The purpose of this study was to indicate the effect of fatigue on the underwater right arm stroke motion during the 100-m front crawl. The arm stroke motions of eight male competitive swimmers were captured three-dimensionally at 60 Hz in the positions of 15 m and 65 m from the start. The hand velocity, the arm angular velocities and the relative contribution of the arm angular velocities to the hand velocity were computed at each instant during the arm stroke motion. A significant decrease of the hand velocity and the peak angular velocity of shoulder adduction were observed in the second half than in the first half. The contribution of shoulder adduction was especially large in the pull phase and subsequently that of shoulder horizontal abduction became dominant in the push phase. However, in the second half, the contribution of shoulder adduction tended to decrease while that of shoulder internal rotation tended to increase. Thus, it is quite likely that the arm stroke motion of swimmers were driven to be influenced by induced fatigue and resulted in an increase in the contribution of shoulder internal rotation angular velocity.

Keywords: hand velocity, angular velocity, joint contributions

In swimming, propulsive force is induced by motion of the arms and legs. During the front crawl, the propulsive force is known to be mainly generated by the arm stroke motion (Hollander et al., 1988; Deschodt et al., 1999). It is known that the hydrodynamic forces consist of two components: drag force ($F_D$) and lift force ($F_L$).

Several studies have been made on the estimate of drag and lift forces acting on hand or hand and forearm (Berger et al., 1995; Bixler & Riewald, 2002; Rouboa et al., 2006; Schleihauf, 1979). The drag and lift forces were first experimentally measured by Schleihauf (1979) using a hand model. Berger et al. (1995) followed this and conducted a similar study using a model including the hand and forearm. Recently, Bixler & Riewald (2002) and Rouboa et al. (2006) estimated the drag and lift forces using computational fluid dynamics system. The result indicated that the drag coefficient was higher than the lift coefficient. Berger et al. (1995) reported also a lower value of the lift coefficient when the forearm was accounted into the model. This implies that the contribution of the forearm for the lift force is negligible.

Generally, the drag and lift forces are proportional to the square of velocity, and projected area of the hand and forearm toward the moving direction. Of the main upper limb segments, the hand will reach the highest velocity during the underwater arm stroke motion and has the biggest projected area and drag and lift coefficients of the hand will also be larger because of its flat plate shape compared with cylindrical shape of the forearm. For these reasons, it is reasonable to state that the hand is the main generator of propulsive force and its velocity is one of the main factors when discussing the propulsive force for the front crawl.

By contrast, Craig et al. (1985) showed a decrease in swimming velocity during the second half of competitive events. A number of studies in swimming have reported a strong relationship between swimming velocity and arm power (Sharp et al., 1982). Toussaint et al. (2006) reported that the decrease in swimming velocity throughout a 100-m front crawl race is the result of decreases in the power-producing capacity of a swimmer due to fatigue. Typically, swimmers find it difficult to retain stroke motion during competition due to muscle
Fatigue. It is likely that fatigue worsens some part of the arm stroke motion thereby causing a decreased swimming velocity in the final part of swimming. However, little is known about how fatigue affects the kinematics of arm stroke motion.

The motions of the hand result from rotational motions of the arm segments, and it is theoretically possible to quantify the contributions of the rotations of the various parts of the arm segment to hand velocity. However, most of the previous studies focused on several simple kinematic and temporal parameters: e.g., the trajectory of the middle fingertip and wrist or stroke length and stroke rate (Craig & Pendergast, 1979; Pai et al., 1984; Craig et al., 1985; Kennedy et al., 1990; Keskinen & Komi, 1993; Arellano et al., 1994; Cappaert et al., 1995; Chollet et al., 1997; Cardelli et al., 1999). To date, detailed contributions of the various parts of the arm segments’ motion to hand velocity have never been investigated for arm stroke motion in swimming. Sprigings et al. (1994) established a kinematic method for determining anatomical angular velocities of racquet-arm segments and the contribution of these rotations to racquet head speed. This method is applicable to determine the relative contributions of arm segments to hand velocity during underwater arm stroke motion and its change due to fatigue is of considerable interest to both swimmers and coaches.

The present study, therefore, aims to investigate the effect of fatigue on underwater arm stroke motion during the performance of the full-exertion 100-m front crawl from the aspects of arm angular motion and the relative contributions of arm segments to hand velocity using the methods of Sprigings et al. (1994).

