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Improved accuracy and reliability of sweepback angle, pitch angle and hand velocity calculations in swimming

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Abstract

The estimation of forces in swimming using the *quasi-static* approach (Schleihauf, In: J. Terauds, J.P. Clarys (Eds.), Swimming III, International Series on Sports Sciences, Vol. 8, University Park Press, Baltimore, 1979, 70–109) has been popular in recent years as propulsion is an important determinant of performance. The aim of this study was to establish the accuracy and reliability of current and newly proposed procedures for the reconstruction of hand velocity, sweepback angle and pitch angle from underwater three-dimensional video analysis. A full-scale mechanical arm capable of simulating a controlled and highly repeatable underwater phase of the front-crawl stroke was filmed for a set of five trials. A seven-point model of the arm and hand was then digitised at 25 Hz. Hand velocity, sweepback angle and pitch angle were calculated using the procedures of Schleihauf (1979), Berger et al. J. Biomech. 28 (1995) 125–133 and a newly proposed procedure (Lauder). Statistical comparisons were made between procedures to establish their relative accuracy and reliability throughout the stroke. The mean absolute error in measurement of hand velocity between points on the hand was very small (± 0.04 and $\pm 0.06\,\mathrm{m\,s^{-1}}$ in the x and z directions, respectively). The mean errors in sweepback angle and pitch angle were, respectively, 9.3° and 7.6° (Berger), 10.1° and 8.1° (Schleihauf) and 10.7° and 7.0° (Lauder). Agreement between procedures showed the standard error between Schleihauf and Lauder to be the least (Schleihauf and Lauder, 0.4°; Berger and Schleihauf, 1.3°; Berger and Lauder; 1.6°). The use of four points in the reconstruction of the orientation of the hand (Schleihauf and Lauder procedures) was shown to be less sensitive to errors in the digitising procedure. The reconstruction procedure proposed in this study (Lauder), further reduced the sensitivity to digitising error in the reconstruction of sweepback and pitch angles in swimming. © 2000 Elsevier Science Ltd. All rights reserved.

Keywords: Hand orientation; Quasi-static approach; Sweepback angle; Pitch angle; Reliability

1. Introduction

The most popular procedure for estimating propulsive forces of the hand in swimming (the *quasi-static* approach) uses a combination of kinematic data derived from underwater video analysis and hydrodynamic lift and drag force coefficients for the hand–forearm obtained from water channel experiments (Schleihauf, 1979; Berger et al., 1995). Schleihauf (1979) and Berger et al. (1995) determined lift and drag coefficients using tests performed with a hand–forearm model immersed in various orientations in an open water channel under steady flow conditions. The lift and drag coefficients are functions of the hand's orientation and essentially independent of the magnitude of the velocity vector across the range of swimming speeds.

The method of Schleihauf is not without limitations. Its accuracy is dependent on both the accuracy of the three-dimensional kinematic data from the underwater video analysis — used in the calculation of hand velocity, sweepback angle and pitch angle — and the accuracy of the drag and lift coefficients which are used (Eqs. (1) and (2)) to calculate the propulsive forces in the swimming environment (Fig. 1):

$$F_L = \frac{1}{2}(\rho \cdot v^2 \cdot C_L \cdot A), \tag{1}$$

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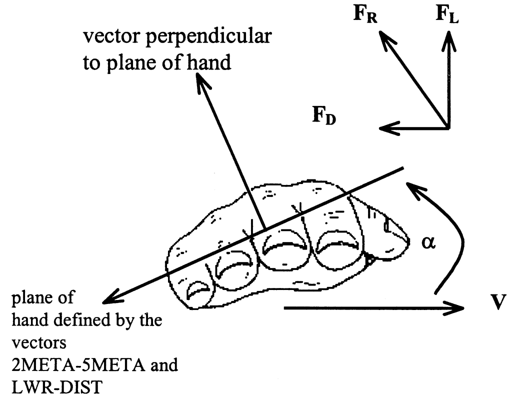

Fig. 1. Lift (F_L), drag (F_D) and resultant (F_R) forces in swimming as determined by the angle of attack (α) (adapted from Toussaint *et al.*, 2000).

$$F_D = \frac{1}{2}(\rho \cdot v^2 \cdot C_D \cdot A). \quad (2)$$

The sweepback angle defines the leading edge of the hand relative to the fluid flow and is found by projecting the hand velocity vector onto the plane of the hand (Fig. 2). The pitch angle is defined as the angle between the hand velocity vector and the plane of the hand (Fig. 1). The *quasi-static* approach requires that these angles are calculated accurately, as it is these angles which determine the coefficients of lift and drag that are used in the hydrodynamic Eqs. (1) and (2).

