Contribution of upper trunk rotation to hand forward-backward movement and propulsion in front crawl strokes

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ABSTRACT

The study aims to test three hypotheses: (a) the rotation of the upper trunk consists of roll, pitch and yaw of frequencies harmonic to the stroke frequency of the front crawl stroke, (b) the rotation of the upper trunk generates back-and-forth movements of the shoulders, which enhances the movements of the stroking arms, and (c) the angular velocities of roll, pitch and yaw are associated with hand propulsion (HP). Front crawl strokes performed by twenty male swimmers were measured with a motion capture system. The roll, pitch and yaw angles about the three orthogonal axes embedded in the upper trunk were determined as three sequential Cardan angles and their angular velocities were determined as the three respective components of the angular velocity. HP and the drag and lift components of HP (HP_D and HP_L) were estimated by the hand positions and the data from twelve pressure sensors attached on hands. The roll, pitch, and yaw angles were altered in frequencies harmonic to the stroke frequency during the front crawl stroke. Shoulders alternately moved back and forth due to the upper trunk rotation. In the pull phase the angular velocity of roll was correlated with HP_L ($r = -0.62$, $p = 0.004$). Based on the back-and-forth movements of the shoulders and roll motion relative to a hand movement, the arm-stroke technique of the front crawl swimming was discussed in terms of increasing the hand velocity and HP.

1. Introduction

One of the important techniques in the front crawl swimming is a body roll, which is the body rotation about its longitudinal axis (Counsilman, 1968). According to Maglischo (2003), a body roll is to enhance propulsive force, to maintain a better lateral body alignment, and to facilitate the recovery of the arm. For describing the rolling characteristics of the trunk accurately, Psycharakis and Sanders (2008) suggested that a body roll should be examined separately for shoulders and hips. Constant rolling rhythms were then identified during 200 m front crawl swimming (Sanders & Psycharakis, 2009). Although studies to date analysed various aspects of body roll, most studies assumed that the shoulder or upper trunk roll was performed about the horizontal axis aligned with the propulsive direction and the shoulder roll axis was fixed with the global coordinate system through the stroke cycle of the front crawl swimming (Kudo, Sakurai, Miwa, & Matsuda, 2017; Payton, Baltzopoulos, & Bartlett, 2002; Payton, Hay, & Mullineaux, 1997;

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Psycharakis & McCabe, 2011; Psycharakis & Sanders, 2008). Thus, the roll motion was considered to contribute to the hand movement only in the vertical plane perpendicular to the swimming direction.

Apart from the upper trunk roll in the front crawl strokes, the upper trunk may undergo pitch and yaw motions. Pitch is the rotation about the transverse axis of the upper trunk, and yaw is the rotation about the vertical axis. During each cycle of the arm strokes, the upper trunk may slant vertically to alter pitch angle in a systematic manner due to possibly four factors: Wave action acting on the swimmer (Toussaint & Truijens, 2005) pushes the upper trunk of the swimmer upward during the front crawl stroke, oncoming flow to the swimmer that deflects downward exerts a counterforce on the upper trunk upward (Sprigings & Koehler, 1990), hydrodynamic forces acting on the hands in the front crawl stroke raises the head and the upper trunk and lowers the legs (Yanai, 2001), and the buoyant force acting on the upper trunk lowers the legs (Hay, 1993). The upper trunk roll with pitch slanted vertically upward can contribute to the forward and backward movement of the upper limb and shoulder joint during the front crawl strokes. The forward and backward movements of hands would be then partly a consequence of the shoulder joint movements.

During the front crawl stroke, a swimmer may perform lateral movement of the upper trunk, alternating with each stroke, consisting of the scapula elevation/depression and the side-bending of the trunk (Yanai & Hay, 2000). This movement causes the yaw angle of the upper trunk to change synchronously with the cycle of alternate arm strokes. The upper trunk with a yawing action moves the shoulder joints forward and backward, which should contribute to hand forward and backward movements during the front crawl strokes.

Thus the upper trunk is most likely to rotate about its three orthogonal axes in a rhythmic or harmonic pattern relative to the stroke cycle and has potential for contributing to the hand movements in forward/backward in addition to lateral and vertical directions. If, in fact, the upper trunk rotations contribute to increasing hand velocity and/or acceleration, roll, pitch and yaw of the upper trunk must contribute to generating hand propulsion (HP). This concept was supported by a recent study (Kudo et al., 2017) that reported the roll velocity about the propulsive direction during the front-crawl stroke was correlated to the lift component of HP in the later part of an underwater stroke (push phase). This finding indicates that the swimmers who attained a faster roll velocity in the push phase might generate a greater lift component of the HP. However, the contributions of the other components of upper trunk rotations, namely the pitch and yaw, to HP have not been examined. The pitch and yaw velocities may contribute to drag and lift components of HP.