**Methods**

Eight experienced male collegiate swimmers (age = 20.5 ± 1.4 yr; height = 170.0 ± 4.2 cm; mass = 63.1 ± 4.2 kg; the season’s best time of 100 m = 29.47 ± 2.72 s) volunteered to participate in this study. Participants were completely informed about the procedures and demands of the study and signed a written informed consent form.

All swimmers performed the full-exertion 100-m front crawl in a 25-m pool (water temperature = 29.0°C). All swimmers started from the water, using a push-off start. Before the start of measurement, the swimmers conducted a self-selected warm-up for 30 min. Before the trials, half-spherical markers (diameter = 15 mm for hand, and 30 mm for wrist, elbow, shoulder and upper body) were fixed securely onto the lateral side of bony anatomical landmarks of the right arm, i.e., the 3rd fingertip (hand), 3rd knuckle (hand), 5th knuckle (hand), styloid process of the ulna (wrist), radial head (elbow), acromial process (shoulder), and substernal region (upper body).

Two electrically synchronized video cameras (SONY Inc., CCD-IRIS) were used to capture the right upper limb motion at 60 Hz (exposure time 1/1000 s).

Each camera was enclosed in a waterproof cylinder and fixed underwater at a depth of approximately 0.6 m from the surface. The cameras were positioned to the right front and the right rear of the participant (Figure 1). To calibrate the performance area, a calibration frame (1.0 × 2.0 × 1.0 m) with 27 control points was videotaped before the trials.

To compare the first and second halves of the full-exertion 100-m front crawl, the entire underwater stroke motion of the right arm was recorded at 15 m and 65 m using the same camera set-up. A digitizing system (DKH Inc., Frame-DIAS) was used to manually digitize the eight body landmarks. The upper body landmark encountered a difficulty in its visualization when the marker was obscured by the arm action. Such cases typically occurred in four or five consecutive fields. Cubic spline function was used to interpolate the hidden part of the upper body marker. Each trial was digitized from the entry of the right hand into the water to the release of the right hand from the water.

The direct linear transformation method (Abdel Aziz & Karara, 1971) was used to obtain the three-dimensional coordinates of each landmark. The three-dimensional coordinates were expressed as a right-handed orthogonal reference frame fixed on the surface of the water (Z was vertical and pointed upward, Y was pointed in the swimming direction, X was perpendicular to Y and Z). The net root mean square error for the X, Y, and Z components in the performance area (X = 1.0 × Y = 2.0 × Z = 1.0 m) were 5 mm, 3 mm, and 2 mm, respectively.

The swimming velocity was computed as the first derivative of displacement of the upper body landmark ( substernal region) using central differentiation. The hand velocity was also computed in the same manner, as the first derivative of displacement of the hand’s center of mass, which was defined by the fingertip and wrist markers. The absolute magnitude of hand velocity was calculated from the values of each velocity component (X, Y, and Z).

For calculating the absolute angular velocity of each segment, we defined the segment coordinate system that consists of three orthogonal principal axes of inertia of the upper arm (RU), forearm (RF), and hand (RH) segments, respectively (Figure 2a). The term \( Z_U \) was a vector directed from the right elbow to
As shown in Figure 2b, the relative angular velocity vectors were divided into orthogonal components using unit vectors included in anatomically relevant joint coordinate system defined at the shoulder (RAS), elbow (RAE), and wrist (RAW) joints; Z_{AS}, Z_{AE}, and Z_{AW} were equal to Z_U, Z_F, and −Z_F, respectively. The term Y_{AS} was the vector product of a vector directed from the subscapular region to the acromial process and Z_{AS}. The term X_{AS} was the vector product of Y_{AS} and Z_{AS}. The term Y_{AE} was the vector product of Z_{AE} and Z_{AS}. X_{AE} was the vector product of Y_{AE} and Z_{AE}. X_{AW} was the vector product of Y_{H} and Z_{AE}. Y_{AW} was the vector product of −X_{AW} and Z_{AW}. The shoulder angular velocity vector was separated into three components: horizontal adduction (+X_{AS}) / horizontal abduction (−X_{AS}), adduction (+Y_{AS}) / abduction (−Y_{AS}), internal rotation (+Z_{AS}) / external rotation (−Z_{AS}). The elbow angular velocity vector was one component: extension (+Y_{AE}) / flexion (−Y_{AE}). The wrist angular velocity vector was separated into two components: dorsal flexion (+X_{AW}) / palmar flexion (−X_{AW}), and radial flexion (+Y_{AW}) / ulnar flexion (−Y_{AW}).