This widely used approach has never been experimentally verified. Two issues need to be explored; the influence of the accuracy of reconstruction and validity of the utilised models. The current work attempts to address the first issue. The aim of this study was to establish the accuracy and reliability of current and newly proposed procedures for the reconstruction of hand velocity, sweepback angle and pitch angle from underwater three-dimensional video analysis.

2. Methods and materials

A full-scale mechanical arm capable of simulating a controlled and highly repeatable underwater phase of the front-crawl stroke was filmed using a three-dimensional underwater set-up. Two Panasonic VHS video cameras (WV-F15E) fitted with ×12 zoom lenses (WV-LZ15/12E) and connected to Panasonic VHS video recorders (AG 7350) were used to record the images. One camera (Camera 1) was mounted within a perspex underwater housing, positioned 3.7 m from the arm support, while the other camera (Camera 2) was mounted on a tripod (Monferotto) and positioned 1.25 m behind a glass underwater window beneath the pool. The distance from the glass to the arm in this direction was 1.8 m perpendicular to the front-on camera. Both cameras were aligned vertically and horizontally and checks were made to ensure that the focal axis of each camera was perpendicular to the glass. The cameras were event synchronised using a Panasonic Genlock and cable.

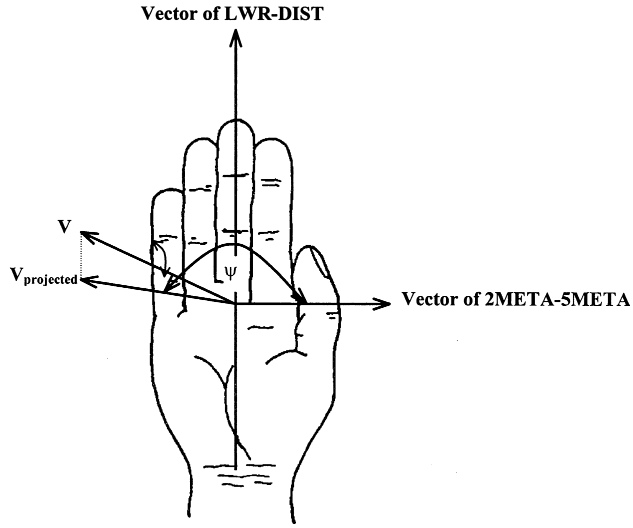

Fig. 2. Determination of sweepback angle (ψ) (adapted from Schleihauf, 1979).

The arm movement simulated strict shoulder rotation. However, the movement involved both acceleration and deceleration phases and the hand was orientated at an angle to the direction of rotation. Due to inherent degrees of freedom in the construction and lateral movement caused by the water resistance, the motion required three-dimensional reconstruction.

All digitising was undertaken manually using an M-image video capture board and an Acorn 5000 computer with associated software (Bartlett and Bowen, 1993). Three-dimensional reconstructions were performed using 12 calibration points (Lauder et al., 1998). The calibration object used was the Peak Performance® 24-point calibration frame. Only the inner 16 points were used for reconstruction, providing a reconstruction volume of 1.0 m × 0.5 m × 0.8 m in the *x*, *y* and *z* directions, respectively. The absolute mean error in each axis was recorded as 0.15, 0.4 and 0.11% of calibration volume length in the *x*-, *y*- and *z*-axis, respectively. For a set of five trials, a seven-point model of the left shoulder, right shoulder, elbow and wrist, second metacarpophalangeal joint, fifth metacarpophalangeal joint and distal end of third phalange, was digitised at a sampling rate of 25 Hz. Each trial started at the first frame of the movement and ended when the arm reached its maximum range of movement (approximately 160° from the start position).

2.1. Vector length reconstruction

In the *quasi-static* approach for estimation of hand forces, it is necessary to define the plane of the hand using