An approach to estimate hand propulsion was developed from measurements using a hand model in a swimming flume (Sanders, 1999; Schleihauf, 1979). The approach used hand kinematics obtained from swimming testing and the coefficient of fluid forces on the hand model or the coefficients of velocity and acceleration of on-coming flow to the hand model obtained from the model testing in the linear motion. The approach proposed by Sanders (1999) was modified to improve the accuracy of estimated hand propulsion (Gomes, Boeira, & Loss, 2017). A dynamic pressure approach was also developed to estimate hand propulsion during swimming (Kudo, Yanai, Wilson, Takagi, & Vennell, 2008; Kudo et al., 2017). A hand model was rotated in a swimming flume while dynamic pressure and fluid forces on the hand model were measured, and best-fit equations using dynamic pressure on the hand surface as an independent variable were derived to estimate fluid forces on a hand in swimming. Both approaches used a hand model to acquire mathematical models to estimate hand propulsion during swimming. Flow condition around the hand model during measurements in the dynamic pressure approach were more similar to flow conditions around a hand during swimming so that the dynamic pressure approach may be more accurate than a quasi-static approach for estimating hand propulsion in swimming (Kutner, Nachtsheim, & Neter, 2004).

The present study was therefore conducted to test three hypotheses that (a) the rotation of the upper trunk consists of roll, pitch and yaw of frequencies harmonic to the stroke frequency of the front crawl stroke, (b) the rotation of the upper trunk generates back-and-forth movements of the shoulders, and (c) the angular velocities of roll, pitch and yaw of the upper trunk are associated with HP.

2. Method

2.1. Swimmers

Twenty male swimmers with no history of injury within the last six months (age: 21 $\pm$ 5 years; body mass: 70 $\pm$ 6 kg; height: 1.76 $\pm$ 0.06 m; personal best time in the 100 m front crawl stroke: 54.0 $\pm$ 3.2 s) participated in the present study. The swimmers consisted of nineteen swimmers belonged to a university swimming team and one swimming coach. The experimental procedure was approved by the institutional ethics committee and written informed consent forms were obtained from all swimmers.

2.2. Experimental set-up and procedures

A motion capture system with nine cameras on the pool deck and eighteen underwater cameras (Qualisys, Sweden) was set around the middle lane of a 25 m swimming pool (Fig. 1) and calibrated in an imaginary volume of 7.5 m long (from the 12.5 to 20 marks), 2.5 m wide, and 2.3 m high (1.3 m underwater and 1 m above the water surface). The mean error in the dynamic calibration within the imaginary volume was 0.0024 $\pm$ 0.0006 m. A global coordinate system (GCS) fixed to the swimming pool was defined as the X-axis in the swimming direction, the Y-axis in the lateral direction and the Z-axis in the vertical direction. Four retro-reflective markers were attached on the right and left sides of the acromion processes and the lowest points of the 10th rib to construct a local coordinate system (LCS) in the upper trunk. A retro-reflective tape marker was attached on the third fingertip of both hands and two retro-reflective markers were attached on the triquetral and scaphoid of both hands. Two sets of a system consisting of twelve pressure sensors with one portable data logger (MMT Inc, Japan) were used to estimate hydrodynamic forces acting on both hands.
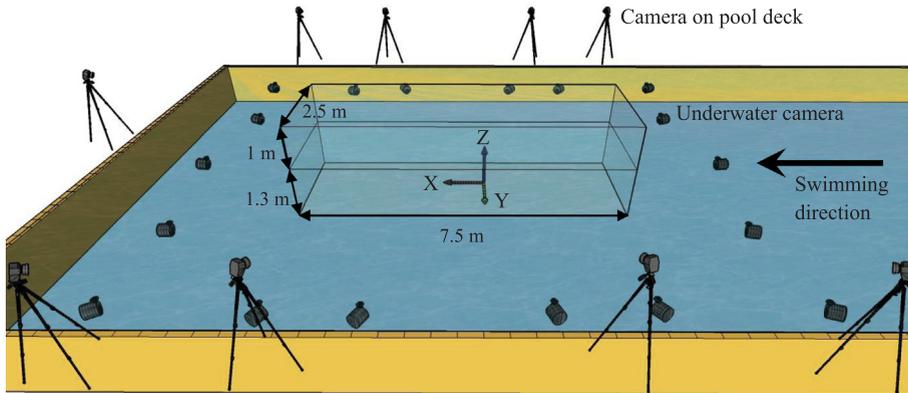
Fig. 1. Experimental set-up: a motion capture system consisting of 9 cameras on the pool deck and 18 underwater cameras was used. The imaginary volume of $7.5 \times 2.5 \times 2.3\,\text{m}^3$ was calibrated in the present study.

The two data loggers (approximately $90 \times 50 \times 40\,\text{mm}$ for each) were attached on the back of the swimmers and synchronized with the motion capture system to record the signals at 100 Hz.

After a self-selected, moderate intensity warm up, the swimmers performed 25 m of the front crawl stroke at their maximal sprinting pace without breathing. The swimmers were asked to push off the wall at the start and reach their maximal swimming speed by the first 12.5 m and maintain the swimming speed at the latter half of 12.5 m where the imaginary volume was located. One complete cycle of a stroke for each arm from the entry of the hand into water to the exit of the hand out of water within the calibrated volume were used for the analysis.