Sprigings et al. (1994) established a kinematic method for determining anatomical angular velocities of racquet-arm segments and the contribution of these rotations to racquet head speed. In the current study, the relative contributions of arm segments to the hand velocity were computed using the methods of Sprigings et al. (1994). According to Sprigings et al. (1994), the velocity of the hand’s center of mass (V_H) relative to the shoulder was considered to be the sum of the linear velocities contributed by the angular velocities of the shoulder, elbow, and wrist joints (ω_S, ω_E, and ω_W, respectively):

\[ V_H = ω_S \times r_{HS} + ω_E \times r_{HE} + ω_W \times r_{HW} \]  

where \( r_{HS}, r_{HE}, \) and \( r_{HW} \) were vectors pointing from the shoulder, elbow, and wrist to hand’s center of mass,
respectively. Each term in Equation 3 is computed as follows:

\[ \omega \times r_{1w} = (\omega_x \times X_{AS} + \omega_y \times Y_{AS} + \omega_z \times Z_{AS}) \times r_{1w} \]

\[ = (\omega_x \times X_{AS} \times r_{1w}) + (\omega_y \times Y_{AS} \times r_{1w}) + (\omega_z \times Z_{AS} \times r_{1w}) \]

(4)

where \( X_{AS}, Y_{AS}, \) and \( Z_{AS} \) were the unit vectors that indicate each across vector of the joint coordinate system for the shoulder joint (x, y, and z).

\[ \omega_x \times r_{1w} = (\omega_{lx} \times X_{AE} + \omega_{ly} \times Y_{AE} + \omega_{lz} \times Z_{AE}) \times r_{1w} \]

\[ = (\omega_{lx} \times X_{AE} \times r_{1w}) + (\omega_{ly} \times Y_{AE} \times r_{1w}) + (\omega_{lz} \times Z_{AE} \times r_{1w}) \]

(5)

\[ \omega_y \times r_{1w} = (\omega_{y} \times X_{AW} + \omega_{y} \times Y_{AW} + \omega_{z} \times Z_{AW}) \times r_{1w} \]

\[ = (\omega_{y} \times X_{AW} \times r_{1w}) + (\omega_{y} \times Y_{AW} \times r_{1w}) + (\omega_{z} \times Z_{AW} \times r_{1w}) \]

(6)

where \( X_{AE}, Y_{AE}, \) and \( Z_{AE} \) were the unit vectors that indicate each across vector of the joint coordinate system for the elbow joint (x, y, and z). From the degree of freedom of the elbow joint,

\[ \omega_{lx} = 0, \quad \omega_{lz} = 0, \]

then

\[ \omega_{ly} \times r_{1w} = (\omega_{ly} \times Y_{AE} \times r_{1w}) \]

\[ \omega_{y} \times r_{1w} = (\omega_{y} \times X_{AW} \times r_{1w}) + (\omega_{y} \times Y_{AW} \times r_{1w}) + (\omega_{z} \times Z_{AW} \times r_{1w}) \]

(7)

where \( X_{AW}, Y_{AW}, \) and \( Z_{AW} \) were the unit vectors that indicate each across vector of the joint coordinate system for the wrist joint (x, y, and z). From the degree of freedom of the wrist joint,

\[ \omega_{z} = 0, \]

then

\[ \omega_{y} \times r_{1w} = (\omega_{y} \times Y_{AW} \times r_{1w}) \]

where \( \omega_{x}, \omega_{y}, \omega_{z} \) were angular velocity vectors of horizontal adduction / abduction, adduction / abduction, and internal rotation / external rotation; \( \omega_{y} \times Y_{AE} \) was angular velocity vector of extension / flexion; and \( \omega_{y} \times X_{AW} \) and \( \omega_{y} \times Y_{AW} \) were angular velocity vectors of dorsal / palmar flexion and radial / ulnar flexion. Thus, the contribution of these anatomical rotations to the hand velocity can be determined by substituting Equations 4, 5, and 6 into Equation 3:

\[ V_H = (\omega_x \times X_{AS} \times r_{1w}) + (\omega_y \times Y_{AS} \times r_{1w}) + (\omega_z \times Z_{AS} \times r_{1w}) \]

\[ + (\omega_{lx} \times X_{AE} \times r_{1w}) + (\omega_{ly} \times Y_{AE} \times r_{1w}) + (\omega_{ly} \times Y_{AW} \times r_{1w}) \]

The algorithm developed in this article relies on the following assumptions: (a) the constructed orthogonal axes for the upper limb segments closely approximate their anatomical axes and (b) the pronation / supination rotations at forearm do not largely affect the hand velocity. All parameters were digitally smoothed by a fourth-order Butterworth low-pass digital filter at 7 Hz (Winter, 2004).