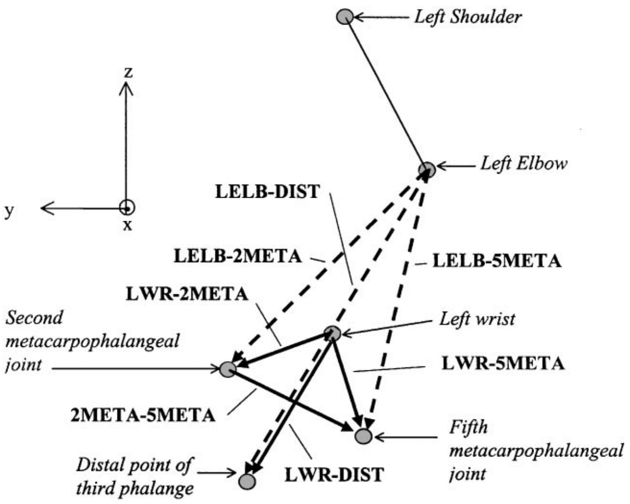

Fig. 3. Diagram showing the points used for unit vector reconstruction of hand orientation.

digitised landmarks to calculate sweepback angle and angle of pitch (Schleihauf, 1979). The ability to reconstruct these vectors accurately is therefore of prime importance. To assess accuracy, the following unit vectors were defined and derived from the raw coordinate data (see Fig. 3).

For each vector, the percentage error in length was calculated across the five trials. The results provide an indication of the variability in the three-dimensional reconstruction of these vectors. Mean, standard deviation (S.D.) and coefficient of variation were calculated for each error in vector length. The reliability of each vector length reconstruction was again calculated by the Limits of Agreement method. Accuracy was assessed by estimation of the absolute error of the mean percentage errors for each vector length reconstruction.

The purpose of the analysis of variation in vector length was to establish which vector lengths were consistent throughout the motion. The most reliable vectors can then be used in subsequent calculations for sweepback angle and pitch angle (see below) to assess if more reliable estimates of both angles can be obtained from combinations of different vectors.

2.2. Hand velocity data

In the *quasi-static* approach, the velocity of the hand and forearm has a significant influence on the magnitude of hand and forearm propulsive forces, since their calculation is dependent on the square of the velocity (Eqs. (1) and (2)). To assess the accuracy and reliability of hand velocity calculations, the velocity components in the x and z directions of the second and fifth metacarpophalangeal joint, distal end of the third finger and the midpoint between the second and fifth metacarpophalangeal joint, were calculated for each trial using the raw coordinate data of each point and the angular velocity data of the shoulder. The y (medio–lateral) direction was not considered for this study as there was little or no hand motion in this direction due to the mechanical constraints. Limits of Agreement was used to assess reliability and an Analysis of Variance (ANOVA) was used to assess for differences in reconstruction of hand velocity between points. The absolute error of the mean measurements of hand velocity in the x and y directions across the four points was used to estimate accuracy.

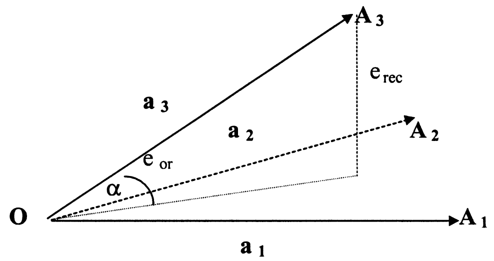

Fig. 4. Vector definitions for error estimation in plane reconstruction.

2.3. Sweepback angle (ψ) and Pitch angle (α)

Two methods have been used in swimming research to reconstruct sweepback and pitch angles, one by Schleihauf et al. (1983) and the other by Berger et al. (1995). The difference between these two methods lies in the combination of vectors used to reconstruct sweepback and pitch angles. To assess the accuracy and reliability of both methods, the raw data were used to reconstruct the sweepback angle and pitch angles as described by Schleihauf et al. (1983) and Berger et al. (1995) (for a full definition see Payton and Bartlett (1995) and Berger et al. (1995), respectively). In addition, sweepback angle and pitch angle were calculated, using newly proposed algorithms (Lauder 1–5), using a different combination of vectors. The basis of this was to establish whether the points and vectors previously used, yield the most accurate and reliable sweepback and pitch angles.

The theoretical estimate of the error of reconstruction is outlined below.

If four points are known then the following three vectors can be defined (see Fig. 4)

If it is known that these points lie in a plane then an error of reconstruction can be defined. The measure of error of reconstruction (e_{rec}) of a plane from four known points in terms of distance can be defined as follows:

$$e_{\text{rec}} = \frac{1}{3}\frac{\mathbf{a}_1\mathbf{a}_2\mathbf{a}_3}{|\mathbf{a}_1 \wedge \mathbf{a}_2|}, \tag{3}$$

where $\mathbf{a}_1\mathbf{a}_2\mathbf{a}_3$ is the mixed product of the above vectors (three times the volume of the tetrahedron) and $|\mathbf{a}_i \wedge \mathbf{a}_j|$is the relevant vector product.