2.3. Angular displacement and velocity

The signals measured by the motion capture system were smoothed using a fourth-order zero-lag low-pass Butterworth filter (Winter, 2005) with a 9 ± 5 Hz cut-off frequency (Yu, Gabriel, Noble, & An, 1999). The upper trunk LCS was defined as the y-axis connecting from the right to the left acromion processes, the z-axis formed by the cross product of the y-axis and a vector connecting
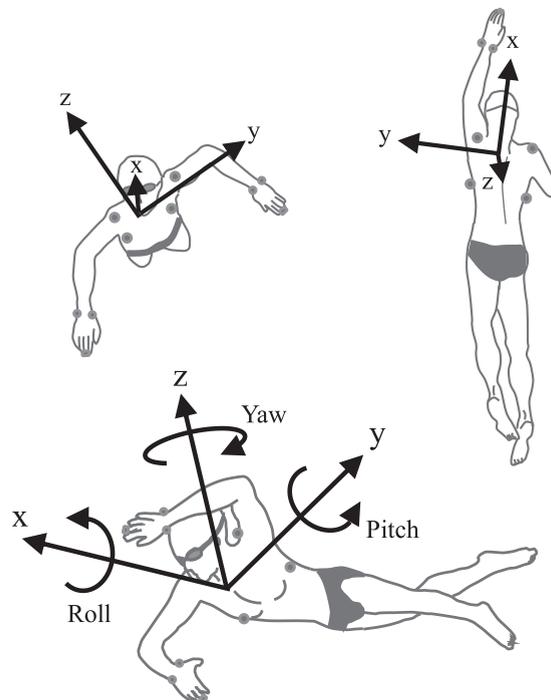

Fig. 2. Three different views of the local coordinate system embedded in the upper trunk of swimmers and the retro-reflective markers on the upper trunk, the triquetral and scaphoid of both hands, and the retro-reflective tape marker on the third fingertip.

from the midpoint of the right and left acromion processes to the midpoint of the lowest points of the right and left 10th rib, and the x-axis formed by the cross product of the y- and the z-axes (Fig. 2). The Cardan rotation sequence zyx was used to describe the orientation of the upper trunk LCS relative to the global coordinate system (roll = α, pitch = β, and yaw = γ) using a 3 × 3 rotation matrix (R) in the following.

$$R = R_x R_y R_z$$

where $R = \begin{bmatrix} \cos\beta\cos\gamma & -\cos\beta\sin\gamma & \sin\beta \\ \sin\alpha\sin\beta\cos\gamma + \cos\alpha\sin\gamma & \cos\alpha\cos\gamma - \sin\alpha\sin\beta\sin\gamma & -\sin\alpha\cos\beta \\ \sin\alpha\sin\gamma - \cos\alpha\sin\beta\cos\gamma & \cos\alpha\sin\beta\sin\gamma + \sin\alpha\cos\gamma & \cos\alpha\cos\beta \end{bmatrix}$,

$$R_x = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\alpha & -\sin\alpha \\ 0 & \sin\alpha & \cos\alpha \end{bmatrix}, \quad R_y = \begin{bmatrix} \cos\beta & 0 & \sin\beta \\ 0 & 1 & 0 \\ -\sin\beta & 0 & \cos\beta \end{bmatrix}, \quad R_z = \begin{bmatrix} \cos\gamma & -\sin\gamma & 0 \\ \sin\gamma & \cos\gamma & 0 \\ 0 & 0 & 1 \end{bmatrix}$$

The rotation matrix R can be also driven from the upper trunk LCS and the global coordinate system and expressed as:

$$R = AI^T$$

where $R = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}$, A is a 3 × 3 matrix of the upper-truck LCS in the front crawl stroke and I is an identity matrix.

The upper trunk rotation angles were determined in the following.

$$\alpha = \tan^{-1}(r_{23}/r_{33})$$

$$\beta = \tan^{-1}(-r_{13}/\sqrt{r_{11}^2 + r_{12}^2})$$

$$\gamma = \tan^{-1}(r_{12}/r_{11})$$

The angular velocity of upper trunk in LCS (ω) at time t was determined with matrix operations as follows:

$$A_t = B_{t-\Delta t}{}^T B_{t+\Delta t}$$

where $A_t = \begin{bmatrix} a_{11} & a_{12} & a_{13} \\ a_{21} & a_{22} & a_{23} \\ a_{31} & a_{32} & a_{33} \end{bmatrix}$ which comprised of three column vectors representing the unit vectors of LCS at t + Δt expressed in LCS at t-Δt, and B is comprised of three column vectors representing the unit vectors of LCS at the respective time expressed in GCS.

$$|\omega_t'| = (\varphi/2\Delta t)$$

where $\varphi = \cos^{-1}[(trace(A_t) - 1)/2]$ and ω_t' represents the instantaneous angular velocity of the upper trunk at t_i expressed in LCS t_{i-1}.