The propulsive phase when propulsive force was generated by arm stroke motion was divided into two phases by the three key moments shown in Figure 3, defined by Chollet et al. (2000). Propulsive force begins to be generated when the hand moves backward against the water. The pull phase was defined as a time period from the moment when the hand begins to move backward to the moment when the hand reaches the vertical line from the shoulder. The push phase followed and ended when the hand moved forward against the water at the end of the underwater arm stroke motion. In the current study, stroke motions were analyzed for propulsive phase, and the duration of propulsive phase was normalized to 100%.

Mean and standard deviations were calculated for the average swimming velocity, average hand velocity, and the peak angular velocities of shoulder adduction, shoulder horizontal abduction, elbow flexion and elbow extension through the propulsive phase. Comparisons between the first and second halves of the full-exertion 100-m front crawl were made using one-paired Student's t tests with Bonferroni correction. Bonferroni correction was made by dividing alpha level by the number of tests (6) conducted in the current study. Probability values less than 0.0083 (alpha level = 0.05 / 6) were judged to be significant.

**Results**

The average swimming velocities of the first and second halves were 1.62 ± 0.06 m/s and 1.49 ± 0.06 m/s, respectively. The average hand velocities of the first and second halves were 2.54 ± 0.17 m/s and 2.29 ± 0.19 m/s, respectively. Both the average swimming velocity and hand velocity in the second half were significantly lower than those in the first half (\( p < .0083 \), respectively).

The average changes of average angular velocity of the shoulder, elbow, and wrist in the first and second halves are presented in Figure 4. The general patterns of shoulder, elbow, and wrist angular velocity were similar in both halves. In the pull phase, shoulder adduction angular velocity was the largest and the peak angular velocity occurred at the end of the pull phase. In the push phase, shoulder horizontal abduction and elbow extension angular velocities began to be larger than those of the others. The peak magnitudes of shoulder adduction, shoulder horizontal abduction, elbow flexion, and elbow extension are summarized in Table 1. A significant difference was found between the two halves for the peak angular velocities of shoulder adduction in the pull phase (7.2 ± 0.7 rad/s vs 6.6 ± 0.8 rad/s, \( p < .0083 \)).

The average changes of contribution of effective segmental rotation to the hand velocity relative to the
The average changes of relative contribution of the shoulder joint to the hand velocity are highlighted in Figure 5. Overall, these changes were similar between the first and second halves. Among the three upper limb joints (shoulder, elbow, and hand), the contribution of the angular velocity generated by the shoulder joint was larger than those of the others.

The average changes of relative contribution of the shoulder joint to the hand velocity are highlighted in
In the current study, the decrease of swimming velocity was approximately 7.7% between the first and second halves in the full-exertion 100-m front crawl. Chollet et al. (1997) reported a 5.7% decrease in swimming velocity during the second half of a long-course 100-m race. Pai et al. (1984) reported a difference in velocity of 6.3% between the first and second halves. The decrease of swimming velocity observed in the current study was slightly greater than those found in the literature. Craig et al. (1985) reported that higher skilled swimmers were greater in maintaining their swimming velocity than...
lower skilled swimmers. Despite there being a difference for calculating procedure of the swimming velocity between the present and previous studies, the average swimming velocity of the current study (1.62 ± 0.06 m/s), was distinctively slower than the range of average values (1.92–1.93 m/s) reported previously (Pai et al., 1984; Chollet et al., 1997). The slower velocities represented the skill level of the present subjects and may account for the larger decrease of swimming velocity observed in the current study.

The propulsive forces by the arm stroke motion were strongly related to the hand orientations relative to water flow and proportional to the square of hand velocity (Schleihauf, 1979). Thus it can be considered that hand velocity is one of the main factors to predict swimming velocity in the front crawl. In the current study, the decline of hand velocity was significant (approximately 9.9%) between the first and second halves. It is reasonable to suggest that the induced fatigue decreased the hand velocity, thereby most likely leading to the reduced swimming velocity.