Table 1
Vector combinations used for hand orientation reconstruction

Method	Vector combination[a]						
	LWR-2META	LWR-DIST	LWR-5META	2META-5META	LELB-2META	LELB-DIST	LELB-5META
Berger		✓	✓				
Schleihauf		✓		✓			
Lauder 1				✓		✓	
Lauder 2						✓	✓
Lauder 3					✓	✓	
Lauder 4			✓			✓	
Lauder 5	✓					✓	

[a]For definitions of vectors refer to Fig. 4.

The geometrical meaning of the above relationship is that the error is equal to the distance between the end point of the vector and the base of the tetrahedron. This estimate is highly dependent on the vector's length. However, the more important, and normalised, measure is the angle between the vector $\mathbf{a}_3$ and the same base. This is the error of orientation (e_{or}) and can be expressed as

$$e_{or} = \sin^{-1}\left(\frac{e_{rec}}{|\mathbf{a}_3|}\right); \quad (4)$$

in each case $|.|$ denotes the standard Euclidean norm, namely

$$|\mathbf{a}_i| = \sqrt{\textstyle\sum_i a_{ij}^2}. \quad (5)$$

The rationale for introduction of an angular measure for the orientation error is that this error is a function of the out-of-plane deviation of the fourth point in relation to the plane defined by the other three. It is obvious that in the static case the error could be minimised by an appropriate selection of three out of the four points:

$$e_{or} = \min_k \sin^{-1}\left(\frac{e_{rec}}{|\mathbf{a}_k|}\right), \quad (6)$$

However, this cannot be applied to quasi-static or dynamic case as one cannot change the selected configuration as this could lead to an even greater error owing to loss of continuity in the time series. In this case, the strategy should aim for stability of the selected configuration (reduced sensitivity to random errors in the derived data). It is claimed, therefore, that a way of improvement of the accuracy is to select points on the arm which are as far away from each other as possible. The rationale is that the scale of error has a lower limit of at least one pixel. Depending on the resolution of the system and size of field of view, the real life length could vary but is normally a few millimetres; it would not exceed, in normal circumstances, two to three pixels. If the ratio between the digitising error and the average vector length is expressed as

$$\varepsilon = e_{dig}/|\text{mean}\mathbf{a}_i|, \quad (7)$$

and is noted that

$$\Rightarrow e_{rec} \leqslant e_{dig}$$

Then the error of orientation $e_{or} \approx sin^{-1}\varepsilon$ and the following is valid:

$$\lim_{\varepsilon\to 0} \sin^{-1}\varepsilon = 0, \quad (8)$$

Hence the greater the length of the vectors, the smaller the error factor ε and, therefore, the less the error of orientation. The analysis strongly suggests that a greater distance between the points should be beneficial in reducing the error. This was the rationale for introduction of point combinations.

In total, five additional combinations were identified. In all cases Limits of Agreement were used to assess the reliability of the methods. The points used in construction of sweepback and pitch angles for this study are briefly summarised in Table 1.

As the hand in this study was rigidly fixed to the arm, it fulfils the assumption that the sweepback angle is constant throughout the movement. Hence, any variation of sweepback angle with time provides a direct initial assessment of the accuracy of each method. For sweepback angle and pitch angle, the absolute error of the mean measurements was calculated for each method of reconstruction. This approach was used to assess the accuracy of the Berger and Schleihauf methods together with the "best" of the new algorithms proposed in this study (Lauder 1–5). The reliability of each method was assessed using Limits of Agreement (Bland and Altman, 1986). To assess the comparability between these three methods, Limits of Agreement (Bland, 1995) were calculated between Berger and Schleihauf, Berger and Lauder 1–5 and Schleihauf and Lauder 1–5.

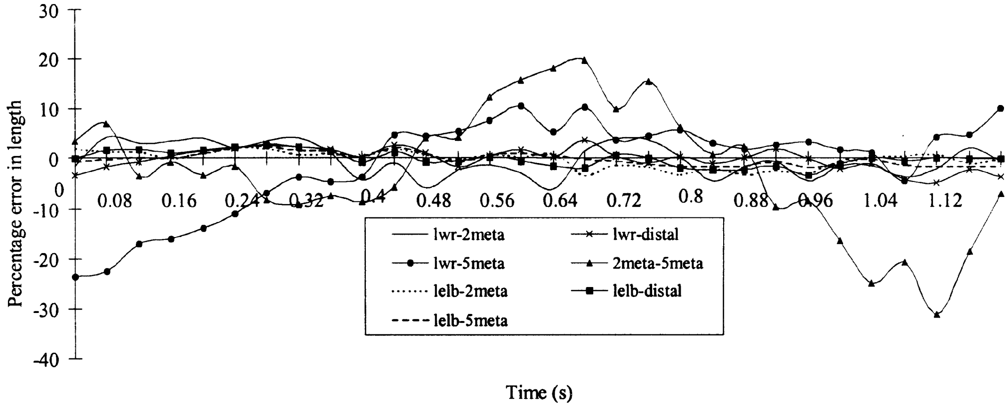

Fig. 5. Mean percentage error in vector length reconstruction for the hand model across five trials.

