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Determining propulsive force in front crawl swimming: A comparison of two methods

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To evaluate the propulsive forces in front crawl arm swimming, derived from a three-dimensional kinematic analysis, these values were compared with mean drag forces. The propulsive forces during front crawl swimming using the arms only were calculated using three-dimensional kinematic analysis combined with lift and drag coefficients obtained in fluid laboratories. Since, for any constant swimming speed, the mean propulsive force should be equal to the mean drag force acting on the body of the swimmer, mean values of the calculated propulsive forces were compared with the mean drag forces obtained from measurements on a Measuring Active Drag (MAD) system. The two methods yielded comparable results, the mean difference between them being only 5% (2 N). We conclude that propulsive forces obtained from three-dimensional kinematic analysis provide realistic values. The calculation of the propulsive force appears to be rather sensitive to the point on the hand at which the velocity is estimated and less sensitive to the orientation of the hand.

Keywords: front crawl swimming, propulsive force, three-dimensional kinematic analysis.

Introduction

Although swimming by humans is frequently the subject of scientific research, detailed quantitative information concerning technique is often lacking. This is mainly a result of the limited possibilities to gather objective information describing swimming techniques. Stroke rate and stroke length are often reported (e.g. East, 1970; Letzelter and Freitag, 1983; Hay, 1988; Keskinen and Komi, 1993), but such data describe the result of the swimming technique rather than the propulsive mechanism. For a more detailed description and more detailed quantification, three-dimensional kinematic analysis would appear to be appropriate.

Schleihauf (1979; Schleihauf *et al.*, 1983) introduced a method to describe patterns of hand and forearm movement for any style of stroke, based on three-dimensional kinematic analysis. Combining this form of analysis with hydrodynamic data, Schleihauf was able to calculate propulsive forces. Schleihauf's method relied on the notion that the propulsive force during swimming is induced by hand and arm movements that generate lift and drag forces (Counsilman, 1971; Schleihauf *et al.*, 1983). The drag and lift forces can be calculated from three-dimensional kinematic analysis when information on hand and forearm position and velocity is combined with the results of research from fluid laboratories, from which coefficients of drag and lift for the hand and the forearm can be obtained. This combination results in a drag force that is opposite to the direction of movement of the hand and forearm, and a lift force that is perpendicular to the direction of hand movement. The vector sum of these forces allows the component in the swimming direction to be defined as the propulsive force.

Although Schleihauf's approach was an important step in quantifying swimming technique, especially quantifying the propulsive force generated by the arms, it had its limitations. First, the coefficients of drag and lift describing the hydrodynamic behaviour of the arm as a whole were obtained for the hand and forearm separately. The assumption that the force on the arm as a whole can be derived from separate coefficients for the hand and forearm is false because of the interaction between the hand and arm segments. Secondly, the force measurements on the hand models were made in two dimensions only (Schleihauf, 1979). One of the directions was opposite to the line of motion and, therefore, was adequate for determining drag forces and drag coefficients. With a two-dimensional approach,

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however, the values reported for the lift coefficient may be too low compared with three-dimensional, real-life swimming, in which the lift force is directed in a plane perpendicular to the drag force. The lift force can only be estimated correctly when forces in three dimensions are measured. Thirdly, the resolution of the kinematic analysis used by Schleihauf was limited, which makes it difficult to obtain accurate hand and forearm orientations and velocities and, from these, to select appropriate values for the drag and lift coefficients. Such inaccuracies will also influence the calculation of propulsive force. To allow a more accurate description of swimming technique and the correct calculation of propulsive forces, the kinematic analysis described here was performed using a video system with a higher resolution. Also, more accurate values of the lift and drag coefficients were used, based on three-dimensional force measurements and determined for the hand and forearm in combination (Berger *et al.*, 1995).

Even using an improved set-up and a fully three-dimensional kinematic analysis of swimming, the question remains as to whether the propulsive forces calculated are in the right direction and of the correct magnitude. This uncertainty is based on certain assumptions that have to be made. One such assumption is that coefficients derived from research in steady-state flow conditions (with constant velocity) can be used in the unsteady flow conditions experienced during real swimming. A comparison of the resulting propulsive forces would be necessary before a three-dimensional kinematic analysis could be applied to calculate these forces and their relation to swimming technique.

According to Newton's third law, the mean propulsive force should equal the mean drag force for any constant swimming speed. The mean drag force on the body during front crawl swimming can be determined using a Measuring Active Drag (MAD) system (Hollander *et al.*, 1986). If, for a particular swimmer at a given speed, the mean propulsive force can be measured correctly, this force should match the mean drag force for that swimmer at the same speed.