In swimming, arm stroke motion biomechanics have been studied by several authors using three-dimensional cinematographic procedures (Aujouannet et al., 2006; Cappaert et al., 1995; Schleihauf, 1979). However, these studies solely reported fingertip trajectories as kinematic parameters, in which the angular velocity changes of the arm joints have never been clearly illustrated. In the current study, the angular velocity changes of the arm were clearly illustrated and the change between the first and second halves was examined in detail.

In the pull phase, a significant difference was observed in the peak angular velocity of shoulder...
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pull phase, the main results were not affected by the above phenomena.

From the aspects of the relative contribution, it was revealed that the shoulder adduction motion was the dominant contributor during the pull phase and the horizontal abduction motion of the shoulder become the dominant contributor during the consecutive push phase. In the current study, we indicated more dominant role of shoulder motion to hand velocity in the front crawl.

Basically, these contributions to hand velocity were similar throughout the first and second halves of swimming. However, at the beginning of the pull phase, the average contribution of shoulder adduction tended to decrease in the second half (91.1–87.0%). In contrast, the average contribution of shoulder internal rotation at the beginning of the pull phase tended to increase in the second half (8.5–14.7%). Aujouannet et al. (2006) showed that the maximal isometric force of shoulder flexion (corresponds to shoulder adduction in the current study) was significantly decreased by fatigue induced during swimming. This finding is in line with the results of the current study, in particular when looking at the significant decrease of shoulder adduction angular velocity and its reduced contribution to hand velocity in the second half of swimming. Thus, it is quite likely that, for the swimmers of the current study, their arm stroke motion was influenced by fatigue and resulted in an increase in the contribution of shoulder internal rotation to compensate for the decreased shoulder adduction angular velocity.

In summary, the current study succeeded in delineating the effect of fatigue on the aspects of arm angular

adduction. Rouard & Billat (1990) observed higher reciprocal contractions of biceps-triceps during the pull phase than during the push phase. Clarys & Rouard (1996) and Rouard et al. (1997) also showed that muscle activity during the pull phase was higher than that of the push phase. It can be considered that the pull phase requires a larger burst of muscle activity than the push phase, and thereby the stroke motion in the pull phase would be more susceptible to fatigue.

Furthermore, the current study investigated the contributions of arm rotational motion to hand velocity relative to the shoulder velocity in the first half and second half of 100 m of the front crawl. Figure 7 shows the measured (solid line) and predicted (dashed line) hand velocities of one typical subject. It can be seen that there was a good agreement between the two curves throughout the arm stroke motion. To quantify the agreement of the two curves, the root mean square errors of the predicted velocity to the measured velocity was calculated for all subjects. The average error of 5.7 ± 1.6% (maximum = 8.4%, minimum = 3.2%, respectively) was acceptable. This guaranteed that the hand velocity was accurately predicted in the current study. However, there was a relatively larger gap between the two curves at the end of the push phase. In the end of push phase, it was observed for all subjects that the shoulder position became near the surface of the water. The accuracy of the three-dimensional coordinates of the shoulder will decline when the shoulder was near to the waved water surface. Thus, the relatively large error was most likely caused by the inaccurate shoulder position. However, in the current study, as we focused on the change in the pull phase, the main results were not affected by the above phenomena.

Figure 7 — The comparison of the measured and the predicted hand velocities calculated by the link segment model of the upper limb. Solid line: the measured hand velocity relative to the shoulder. Dashed line: the predicted hand velocity relative to the shoulder.
motion during the performance of full-exertion 100-m front crawl. As a consequence, the swimming velocity, hand velocity, and peak angular velocity of shoulder adduction were reduced significantly from the first half to the second half of full-exertion 100-m front crawl. As the hand is assumed to be the main generator of the propulsive force, it is quite likely that the decreased swimming velocity was caused by the reduced hand velocity. Moreover, from a kinematic procedure, it was revealed that the shoulder joint rotations accounted for most of the hand’s velocity and these aspects were influenced by fatigue, in which an increased contribution of shoulder internal rotation and a reduced contribution of shoulder adduction were simultaneously observed at the beginning of the pull phase. These results suggest that the effect of fatigue appeared on the shoulder muscle, thereby inducing a decrease in hand velocity and change of the stroke maneuver.

References