3. Results

3.1. Vector length reconstruction results

Fig. 5 shows the mean percentage error in length of each vector for the five trials analysed. The mean percentage error in vector length reconstruction ranged from 1.28% (LELB-5META) to 8.3% (2META-5META) as shown in Table 2. These results, and those in Table 2 for coefficient of variation, show improved reliability in vector length reconstruction for those vectors that include the elbow and the distal end of the third finger as points for reconstruction.

3.2. Hand velocity results

The velocity profiles of the four points of the hand, for one trial, are shown in Fig. 6. The mean absolute error in measurement of hand velocity between points on the hand was 0.04 and 0.06 $\mathrm{m\,s^{-1}}$ in the x and z directions, respectively. Maximum values were calculated to be 0.08 and 0.20 $\mathrm{m\,s^{-1}}$ in the x and z directions.

Statistical analysis of the reliability of hand velocity reconstruction (Fig. 6) shows good agreement between different points used to reconstruct hand velocity. Agreement values ranged between ± 0.66 and $\pm 0.91\,\mathrm{m\,s^{-1}}$. The error in measurement of hand velocity between points on the hand was very small. Mean values of 0.04 and 0.06 $\mathrm{m\,s^{-1}}$, were recorded for error in the x and z directions, respectively. These values equate to 1.9 and 2.8% of the mean hand velocity throughout the stroke.

3.3. Sweepback angle and Pitch angle results

Fig. 7 shows the mean sweepback and mean pitch angle profiles for the Berger, Schleihauf and "best" Lauder (1) methods of reconstruction. Given that the arm–hand positional data was the same for each method, this figure shows the variation in the calculation of sweepback angle and pitch angle when different methods of reconstruction are used. Clearly from the results presented in Table 3, the methods of reconstruction, Lauder 2–5, gave poorer reliability than the methods of Berger, Schleihauf and Lauder 1.

The mean errors in reconstruction of sweepback angle and pitch angle for the Berger, Schleihauf and Lauder 1 methods are shown in Table 4. For Berger the mean errors were 9.3 and 7.6° for sweepback and pitch angles, respectively. For Schleihauf the errors were 10.1 and 8.1° respectively and for Lauder 1 the errors were 10.7° and 7.0°.

When the best (most reliable) reconstruction from Lauder 1 is compared with Berger and Schleihauf methods, the Standard error between methods was 1.6° between Berger and Lauder 1, 0.4° between Schleihauf and Lauder and 1.3° between Berger and Schleihauf. The

Table 2
Coefficient of variation and mean absolute error in vector length reconstruction across five trials

	Vector						
	LWR-2META	LWR-DIST	LWR-5META	2META-5META	LELB-2META	LELB-DIST	LELB-5META
Coeff. of variation (%)	55.6	73.8	78.6	74.1	68.6	72.9	60.7
Mean absolute error (% length)	4.1	2.7	5.0	8.3	1.9	1.6	1.3

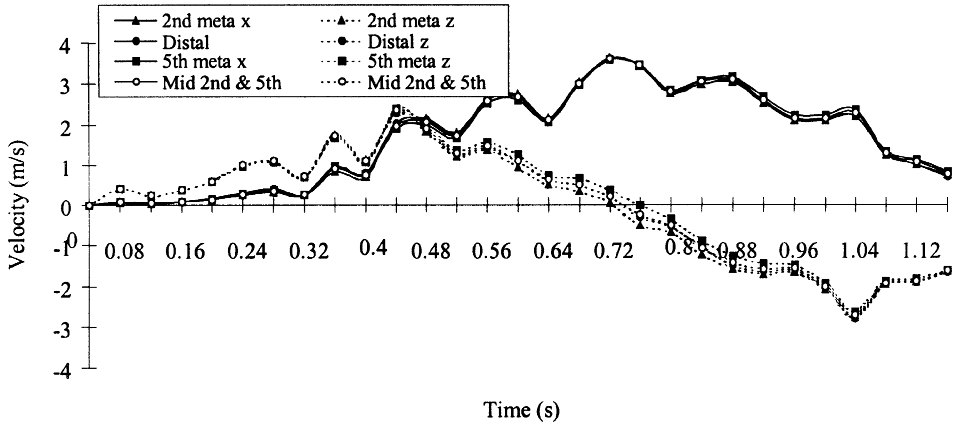

Fig. 6. Velocities of four points on the hand in the x and z direction (raw data).