A comparison of the propulsive forces obtained from kinematic analysis based on underwater video registration of hand movements using Schleihauf's method with the drag forces obtained with the MAD system yielded comparable values of propulsive force (Hollander *et al.*, in press). Nevertheless, particularly at high swimming speeds, the mean propulsive force tended to be lower than the mean drag force, sometimes by more than 10%. Several reasons have been proposed to account for such an underestimation of mean propulsive force (see above). Moreover, the study by Hollander *et al.* (in press) considered one speed only.

The aim of the present study was to compare the mean propulsive forces determined with an improved three-dimensional kinematic analysis with the mean drag forces obtained with the MAD system. With respect to the method of Schleihauf, the kinematic analysis was improved by the use of a video system (s-VHS) with a higher resolution, in combination with the direct linear transformation (DLT) method. Moreover, more reliable values of the lift and drag coefficients were used derived from three-dimensional force measurements for the hand and forearm in combination (Berger *et al.*, 1995). Based on such a comparison, the sensitivity of propulsive force to the orientation of the hand and forearm, the velocity of the hand and swimming speed can be discussed.

Methods

Nine swimmers (6 males, 3 females; age 19–28 years, height 168–190 cm) consented to participate in the study, six of whom were competitive swimmers of international or national standard and three of whom were triathletes of national standrard. In both the three-dimensional kinematic analysis and measurement of mean drag force using the MAD system, the participants swam the front crawl in a 25-m pool using their arms only, with their legs supported and fixed by a small buoy. The video recordings and the data based on the MAD system were collected on separate days, in random order.

Calculation of propulsive force from the kinematic analysis

Three-dimensional underwater video recordings were used to record the position and orientation of the hand and arm during a full stroke of the right upper limb. Underwater pulling patterns were obtained from three directions (from the right, from an oblique frontal position and from below) using four genlocked Panasonic video cameras (s-VHS, WV-CL350) operating at 50 fields per second. Two cameras on the right side were used to increase the field of view at a large focal length. Only the images of one of these two cameras were used for further analysis. Two periscope systems, based on those described by Hay and Gerot (1991), and an underwater housing were used. An overview of the set-up is presented in Fig. 1. The swimmers were asked to swim a range of speeds (slow, moderate and fast) through an object volume that had previously been calibrated with a reference frame of $2.0 \times 1.0 \times 1.0$ m.

The motion and orientation of the hand were assessed using black markers drawn on anatomical landmarks of the hand and forearm. The landmarks were placed