The angular velocity vector ω_t' were computed as follows:

$$\begin{bmatrix} \omega_x' \\ \omega_y' \\ \omega_z' \end{bmatrix} = |\omega_t'| \begin{bmatrix} u_x \\ u_y \\ u_z \end{bmatrix}$$

where $u_x = (a_{32} - a_{23})/2\sin\varphi$, $u_y = (a_{13} - a_{31})/2\sin\varphi$, and $u_z = (a_{21} - a_{12})/2\sin\varphi$ and ω_x', ω_y', and ω_z' indicate roll, pitch and yaw velocities, respectively.

$$\omega_t = B_t{}^T(B_{t-\Delta t}\omega_t')$$

2.4. Upper trunk and shoulder velocity and acceleration in the X-axis

The geometric centre of the four retro-reflective markers on the upper trunk, named as upper trunk centre, was determined to calculate the average forward velocity and acceleration of the upper trunk over one stroke cycle (the duration from the first entry to the second entry of the right hand into water). The forward acceleration indicates if the forward velocity of the swimmer was changed between the beginning and the end of the stroke cycle. To describe the influence of yaw, roll and pitch on each shoulder movement in the backward and forward directions (X-axis), the hand velocity in GCS was derived in the following.

$$v_{hand} = v_{utc} + B_t\omega_t \times r_{shoulder/utc} + v_{hand/shoulder}$$

where v_{hand} is a left or right hand's velocity, v_{utc} is an upper trunk centre's velocity, $B_t\omega_t$ is an angular velocity of the upper trunk (ω_t in LCS was transformed to GCS), $r_{shoulder/utc}$ is a vector from the upper trunk centre to the left or right shoulder (acromion process), and $v_{hand/shoulder}$ is a left or right hand velocity relative to the corresponding shoulder (acromion process). For the hand velocity to calculate $v_{hand/shoulder}$, the middle point of the two reflective wrist markers and the one reflective tape marker on the finger tip were used.

The X-component of a shoulder velocity relative to the upper trunk centre due to the upper trunk rotation ($\omega_G \times r_{shoulder/utc}$) and the hand velocity in the model (v_{hand}) was used to describe the contribution of back-and-forth movements of the shoulders due to the

upper trunk rotation to hand back-and-forth movements. The time-normalised values of the angular displacements and the angular velocities of the upper trunk, the shoulder velocity due to the upper trunk rotation and the hand velocity in the model were calculated as 0% for the first entry of right hand into water (0%Time), 100% for the second entry of right hand into water (100%Time) and 116% for the exit of the left hand out of water (116%Time). In the present study, the downsweep phase was defined as the period commencing from the frame of the entry of the hands into water to the frame before the beginning of the pull phase (catch). The pull phase was defined as the period commencing from the frame in which a hand started moving backwards to the frame in which the hand reached the YZ-plane containing the reflective marker of the acromion process of the ipsilateral side, and the push phase was the period commencing from the frame after the end of the pull phase to the exit of the hand out of water.

2.5. Dynamic pressure approach to estimate hand propulsion

The signals from the pressure sensors were smoothed using a fourth-order zero-lag low-pass Butterworth filter with a 9 ± 2 Hz cut-off frequency. HP as hydrodynamic forces acting on the hand in the X-direction and its drag and lift components (HP_D and HP_L) were estimated with best-fit equations for predicting hydrodynamic forces on the hand, kinematic data from the *retro*-reflective tape and the two retro-reflective markers on both hands (Kudo et al., 2017). The direction of lift force is perpendicular to the direction of drag and there can be two components of lift in the three-dimensional space (Sanders, 1999). HP_L in the present study was the sum of two lift components. The preliminary study validated the dynamic pressure approach to estimate HP (Appendix A).

2.6. Data analysis

A one-sample *t*-test was conducted to determine if the amplitudes of pitch and yaw were different from zero. The cross-correlation analysis was used to identify a rhythmic pattern of roll, pitch and yaw angles in the upper trunk rotations (Ifeachor & Jervis, 2002; Schinkel-Ivy & Drake, 2015) using the time-normalized angles from 0% to 100%. The largest *r*-value (r_{xy}) was reported in this study as the result of the cross-correlation analysis. Fourier analysis was conducted for roll, pitch and yaw angles to determine the power of each frequency component. The power contribution of each frequency component was, then, obtained as the power of the frequency component divided by total waveform power, and the frequency component with the greatest power contribution was reported. Average values of HP, HP_D, HP_L, the roll, pitch and yaw velocities were determined separately for each phase for each hand to examine the association among each other using the Pearson's product moment correlation. For averaging the values of roll and yaw velocities, the values in the right hand were multiplied by -1 to make them the same direction as those for the left hand. For the multiple comparison of the one-sample *t*-test, cross-correlation analysis and Pearson's product moment correlation, a critical p value was set as 0.025, 0.017 and 0.006, respectively, after the Bonferroni correction.

3. Results

The average values of forward velocity and acceleration of the upper trunk were 1.62 ± 0.11 m/s and 0.04 ± 0.08 m/s^2, respectively. The peak HP occurred in the pull phase while the large values of HP_D remained from the late half of the pull phase to the first half of the push phase, and the large values of HP_L were observed at the beginning of the pull phase and at the end of the push phase (Fig. 3). The duration of the pull phase was shorter than that for the push phase. The root mean square difference in HP, HP_D, and HP_L between the left and right hands was 2.4 N, 2.0 N, and 1.7 N, respectively.

