtain the correct relative velocity of the hand to the air and so the direction of propulsion is different for every hand position.) In general, high Forwards-Backwards hand velocities will primarily contribute to propulsion through the action of drag, whereas high Sideways and Up-Down hand velocities will contribute through lift forces.

It is clear from Fig. 5 that the best hand geometry varies

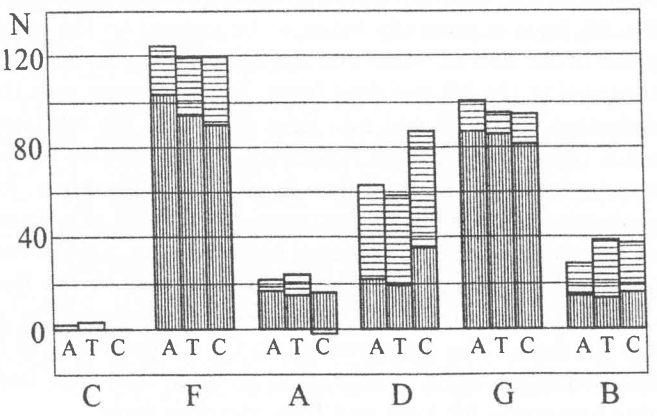


Fig. 5. Propulsive force at selected positions in the stroke. Vertical hatching: drag forces; Horizontal hatching: lift forces

as the pull progresses. This is not surprising because the relative velocity of the hand through the water changes in both magnitude and direction as the stroke progresses, and therefore so does the combination of lift and drag.

At hand position C, the Together geometry is best followed by the Apart geometry. This is an early part of the stroke, termed the catch, and contributes very little to forward propulsion. This contribution arises from lift forces since the velocity vector, and hence the drag force, is essentially vertical. It is interesting to note that the Cupped geometry at this stage of the stroke has no effect on forward propulsion. It might be expected that more lift would have been generated because of the higher camber of the hand profile.

At hand position F, the Apart geometry is best and the Cupped geometry second best, although the difference between the latter and the Together geometry is very small. F is the position of the stroke where maximum propulsive force is developed, more than 20% higher than anywhere else, with the Apart geometry resulting in about 4% more thrust than the other two hand geometry cases. As noted from Fig. 3, although the backward velocity is large and hence results in a high drag component of propulsive force, there is also a significant sideways velocity contributing a significant lift force component. This latter force is largest for the Cupped geometry.

At hand position A, the Together geometry is the best with the Apart geometry second. The magnitude of the propulsive force is surprisingly low compared to other portions of the stroke, particularly considering the high velocity. This is the point of highest Sideways velocity in the stroke, and some re-orientation in the hand position would appear to be feasible in order to generate a higher lift force component in the direction of motion, as appears to be the case for position B, as noted below. The FB velocity component is, however, rather low and low drag force components are therefore to be expected.

Position D is notable for the significant lift forces that are generated, resulting from a significant upward component of velocity, the highest in the stroke, and a hand position with the flow transverse across the fingers. The cupped hand geometry gives a propulsive force significantly larger than the other two hand shapes tested, by over 40%. This is seen to be due to both drag and lift forces, the latter presumably resulting from the larger camber.

Results for position G are similar to those for position F, as is to be expected. They are both at positions of zero downward velocity, strong backward velocity, and significant sideways velocity, the latter being in opposite directions in the two cases. Position G is the second strongest part of the stroke after F and also gives the best results for the Apart geometry. Thus the pattern that emerges is that when strong drag components are present the Apart geometry should be the preferred hand shape.

Conditions at position B are similar to those at A, with strong sideways and limited backward movement. The drag forces are similar in the two cases, but in position B the lift forces are significantly larger than in case A, in fact they are larger than the drag forces. At this position the Together and Cupped geometries are much better than the Apart geometry.

The general conclusions therefore appear to be the following. When the movement is predominantly backward (positions F and G) drag forces are the major contributor to forward propulsion and the best hand geometry is that of the flat hand with the fingers slightly apart. These positions are the major thrust producing positions of the stroke. When the sideways velocity is significantly larger than the backward velocity (positions A and B) the flat hand with fingers together gives the best propulsion. Case B generates significantly more lift force than does case A even though the overall geometry of the flow situations is similar. The main difference is that in case A the thumb is at the leading edge of the movement through the water, whereas for case B it trails. The disturbance induced by the thumb may result in a more disturbed flow across the fingers resulting in less lift. When the velocity is predominantly upward, as at position D, significant lift forces are generated and the cupped hand geometry is best.

There is therefore no single best hand geometry for swimming propulsion for the case tested. This work has only examined a single pull pattern and velocity variation. It is apparent that modifying the pull pattern and hand orientation will have an influence on the results. Nevertheless, these results do indicate that changing hand geometry during the pull could be beneficial. For any particular swimmer a detailed evaluation of the hand path and velocity variation through the stroke would need to be undertaken in order to evaluate benefits that could be obtained by changing hand geometry and orientation. Accounting for flow unsteadiness would be very much more complex, since it arises not only from the acceleration of the hand, but also of the non-uniform induced velocity field, from the rest of the body, through which the hand moves. Methods of computational fluid mechanics are probably the best methods of addressing the problem, although geometrical complexity associated with body motion would make this very expensive.

Acknowledgements

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