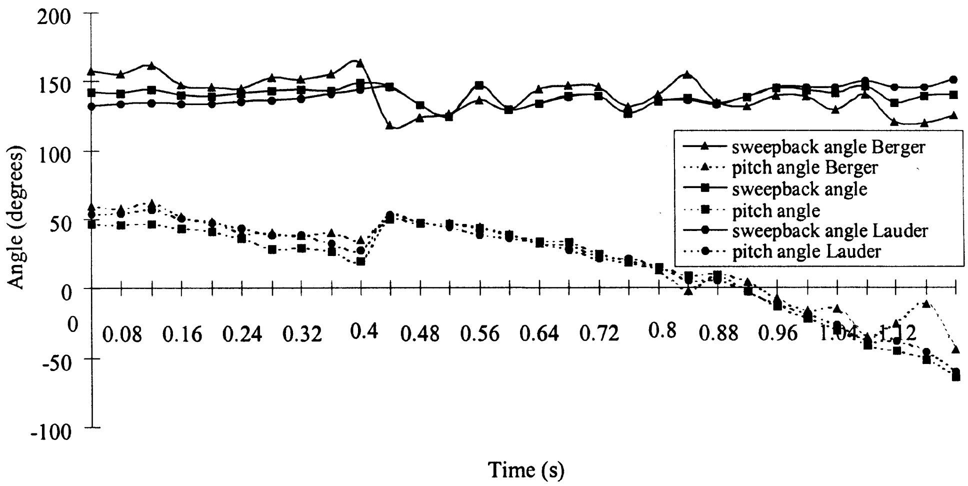

Fig. 7. Comparison of methods for calculating Sweepback angle and Pitch angle.

Table 3
Comparison of reconstruction methods used to determine Sweepback angle and Pitch angle

Method	95% Confidence Intervals (±)	
	Sweepback angle (°)	Pitch angle (°)
Berger	33.0	27.3
Schleihauf	34.2	28.8
Lauder 1	36.3	25.2
Lauder 2	50.9	37.1
Lauder 3	41.8	29.9
Lauder 4	38.5	36.0
Lauder 5	41.8	29.8

SE results clearly indicate that the methods of Schleihauf and Lauder 1 differ greatly from Berger in the reconstruction of sweepback angle. The SE of the mean for each method also differed (Berger: 1.3°; Schleihauf: 1.0° and Lauder 1: 1.1°). The boundaries of agreement between methods are shown in Figs. 8a–c.

4. Discussion

The method introduced by Schleihauf (1979); Schleihauf et al. (1983) for estimation of hand forces through the description of the patterns of movement of the swimming stroke, based on three-dimensional kinematic analysis and hydrodynamic lift and drag coefficients for the hand (*quasi-static* approach), has been persistently questioned (Pai and Hay, 1988; Berger et al., 1997; Toussaint et al., 2000). The aim of this paper has been to address some of the issues that have been raised about the accuracy of the *quasi-static* approach. Specifically, we sought to establish the accuracy and reliability of the kinematic data from underwater video analysis used in the *quasi-static* approach.

4.1. Vector reconstruction

Fig. 5 and Table 2 show that the vectors with the greatest variability and the largest mean error are those

Table 4
Mean, minimum and maximum errors in reconstruction of Sweepback angle and Pitch angle for Berger, Schleihauf and Lauder 1 reconstruction methods

Method	Sweepback angle (°)			Pitch angle (°)		
	Min error	Max error	Mean error	Min error	Max error	Mean error
Berger	1.7	18.1	9.3	1.2	17.1	7.6
Schleihauf	4.8	17.9	10.1	1.5	15.5	8.1
Lauder 1	4.5	20.1	10.7	1.1	14.1	7.0