The upper trunk rotated about the y-axis and the z-axis, resulting in the pitch and yaw angles (Table 1). The yaw angle was strongly cross-correlated with the roll angle with 39%Time of the phase difference while the pitch angle did not show any significant cross-correlation with the roll and yaw angles (Table 2). The strong correlation indicates that the wave patterns of yaw and roll are in phase with the yaw wave delayed (time-shifted) by 39%Time. The greatest power contribution to waveform power for roll and yaw was the fundamental frequency identical to the stroke frequency (one cycle in one stroke) while for the pitch was the second harmonic as two cycles in one stroke (Table 3).

On average, the roll, pitch and yaw angles and the corresponding angular velocities changed in a rhythmic pattern during the
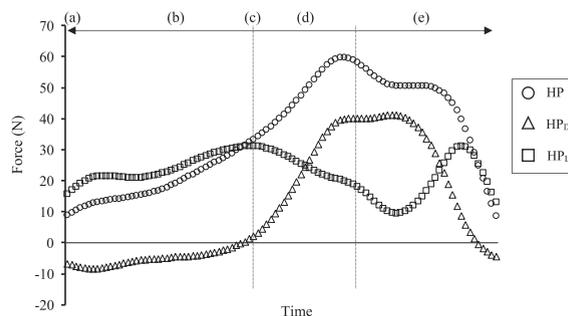

Fig. 3. Average curves of hand propulsion (HP) and its drag and lift components (HP_D and HP_L) exerted on both hands of the 20 swimmers. (a) The entry of the hand in the water, (b) the downsweep phase, (c) catch, (d) the pull phase, and (e) the push phase.

Table 1

Mean and standard deviation of the amplitude of pitch and yaw angles.

	Amplitude of angle (rad)	p value
Pitch	0.78 ± 0.09	p < 0.001
Yaw	0.43 ± 0.10	p < 0.001

Note: p values for the one-sample *t*-test (two-tailed), comparing to 0˚.

Table 2

The maximum value of the cross-correlation coefficient (r_{xy}) for roll, pitch and yaw of the upper trunk.

	r_{xy}	Phase difference	p value
Roll-Yaw	0.99	39%Time	p < 0.001
Roll-Pitch	0.17	25%Time	p < 0.091
Yaw-Pitch	0.22	85%Time	p < 0.028

Note: p values for cross-correlation analysis (two-tailed). All trial contains more than 100 frames before the time-normalised process to perform the cross-correlation analysis.

Table 3

Maximum power contribution of upper trunk rotations to waveform power and the frequency.

	%Power	Fourier harmonic
Roll	99.8	H1
Pitch	89.0	H2
Yaw	98.3	H1

Note: H1 and H2 indicate the fundamental frequency and the second harmonic, respectively.

stroke cycle (Fig. 4). The roll angle increased from the neutral position (=0˚) recorded at the entry of each hand into water to the greatest magnitude attained at the beginning of each pull phase, and then the magnitude decreased until the following neutral position or the following hand entry into water. The variation of the pitch angle was less than that of the other two angles and the greatest magnitude was recorded during the downsweep phase. The yaw angle attained the peak magnitude toward each side when, or shortly after, the hand in the contralateral side entered into water, and then remained the similar magnitude until the following hand entry into water.

The angular motion of the upper trunk generated back-and-forth movements of the left and right shoulders relative to the upper trunk centre (Fig. 5). The positive peak velocity of the shoulders relative to the upper trunk centre occurred just before the entry of hands into water. The peak values were 0.60 m/s at 46%Time for the left shoulder and 0.46 m/s at 97%Time for the right shoulder. At the positive peak, the hand velocity in the X-axis was 2.60 m/s for the left hand and 2.21 m/s for the right hand. The contribution of the positive peak velocities of the left and right shoulders relative to the upper trunk centre to the hand velocities was 23% and 21% in the forward direction, respectively. The negative peak velocity of the shoulders relative to the upper trunk centre occurred at the beginning of the push phase. The peak value was −0.63 m/s at 98%Time for the left shoulder and −0.70 m/s at 47%Time for the right shoulder. At the negative peak, the hand velocity in the X-axis was −2.25 m/s for the left hand and −2.16 m/s for the right hand. The contribution of the negative peak velocities of the left and right shoulder velocities relative to the upper trunk centre to the hand velocities was 28% and 32% in the backward direction, respectively.

During the pull phase, the average roll angular velocity correlated with the average values of HP_L (Fig. 6). There was no significant relationship between the average values of angular velocities and hand propulsions in the push phase (Table 4).

4. Discussion

Our findings supported the first and second hypotheses, that is, the rotation of the upper trunk consists of roll, pitch and yaw of frequencies harmonic to the stroke frequency of the front crawl stroke and the rotation of the upper trunk generates back-and-forth movements of the shoulders. It also supported the third hypothesis partly as the roll velocity of the upper trunk in the pull phase was associated with HP in the front crawl stroke.