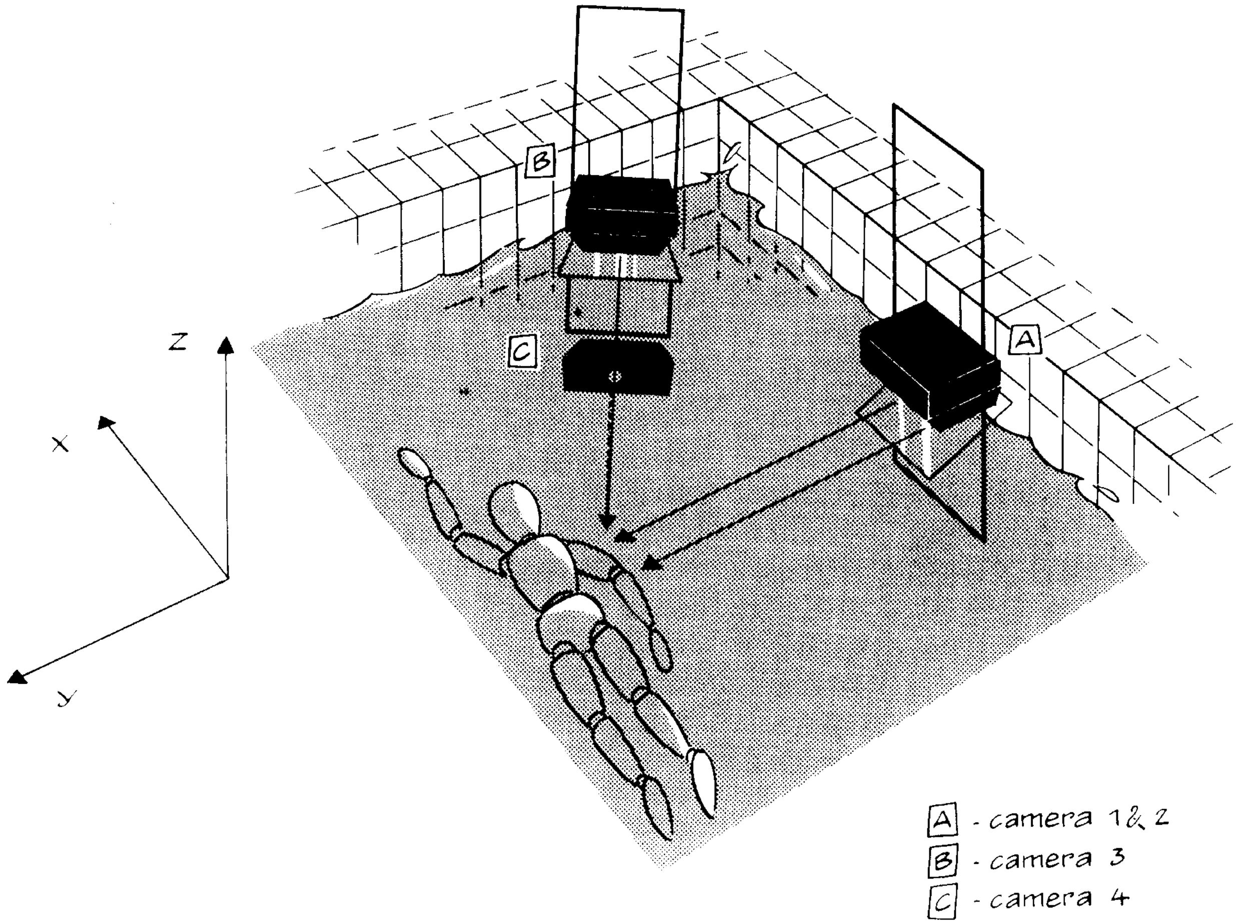


Figure 1 Schematic representation of the experimental set-up. A and B indicate the periscope systems and C represents an underwater housing, which was located ~3 m under water. The angle between the optical axis of cameras 3 and 4 was ~60°. The orientation of the global coordinate system (xyz) is indicated.

on the top of the third finger, the second and fifth metacarpophalangeal joints, the ulnar and radial side of the radiocarpal joint, the olecranon and the radial epicondyle. Image coordinates were obtained manually for every field, and transformed to three-dimensional coordinates using the DLT method (Marzan and Karara, 1975). As almost no propulsive force is delivered when the arm is moving forwards (in the positive x-direction), the analysis of the stroke started at the end of the gliding phase when the hand began to move downwards or sidewards. For each swimmer, about eight strokes were analysed. Absolute coordinates were low-pass filtered (Butterworth fourth-order zero lag filter, with a cut-off frequency of 8 Hz).

The forces generated by the forearm and hand during swimming can be decomposed into drag and lift forces. The magnitudes of the drag force $|\mathbf{F}_d|$ and of the lift force $|\mathbf{F}_l|$ were calculated according to the following equations (boldface is used to indicate a vector quantity and its magnitude is indicated by absolute marks):

$$|\mathbf{F}_d| = 0.5\,\rho A_w C_d |\mathbf{v}_h|^2 \quad (1)$$

$$|\mathbf{F}_l| = 0.5\,\rho A_w C_l |\mathbf{v}_h|^2 \quad (2)$$

where ρ is the density of water, C_d is the coefficient of drag, C_l is the coefficient of lift, $\mathbf{v}_h$ is the velocity of the hand and A_w is the wet surface area.

The wet surface area was estimated, for each swimmer, by taking the circumference of the forearm and hand every 0.02 m along their combined length, and calculated by:

$$A_w = l\left[\sum_{i=0}^{n} y_i - 0.5(y_0 + y_n)\right] \quad (3)$$

where l is 0.02 m, n is the number of segments, y_0 and y_n are the circumferences at the extremes of the hand and forearm (elbow and third finger respectively) and y_i is the circumference of the hand and forearm taken every 0.02 m along the length of the arm.

The drag and lift coefficients were obtained by measuring the force on a model of the hand and forearm when being towed in a water tank (Berger *et al.*, 1995). They are dependent on the orientation of the hand with respect to the direction of hand movement. According to Schleihauf (1979), this direction is expressed by the angle of pitch, defined as the angle between the plane of the hand and the water flow, and the sweep-back angle, which defines the leading edge of the hand. (For a more detailed description of these two angles, see Berger *et al.*, 1995.) With known values of these two angles during swimming, the drag and lift coefficients of the hand–forearm model were obtained from Berger *et al.* (1995).

Hand velocity was measured as the first time derivative of the coordinates of the mid-point between the fifth metacarpophalangeal joint and the top of the third finger. To a first approximation, the velocity of this point represents the velocity of the hand and forearm segment.