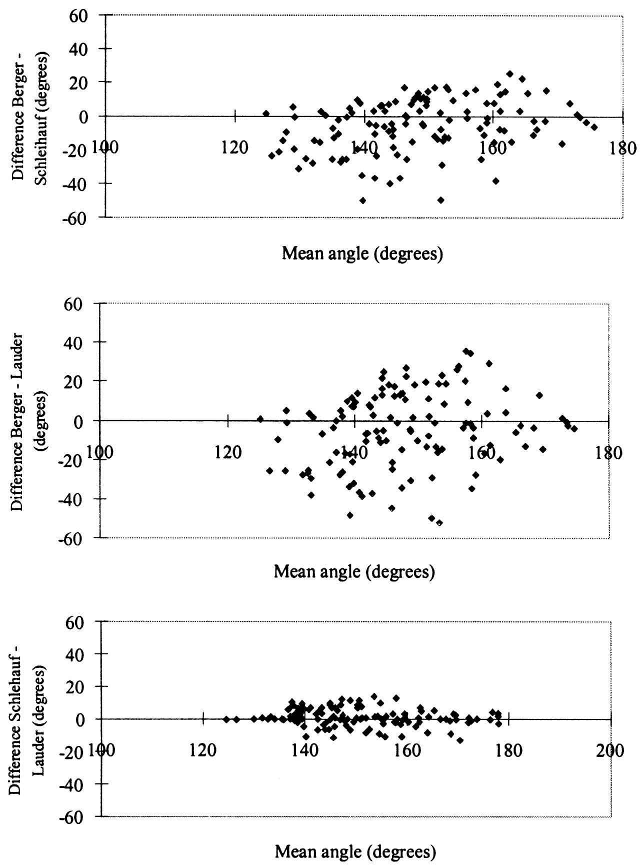

Fig. 8. (a) Agreement between Berger and Schleihauf method for reconstructing sweepback angle. (b) Agreement between Berger and Lauder methods of reconstructing sweepback angle. (c) Agreement between Schleihauf and Lauder method of reconstructing sweepback angle.

vectors where the points are closest together (with the exception in the variability of LWR-2META). The points included in these vectors are the points of the hand that are currently used to reconstruct vectors that define the plane of the hand, in the reconstruction of sweepback and pitch angles (Schleihauf, 1979; Berger et al., 1995). For the vectors that include the elbow and the three points on the hand (fifth metacarpophalangeal, second metacarpophalangeal and distal point of the third finger), the variation and mean error was considerably less (Table 1). Values for these vectors include a range of mean percentage error, from 1.28% (LELB-5META) to 1.92% (LELB-2META). Unfortunately, there are no published data in swimming for comparison.

To define a plane, a minimum of three points are needed. In swimming, wrist angle has been shown to vary very little throughout the stroke, as it is the body roll movement, shoulder movement and elbow movement that changes the motion of the hand through the water (Hay et al., 1993; Lui et al., 1993). Based on the results from the present study, it is feasible that improved accuracy and reliability in hand orientation calculations can be achieved through a combination of vectors which include those with less variability and a greater accuracy in their reconstruction, i.e. those which include the elbow. This approach works best for swimming motions that involve near zero wrist joint angles. This is the case with elite swimmers when they generate the highest propulsive forces (mid-underwater phase of the stroke analysed in this study).

It was from these results that the combinations of vectors described previously were analysed to identify combinations that improved the reliability and accuracy of sweepback angle and pitch angle calculations. The results from these calculations are discussed below.

4.2. Hand velocity

The importance of the accurate and reliable measure of hand velocity is not only reflected in Eqs. (1) and (2) (v^2), but also in the calculation of hand orientation as sweepback angle and pitch angle are both measured relative to the velocity vector. This study sought to establish the reliability and accuracy of hand velocity calculations in the major directions of motion for the arm simulation model (x and z), when using different points on the hand. From Fig. 6 very little difference is evident between the points used for hand velocity reconstruction in the x and z directions. The mean absolute error was 1.9 and 2.8% of the mean resultant hand speed in the x and z directions, respectively, equating to Payton and Bartlett (1995), who reported errors in hand velocity measurement (mid-second and fifth metacarpophalangeal) of 6%

for a single digitisation and 2% for repeated digitisation (10 repeats). The results from the present study are at the lower end of the range of errors presented in Payton and Bartlett (1995) for 10 digitisations and again highlight the accuracy of the data collection procedures followed. Clearly, the calculation of hand velocity reported in the present study shows improved accuracy and reliability compared to previous ones.