The roll and yaw angles involved one cycle of the sinusoidal curve during 100%Time while the two angles had approximately 40%Time of phase difference. The roll angle increased at the entry of the right hand into water (0%Time) whereas the yaw angle decreased at the hand entry. This was consistent with the study which measured the elevation of humero-thoracic and glenohumeral joints (Du & Yanai, 2016). In the downsweep phase of the right hand (0%Time to approximately 30%Time), the yaw rotation should contribute to the lateral and backward movements of the hands. However, the hand was still moving forward in the downsweep phase due primarily to the forward movement of the swimmer. In the push phase of the right hand (approximately
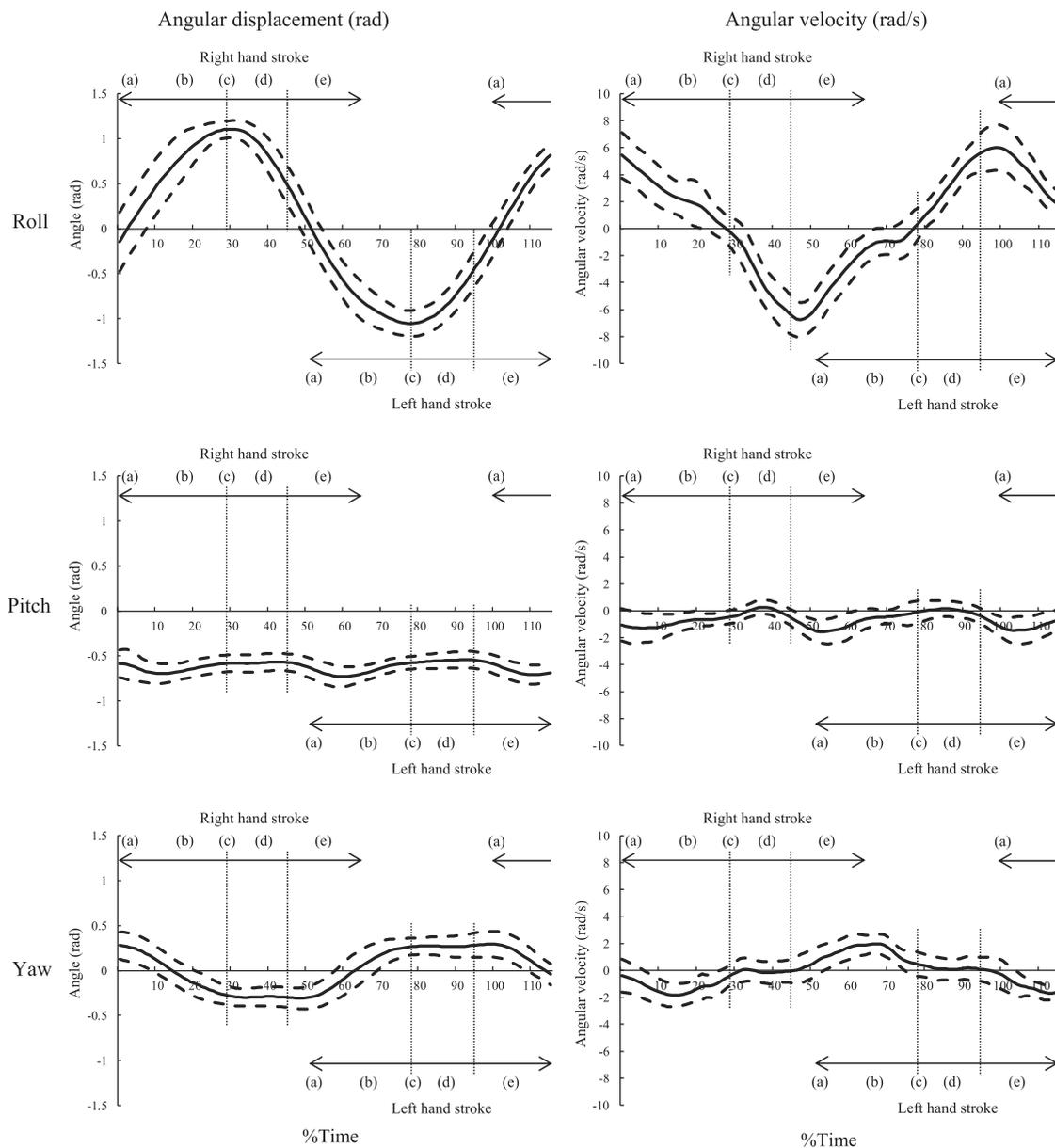
Fig. 4. Average curves of the angular displacement and the angular velocity of the roll, pitch and yaw rotations of the upper trunk for two arm strokes. (a) The entry of the hand into water, (b) the downsweep phase, (c) catch, (d) the pull phase, and (e) the push phase. The solid and dashed lines represent the average and standard deviation of the values, respectively.

45%Time–65%Time), the yaw angle increased as the yaw velocity increased up to the peak, indicating that the swimmers started elevating the right scapula and/or bending the upper trunk to the left in this phase and the yaw velocity increased during the push phase, i.e., the yaw rotation contributed to the forward, rather than backward, movement of the hand during the push phase. The observed pattern of time-lag between the yaw rotation and the hand motion in the downsweep and push phases may be understood as the proximal-to-distal sequence of joint movement (Putnam, 1991). Thus, the scapula movement in the stroke followed by the upper limb motion might contribute to increasing the hand velocity as the proximal-to-distal sequence of joint movement.