The propulsive force – defined as the component of the force in the swimming direction (x) – is equal to the sum of the x-components of the drag and lift forces generated by the hand. Therefore, to calculate the propulsive force, the directions of the lift and drag forces need to be known. The direction of drag force is always opposite to the hand velocity vector $\boldsymbol{v}_h$. The lift force is directed perpendicular to $\boldsymbol{v}_h$. However, all possible vectors perpendicular to $\boldsymbol{v}_h$ lie in a plane. To calculate the direction of the total force vector $\boldsymbol{F}$ during swimming, the force measurements made on a hand-–forearm model in a water tank were used. The measured force $\boldsymbol{F}$ and the hand–forearm model velocity vector, expressed in a local hand coordinate system, can be used to obtain the direction of the force during swimming, if the orientation of this local hand coordinate system with respect to the global system during swimming is known. Therefore, if the direction of the total force $\boldsymbol{F}$ and the drag force $\boldsymbol{F}_d$ (defined opposite to $\boldsymbol{v}_h$) are known, $\boldsymbol{F}_l$ can be obtained by subtracting $\boldsymbol{F}_d$ from $\boldsymbol{F}$. These calculations were made for each video field.

The mean propulsive force during one armstroke was calculated from the sum of the force values divided by the time for one armstroke. The time for one armstroke was obtained from the video fields when the left arm and when the right arm entered the water. To compare the two methods, they were performed at the same swimming velocity. The mean swimming velocity was calculated from a marker on the hip. The forward displacement of the hip divided by the elapsed armstroke time resulted in an estimation of the mean swimming velocity.

Measurement of drag force using the MAD system

The MAD system (Hollander *et al.*, 1986) allows the swimmer to push off from fixed pads at each stroke. The push-off pads, 0.3 m long, were attached to a 23-m long rod, mounted approximately 0.8 m below the surface of the water. The distance between the push-off pads was 1.35 m. The locations of the pads were the same for all swimmers and all swimming velocities. Toussaint *et al.* (1990) concluded that there was no effect of changing the inter-pad distance.

At one end of the swimming pool, the rod was connected to a force transducer, making it possible to measure push-off forces. The push-off forces were low-pass filtered (cut-off frequency of 15 Hz) and digitized at a sample frequency of 100 Hz. To determine the mean drag force and to establish the relationship between drag and swimming velocity, the swimmers were asked to swim 8–10 lengths each at different velocities, from very slow to maximum speed. For each length swum, the mean drag force and the mean swimming velocity were calculated.

To interpolate the drag force at each velocity, the velocity–drag force data were least-squares fitted to the function (Toussaint *et al.*, 1988):

$$D = Av^n \tag{4}$$

where D is mean drag force, v is (mean) swimming velocity, and A and n are parameters that describe the least-squares fit. To obtain the drag force at the velocity performed during the kinematic analysis, the mean swimming velocity was substituted into equation (4). This results in a value for the drag force that can be compared with the mean propulsive force calculated from the kinematic analysis.

Results

A typical example of the side (x–z plane), front (y–z plane) and bottom (x–y plane) views of the trajectories of the top of the third finger are shown in Figs 2a, 2b and 2c respectively. It can be seen from Figs 2a and 2c that, during the first part of the stroke analysed, the hand moved in a forward direction (x-coordinate increases) and almost no propulsion was generated. Figures 2b and 2c show that the diagonal sculling motions are used to create propulsion. The magnitude of the hand velocity is shown in Fig. 2d. The highest hand velocity occurs at the end of the stroke during the 'upsweep phase'.

From the hand velocity, hand orientation and coefficients of lift and drag, the propulsive force during swimming was calculated for each video field (Fig. 3). At the beginning of the stroke, during the first five video fields, the propulsive force is negative, corresponding to the movement of the hand in a forward direction (Fig. 2). A peak force is delivered in the last part of the stroke, corresponding to the upsweep and outsweep