Berger et al. (1999) also illustrated the importance of hand-speed calculation. In their study, hand speed was calculated as the first derivative of the mid-point of the fifth metacarpophalangeal joint and the tip of the third finger. To illustrate differences in hand velocity calculation, two further points were chosen; the fifth metacarpophalangeal joint and the tip of the third finger. The mean difference in hand velocity was calculated as $0.28\,\mathrm{m\,s^{-1}}$. In Schleihauf et al. (1983), the point used for hand velocity reconstruction was the hydrodynamic centre of the hand, which was estimated to be 0.6 of the distance between the wrist and the third fingertip. The velocity of this point must be close to the point used by Berger et al. (1999) and the mid-point of the second and fifth metacarpophalangeal joint used in the present study. Berger et al. (1999) claim that, by using the midpoint of the fifth metacarpophalangeal joint and the tip of the third finger, the greatest correspondence between hand velocity and propulsive force is achieved. It is difficult to see the evidence for this from the reported study as no details of their analysis are presented in the paper.

4.3. Sweepback angle and Pitch angle

The combination of vectors used in Lauder 1 (LELB-DIST and 2META-5META) was in agreement with Berger and Schleihauf for sweepback angle and improved agreement for pitch angle. A comparison of sweepback angle and pitch angle as calculated by Berger, Schleihauf and Lauder 1 methods is illustrated in Fig. 7. As can be seen, all three methods show similar profiles. An analysis of the SE in sweepback angle, between methods, showed that the Schleihauf and Lauder methods were very similar ($\mathrm{SE} = 0.4^{\circ}$). The SE between Berger and Schleihauf and Berger and Lauder were 1.3 and 1.6°, respectively. The boundaries of agreement, shown in Figs. 8a–c, illustrate the similarity between methods. It is clear that the Berger method differed from that of Schleihauf and Lauder 1. Given that Berger et al. (1995) reported the procedure for the calculation of sweepback angle and pitch angle as being based on Schleihauf (1979), the expected results would be that the agreement between these methods would be exceptionally high. This was not the case. It is possible that in defining a local coordinate system for the hand, additional variation in the measurement of these angles was introduced by Berger et al. (1995).

The procedure of Schleihauf has a clear advantage over the Berger's procedure as it utilises four points on the hand. It uses two vectors defined by those four points and although the points do not lie in a single plane, by the means of a simple translation of one of the vectors they would be positioned in a plane. This definition is less sensitive to errors if the errors are random (equiprobable) which is normally the case with digitising and image-processing errors. The other advantage of the procedure is that it is less sensitive to slight changes in the hand shape utilised by different swimmers. This is a significant advantage when the forces acting on the forearm–hand complex are calculated as these calculations will not be significantly influenced by differences in swimmers hand shapes.

Berger's procedure in contrast uses only three points from the four defined above. Therefore, the procedure is more sensitive to errors in the points coordinates and can be affected by relatively small random errors in point reconstruction or a negligible change of shape of swimmers' hands.

Payton and Bartlett (1995) and Berger et al. (1999) also assessed the accuracy of measuring sweepback and pitch angles. Payton and Bartlett, reported errors in sweepback angle and pitch angle ranging from 2.5 to 12.3° and 2.9° to 10.1°, respectively. From these they estimated that average errors in the coefficient of lift and the coefficient of drag, based on measurements of these angles, were 27 and 20%, respectively. The errors reported in Payton and Bartlett (1995) represent the variation in measurement of these angles across 10 trials and not the true measurement error in sweepback and pitch angle. The mean error in measurement for each method in the present study was within the range of variability reported in Payton and Bartlett (1995). Given the relatively small area over which the vectors used in the reconstruction of these angles are measured, it is clear that the method used for reconstruction in the present study is both accurate and reliable compared to previous research. The findings from the present study indicate that the method proposed (Lauder 1) improves the accuracy of measurement of sweepback angle and, more importantly, pitch angle.

5. Conclusions

The accurate estimation of propulsive forces in swimming depends strongly on the selection of the reconstruction points on the hand–arm complex and to a lesser extent on the accuracy of digitising.

A comparison between the two main methods of hand reconstruction (Schleihauf and Berger) showed that Schleihauf's method provides a more accurate and stable reconstruction. The method is less sensitive to random errors in the individual points and is deemed superior in laboratory situations. However, Berger's method requires less points for reconstruction and this could be a clear advantage in real life when some of the points are obscured by the water turbulence.

A new method (Lauder) is proposed with further reduced sensitivity and the experimental tests conducted proved that it yields the same accuracy as Schleihauf in laboratory conditions. However, as this new method possesses a reduced sensitivity and improved visibility of the selected points, it will be better when used in studies of swimming.

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