The pitch angle involved two cycles of the sinusoidal curve in one stroke cycle during 100%Time. The negative pitch angle was maintained presumably due to the four factors discussed previously. Among the four factors, the leg-sinking moment of the hydrodynamic forces acting on the hand (Yanai, 2001) might account for the second harmonic waveform as the negative peak magnitudes were attained in the downsweep phases. Because the pitch angle was negative throughout the stroke cycle and the long-axis of the upper trunk was tilted about 0.62 rad on average, the roll contributed to the hand movements not only in the vertical and mediolateral directions (YZ-plane) but also in the forward and backward direction, i.e., the positive direction of roll contributes to the forward movement of the right hand and the negative direction of roll contributes to the backward movement of the right hand, and
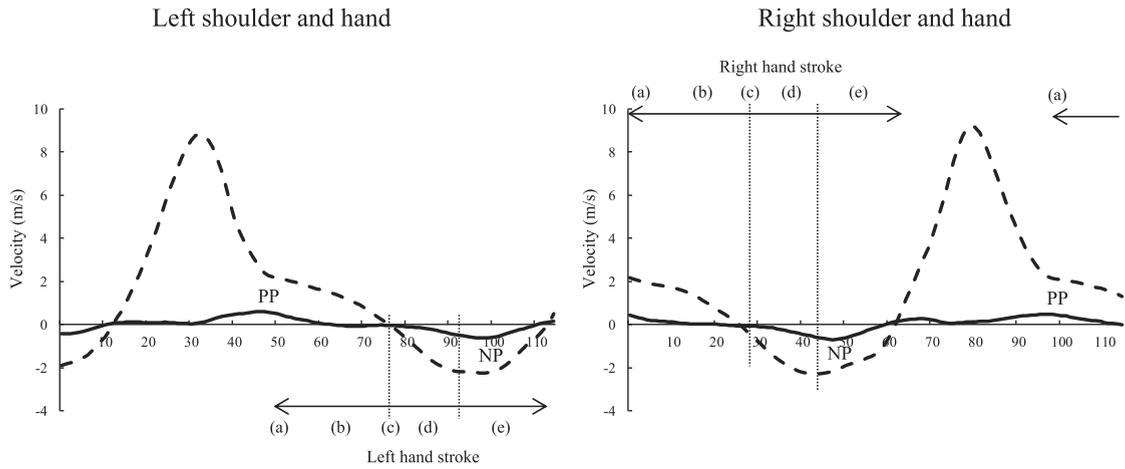
Fig. 5. Average curves of the velocities of the left and right shoulders relative to the upper trunk centre due to the upper trunk rotation (solid line) as $\omega_G \times r_{shoulder/utc}$ in the model in the X-axis and the left and right hand velocities as v_{hand} in the model (dashed line) in the X-axis for two arm strokes. NP and PP represent the negative and positive peak of the relative shoulder velocities. (a) The entry of the hand into water, (b) the downsweep phase, (c) catch, (d) the pull phase, and (e) the push phase.
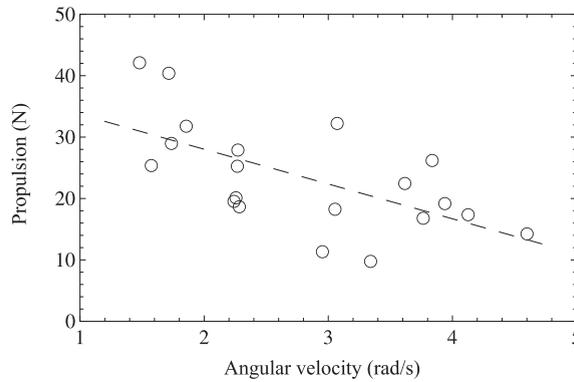

Fig. 6. Significant relationships between the average angular velocity of roll and the average hand propulsive lift force (HP$_L$) in the pull phases ($r = -0.62$, $p = 0.004$).

Table 4
The coefficients of Pearson's product moment correlation between the angular velocities of the upper trunk (ω_{Roll}, ω_{Pitch}, and ω_{Yaw}) and hand propulsion (HP, HP$_D$, and HP$_L$).

	Pull			Push		
	ω_{Roll}	ω_{Pitch}	ω_{Yaw}	ω_{Roll}	ω_{Pitch}	ω_{Yaw}
HP	−0.51	0.04	0.34	0.27	−0.37	0.10
HP$_D$	0.16	0.43	−0.04	−0.18	0.08	0.27
HP$_L$	−0.62*	−0.34	0.36	0.46	−0.54	−0.03

* $p < 0.006$.

vice versa for the left hand.

Just before the entry of each hand into water (PP in Fig. 5), the ipsilateral shoulder moved forward relative to the upper trunk centre. At this instance the angular velocity of the roll around the pitched long-axis generated the largest forward velocity of the shoulder relative to the upper trunk centre, accounting for approximately 20 percent of the forward velocity of the hands. On the other hand, yaw angular velocity did not contribute to the forward movement of the hand because its magnitude remained near zero around the instance. A typical technical recommendation given to swimmers on the hand entry is that roll motion should be encouraged to facilitate a hand forward movement while the body/torso should not be bent laterally, and our findings support this recommendation. At the beginning of each push phase (NP in Fig. 5), the ipsilateral shoulder moved backward relative to the upper trunk centre with the peak backward velocity driven by the roll with pitch. The angular velocity of roll around the pitched long-axis contributed to the backward velocity of the hands at the beginning of the push phase (approximately 30%). However, yaw angular

velocity did not contribute to the backward movements of the hands because its magnitude remained near zero when the peak backward velocity of the shoulders was observed. The hand backward movement from roll together with pitch should contribute to increasing HP_D.