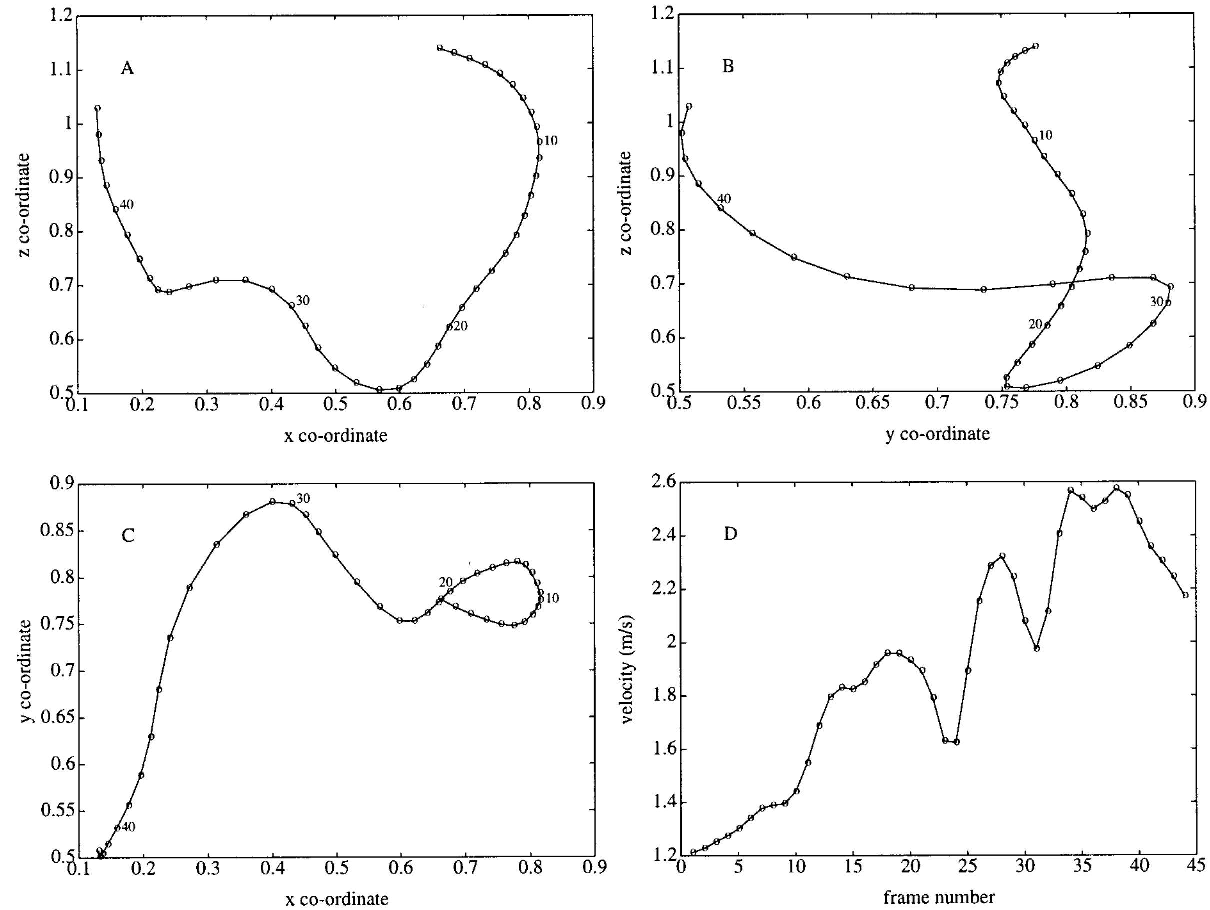


Figure 2 Trajectories of the top of the third finger during one stroke by a female swimmer (in metres). The video field numbers are indicated (one field = 0.02 s). (A) x–z plane, side view; (B) y–z plane, frontal view; (C) x–y plane, bottom view; (D) magnitude of the hand velocity versus video field number.

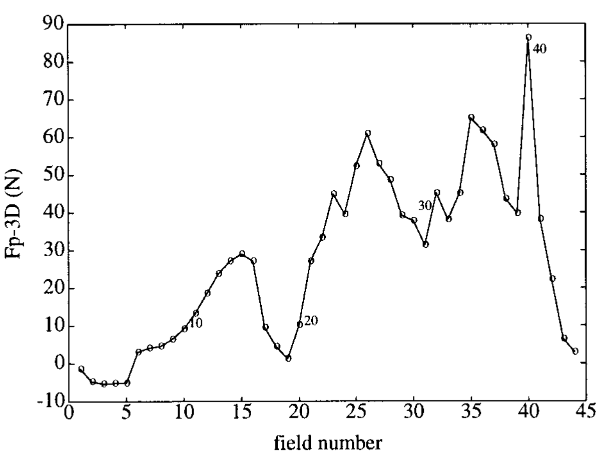


Figure 3 Propulsive force ($F_{p\text{-}3D}$) as a function of time at a mean swimming velocity of 1.3 $m \cdot s^{-1}$ (same swimmer as in Fig. 2).

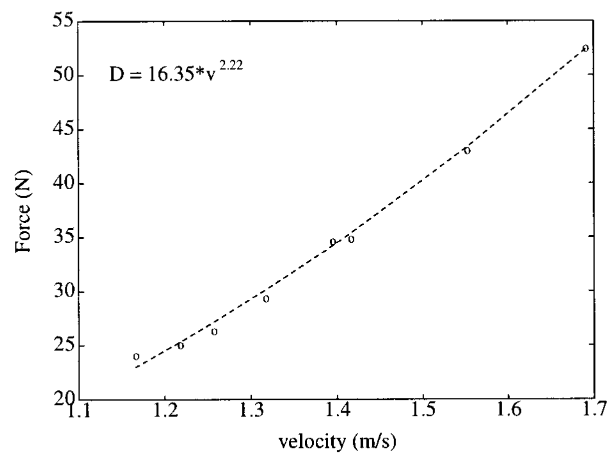


Figure 4 Example of the drag force–velocity relationship (same swimmer as in Figs 2 and 3). The parameters A and n used to determine the regression equation $D = Av^n$ are for this subject: $A = 16.35$, $n = 2.22$.

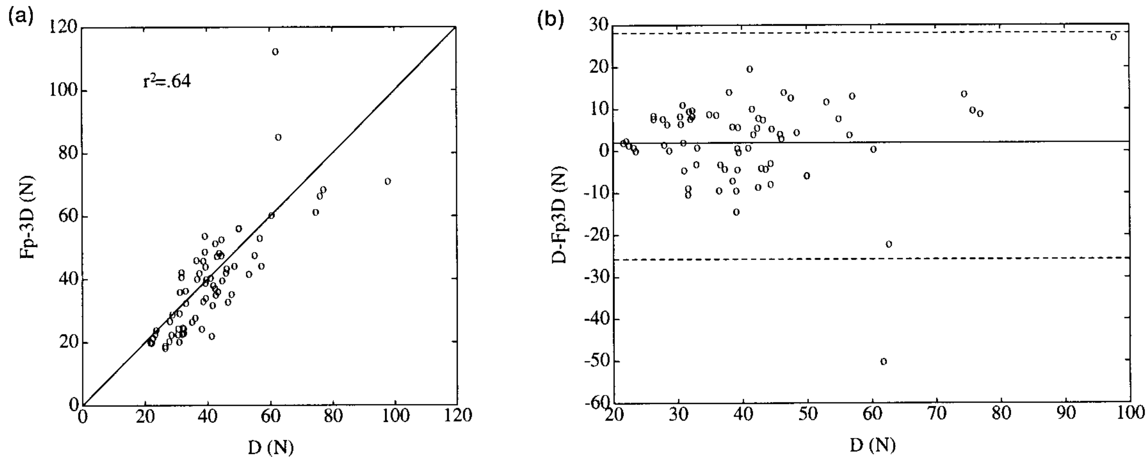


Figure 5 (a) Mean propulsive forces (N) for the two methods: mean drag (D) versus mean propulsive force ($F_{p\text{-}3D}$) for all swimmers and all strokes. The coefficient of determination (r^2) is indicated. (b) The difference between D and $F_{p\text{-}3D}$ for all swimmers and all strokes as a function of D. The horizontal line indicates the mean differences and the dashed lines ± 2 standard deviations.

phase of the stroke. For the stroke shown, the mean propulsive force of 21.1 N was found at a mean swimming velocity of 1.15 $m \cdot s^{-1}$.

The drag force–velocity curve derived using the MAD system is shown in Fig. 4. For this swimmer, the value of exponent n was 2.22 and that of A was 16.4. This curve for each swimmer was used to compare the mean drag force and propulsive forces at the same swimming velocities. The mean value of n was 2.24 ± 0.27 and that of A was 23.6 ± 4.0. These values do not differ from those reported previously (Toussaint *et al.*, 1988).

In Fig. 5a, the mean propulsive forces of all strokes for all swimmers calculated from the kinematic analysis are plotted against the drag forces derived using the MAD system. The data points are more or less spread symmetrically around the line of identity (one point can be considered an outlier). The variance about the regression line is rather small ($r^2 = 0.64$) and shows fairly good correspondence. The mean difference between the mean propulsive and drag forces was 2.0 N (41.1 *vs* 39.1 N), or approximately 5%. The analysis was extended by using the method of Bland and Altman (1986). The individual differences between the mean drag and propulsive forces were plotted against the mean drag (see Fig. 5b). The 95% confidence limits were calculated as −26.1 and +28.1 N, which express the agreement between the mean drag and mean propulsive forces.