The moderate and negative correlation observed between the roll velocity and HP_L in the pull phase ($r = -0.62$) indicates that the swimmers who rolled their upper trunk back to the neutral position more slowly in the pull phase generated a greater amount of HP_L. A possible mechanism that explains this relationship might be describes as follows: The magnitude of the roll angle decreases as the swimmer rolls back during the pull phase. This rolling motion tends to induce outward and vertically-upward movements of the stroking arm. The outward direction of the induced movement is opposite to the actual direction of the hand movement as the hand undergoes insweep in this phase. A slower rate of change in the roll angle (a smaller magnitude of roll velocity) in the pull phase causes less disturbance to the insweep (lateral) motion of the hand, and thus, maximizes the hand velocity on the yz-plane, which resulted in an increasing HP_L. A swimmer may, therefore, consider rolling back to the neutral position slowly in the pull phase to increase HP so as to swim faster.

The angular velocities of pitch and yaw were not associated with HP. In the pull phase, both angular velocities of pitch and yaw were close to 0 rad/s while HP was approximately 50 N so that both angular velocities might not be associated with in HP. The angular velocity of pitch decreased in the push phase. This indicates that the upper trunk rotated to raise the head and lower the hips, which was opposite to the rotational direction of the hand under the push phase due to the shoulder and elbow extensions. This upper trunk rotation may be due to angular action-reaction effects (Hay, 1993) and/or the leg-sinking moment of the hydrodynamic forces acting on the hand through the push phase (Yanai, 2001). As discussed above, in the push phase yaw would not contribute to the backward movement of hands and there was the time-lag between yaw and hand motions. Those may be, therefore, the reason for no relationship between the yaw angular velocity and HP in the push phase. Pitch and yaw may not contribute to increasing the magnitude of HP. However, hands move with the movement of the upper trunk, shoulder and elbow joints so that it may be worth for investigating the relationship between those angular velocities together with HP.

The previous study (Kudo et al., 2017) reported the positive relationship between the angular velocity of shoulder roll about the X-axis and HP_L. This seems to be opposite result from the present study but this is due to the representation of the rotational direction as the value of roll velocity for the right hand multiplied by -1 in the present study. The trend in the previous study was still the same as the one in the present study, which was that HP_L increased as the magnitude of the angular velocity became small.

It should be noted that the upper trunk involving the thorax and the scapulae was considered as the one segment and the movement of the scapula on the thorax was not quantified separately. Thus, the angular movement of yaw was interpreted as the angular displacement/velocity resulted from the thorax and/or scapula movement.

This study described the periodic movement of upper trunk rotations during the stroke of the front crawl swimming. Roll together with pitch contributes to not only the hand movement in the lateral and vertical directions but also the back-and-forth direction. Yaw may contribute to increasing the hand velocity in the forward-backward direction. This study also unveiled the relationship between the angular velocity of the upper trunk and HP in the pull phase, possibly associated with the enhancement of the swimming performance.

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Declaration of Competing Interest

The authors have no conflict of interest to the manuscript entitled "Contribution of upper trunk rotation to hand forward-backward movement and propulsion in front crawl strokes".

Appendix

To validate HP estimated by the dynamic pressure approach used in this study, a swimmer conducted a sculling motion while floating with four different loads (l_1, l_2, l_3 and l_4) without any kicking motion in a swimming pool and attempting to minimize the vertical excursion of the body. The placement of the reflective tape and markers on both hands was the same as described above while another reflective marker was attached on the xiphoid process. The swimmer performed the sculling motion four times and one load per trial was added to the swimmer. All signals were captured for 10 s after the swimmer became stable while performing the sculling motion. The magnitude of upward force (F_{up}) exerted by both hands of the swimmer was estimated by the dynamic pressure approach and compared to the known magnitude of downward force (F_{down}) based on the known weight and buoyancy acting on each load. A data set for 5 s was analysed for each trial when the magnitude of vertical velocity calculated from the marker on the xiphoid process was less than $0.005\,m\cdot s^{-1}$. The differences in F_{down} between the two consecutive sculling trials (Δl_{12}, Δl_{23}, Δl_{34}) were compared with the differences in the average value of an estimated F_{up}. The value of F_{up} in Δl_{12}, Δl_{23}, and Δl_{34} were close to that of F_{down} so that the dynamic pressure approach was valid to estimate F_{up} exerted by the swimmer (Table A1).

Table A1

Measured downward force and estimated upward force by the dynamic pressure approach.

	F_{down} (N)	F_{up} (N)
Δl_{12}	−8.0	6.5
Δl_{23}	−8.2	8.0
Δl_{34}	−8.1	7.9

Note: Δ_{ij} is the different between load i and load j. F_{down} is downward force based on known weight and buoyancy acting on the load. F_{up} is upward force estimated by the dynamic pressure approach.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.humov.2019.05.023.

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