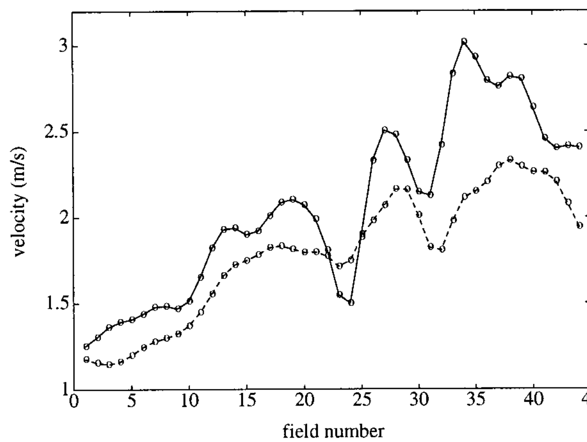


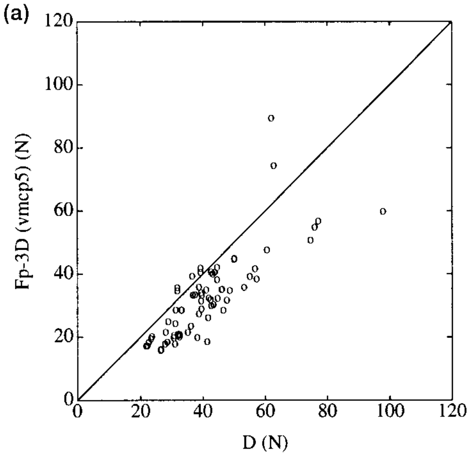
Figure 6 Curve of hand velocity (v_h) versus video field number. v_h calculated using a marker on the top of the third finger (solid line); v_h calculated using a marker on the fifth metacarpophalangeal joint (broken line).

Discussion

In this study, mean propulsive forces, calculated from a three-dimensional kinematic analysis, combined with drag and lift coefficients, were compared with mean drag forces measured using a MAD system. A mean difference of 2 N only was found, or approximately 5%. This fairly good correspondence is surprising on the one hand but satisfactory on the other because of several uncertainties and assumptions. The three-dimensional kinematic analysis would appear to provide realistic values of mean propulsive forces during swimming. The parameters and assumptions determining the degree of correspondence are discussed below.

Velocity of the hand

In a kinematic analysis, the velocity of the hand and forearm has a significant influence on the calculation of



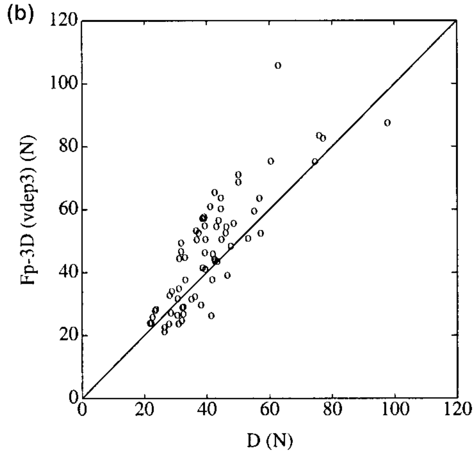


Figure 7 As for Fig. 5 but with different hand velocities: $F_{p\text{-}3D}$ calculated using a marker on (a) the fifth metacarpophalangeal joint (v_{mcp5}) and (b) the top of the third finger (v_{dep3}).

hand and forearm propulsive forces. Since the square of hand speed is used, the effect of this variable on the propulsive forces is magnified. In this study, hand speed was estimated as the first time derivative of the coordinates of the mid-point between the fifth metacarpophalangeal joint and the top of the third finger. To illustrate the effect of choosing a different point on the hand from which to obtain a measure of velocity, two further measures of hand velocity were calculated: with the marker on the fifth metacarpophalangeal joint and with the marker on the top of the third finger. Because of the sculling motions of the hand and arm during swimming, the velocity of the arm can be expected to be higher at the top of the third finger than at the fifth metacarpophalangeal joint. Moreover, the possibility of moving the fingers with respect to the metacarpals can influence the values of both these velocities, which are presented in Fig. 6 for one stroke. The mean difference between these two velocities was $0.28\ m \cdot s^{-1}$ for this stroke, although this difference is not constant throughout a stroke. The mean propulsive forces calculated using the velocity of the fifth metacarpophalangeal joint and of the top of the third finger are compared with the mean drag forces in Figs 7a and 7b respectively. It can be seen that the mean propulsive force is slightly lower when calculated using the fifth metacarpophalangeal velocity and slightly higher when calculated using the velocity of the top of the third finger. The mean difference was −8.65 N (approximately −21%) and 6.85 N (approximately 17%) respectively.

Schleihauf *et al.* (1983) calculated propulsive forces using the velocity at the hand hydrodynamic centre, which was estimated to be 0.6 of the distance between the wrist and long fingertip points. The velocity of this hand hydrodynamic centre must be close to that of the fifth metacarpophalangeal joint. Using this hand velocity, Hollander *et al.* (in press) found that the difference between the mean propulsive and drag forces was 10%. In the present study, using the mean of the velocities of the fifth metacarpophalangeal joint and of the top of the third finger as the estimate of hand velocity, which is a more accurate determination of the orientation of the hand, and drag and lift coefficients derived from a three-dimensional kinematic analysis of force for the hand and forearm combined, resulted in a greater degree of correspondence.

Schleihauf *et al.* (1983) stated that the location of the hand hydrodynamic centre will vary with the angle of pitch and the sweepback angle. The hand-velocity of that centre determines the measured lift and drag forces induced by the hand. However, the velocity of the hand (as a rigid body) will have a translational and rotational component. Moreover, the flow of water around the hand and arm will not be steady. As a consequence, the generation of propulsive force will be more complicated than suggested by equations (1) and (2). The results of this study, however, do show that, to a first approximation, the above simplifications can be applied.

Coefficients of lift and drag

The three-dimensional approach is based on video analysis that includes manual digitizing of markers placed on the hand and forearm of the swimmer. This introduces some errors in the calculation of three-dimensional position data and, therefore, in the orientation of the hand, expressed as the angle of pitch and the sweepback angle. Since the drag

Table 1 Influence of pitch angle (AP) and sweepback angle (SB) on mean propulsive force ($F_{p\text{-}3D}$) for eight strokes of one swimmer

	AP: + 2°	AP: − 2°	SB: + 20°	SB: − 20°
$F_{p\text{-}3D}$ (N)	24.0	22.0	21.5	25.6
Δ (N)	0.8	−1.2	−1.7	2.4
Δ (%)	3.4	−5.1	−5.3	7.5

Note: The change in force caused by a change in angle is shown as Δ in Newtons and as Δ in percent.

and lift coefficients are dependent on these two angles, errors in these angles can lead to errors in the two coefficients.

Payton and Bartlett (1995) quantified the measurement error in propulsive forces calculated from kinematic data. Ten individuals digitized the pull sequence of a breaststroke, which was filmed using two cameras. Payton and Bartlett reported that errors in the pitch and sweepback angles produced mean errors in the lift and drag coefficients of 9% and 6% respectively, which produced a mean error in the resultant force of 8% when combined with a mean hand speed error of 2%. It is plausible that the use of four cameras in the present study, instead of the two used by Payton and Bartlett, led to smaller errors in the two angles and, therefore, a smaller error in the mean propulsive force. To evaluate the sensitivity of this force on each of the two angles, the deviation in the mean propulsive force owing to systematic errors in the pitch angle (2°) and sweepback angle (20°) was evaluated. The magnitudes of these angle variations were the maximum calculated deviations. They are a consequence of the set-up of the towing experiments (Berger *et al.*, 1995) in which the coefficients of lift and drag were measured at distinct steps in pitch and sweepback angle (not always resembling the actual angles during swimming). The results of this sensitivity analysis are presented in Table 1. It is clear that the propulsive force is not very sensitive to these angle deviations (8.5% and 12.8% force change respectively). Moreover, the angle deviations will not be systematic but random, resulting in a smaller deviation in the mean value of the propulsive force.

Swimming velocity

Measurement of the drag force (= mean propulsive force) was not possible in the same session as the video recordings for the three-dimensional kinematic analysis. Since a comparison of propulsive forces should be made at the same swimming velocity, the velocity during the three-dimensional analysis was used for the calculation of mean drag. The only indirectly obtained parameter in the drag is the swimming velocity. Calculation of the mean drag with a velocity 0.1 $m \cdot s^{-1}$ higher resulted in a deviation of 4.9 N, or approximately 16%. Small errors in the estimation of swimming velocity are inevitable. The position of the hip (used to estimate swimming velocity) could not be determined for the complete stroke; therefore, only the positions of the hip at the point of entry into the water of the left and of the right hand were analysed. This resulted in a displacement in the x-position of the hip based on two video fields only. The mean drag is sensitive to swimming velocity because of the exponent n (~2) in equation (4). As a consequence, a small deviation in this velocity can lead to a large deviation in the mean drag. This inaccuracy in the velocity is the consequence of creating a relatively small field of view around the swimmer's arm. Therefore, the position of the hip was not always in the view of all four cameras.

The MAD system enables the quantification of the propulsive force during front crawl swimming for a range of speeds. Although the manner of swimming with the MAD system is similar to real front crawl swimming, when observed from above the water surface (Hollander *et al.*, 1986), and EMG data show comparable muscular patterns (Clarys *et al.*, 1987), the technique during the push-off phase is different. Therefore, it can be expected that the variation in velocity of actual swimming is different from the variation in swimming velocity using the MAD system. If the variation in velocity with the MAD system is larger than in actual swimming, the mean drag calculated will be an overestimate.

Concluding remarks

According to Newton's laws, the mean drag force will be equal to the mean propulsive force at constant velocities. The calculation of propulsive forces from a three-dimensional kinematic analysis, combined with coefficients of lift and drag, provided realistic values of mean propulsive force during front crawl swimming. Although this method is sensitive to some errors, the mean propulsive force deviated 5% only from the mean drag force. Our results indicate that this method of three-dimensional kinematic analysis can be used to estimate the contributions of lift and drag forces to the propulsive force and to describe swimming technique in a more quantitative manner. However, the study of swimming technique remains somewhat artificial, since the entire stroke (including the leg kick) cannot yet be investigated in detail using the specific methods described.

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