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The effect of unsteady flow due to acceleration on hydrodynamic forces acting on the hand in swimming

Shigetada Kudo [a,*], Ross Vennell [b], Barry Wilson [c]

[a] School of Physical Education, University of Otago, Dunedin, New Zealand
[b] Ocean Physics Group, Department of Marine Science, University of Otago, Dunedin,New Zealand
[c] National Institute of Sport, Kuala Lumpur, Malaysia

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ABSTRACT

This study describes the effect of hand acceleration on hydrodynamic forces acting on the human hand in angular and general motions with variable hand accelerations. Even if accelerations of a swimmer's hand are believed to have an important role in generating hydrodynamic forces on the hand, the effect of accelerations in angular and general motions on hydrodynamic forces on the swimmers hand has not been previously quantified. Understanding how hand acceleration influences force generation can provide useful information to enhance swimming performance. A hand-forearm model attached to a tri-axial load cell was constructed to measure hydrodynamic forces acting only on the hand when the model was rotated and accelerated in a swimming flume. The effect of acceleration on hydrodynamic forces on the hand was described by comparing the difference between accelerating and non-accelerating hands in different flow conditions. Hydrodynamic forces on the accelerating hand varied between 1.9 and 10 times greater than for the non-accelerating hand in angular motion and varied between 1.7 and 25 times greater than for the non-accelerating hand in general motion. These large increases occurred not only during positive acceleration phases but also during negative acceleration phases, and may be due to the added mass effect and a vortex formed on the dorsal side of the hand. This study provides new evidence for enhanced stroke techniques in swimming to generate increased propulsion by changing hand velocity during a stroke.

1. Introduction

In swimming hydrodynamic forces acting on the accelerating hand are important contributors to propulsive forces. Additional force on an accelerating object results from the change of flow patterns around the object compared to a non-accelerating object because of viscous effects and the presence of local vortices (Denny, 1988). Additional force due to object's acceleration has been described as added mass effect (Newman, 1977; Streeter et al., 1997). The effect of acceleration on hydrodynamic forces acting on the hand needs to be considered in swimming motion (Pai and Hay, 1988, Toussaint et al., 2002, Lauder and Dabnichki, 2005). Despite knowing of the importance of hand acceleration in swimming, its effect has not yet been well quantified.

Experimental measurement and computational fluid dynamics (CFD) have shown the effect of acceleration on hydrodynamic forces acting on the hand and the hand/forearm in linear motion (Sanders, 1999; Rouboa et al., 2006). Lauder and Dabnichki (2005) measured torque about the shoulder joint in angular motion to investigate the effect of unsteady flow on the torque in a single plane. A recent CFD study reported the added mass effect on hydrodynamic forces acting on the arm while the contribution of vortices was not taken into account (Dabnichki, 2011). A swimmer sweeps their hand using the body roll and shoulder, elbow and wrist joints to move their body forward. Thus, the hand motion must be the combination of linear and angular motions where hand velocity and orientation change during the stroke (general motion).

The experimental quantification of the effect of acceleration of a swimmer's hand in angular and general motions is, therefore, essential for further understanding of the hydrodynamic forces acting on the hand and for verification of CFD models. Thus, the aim of the present study was to investigate the effect of hand accelerations on hydrodynamic forces acting on hands in the three orthogonal directions in angular and general motions.

2. Methods

2.1. Experimental conditions

Experiments of accelerating and non-accelerating hands were conducted in a swimming flume (StreamliNZ, E-Type Engineering Ltd., New Zealand), so as to

* Corresponding author at: Republic Polytechnic, School of Sports, Health and Leisure, Woodlands Campus, 9 Woodlands Ave 9, Singapore 738964, Singapore. Tel.: +65 6697 1452; fax: +65 6415 1310.
E-mail addresses: shige_kudo@rp.sg, k_shigetada@hotmail.com (S. Kudo).

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measure hydrodynamic forces acting on the hand in angular (non-flowing flume) and general (flowing flume) motion in a hand-fixed reference system *xyz* (Fig. 1). A hand-forearm model was constructed to measure at 200 Hz forces acting only on the hand using a tri-axial load cell (AMTI, MA, USA) (Kudo et al., 2008a). The hand was attached to a stainless steel support covered with a hollow cylindrical "forearm", so that the support did not touch the surrounding forearm. The model surrounding forearm was attached rigidly above the load cell so that any forces on the surrounding forearm did not influence values measured by the load cell. A rubber shield was used to form a watertight seal over the small gap between the hand model and the surrounding forearm. The error in the measured force on the hand due to a cross talk error and due to the rubber shield was found to be less than 4 N in each of the three axes.

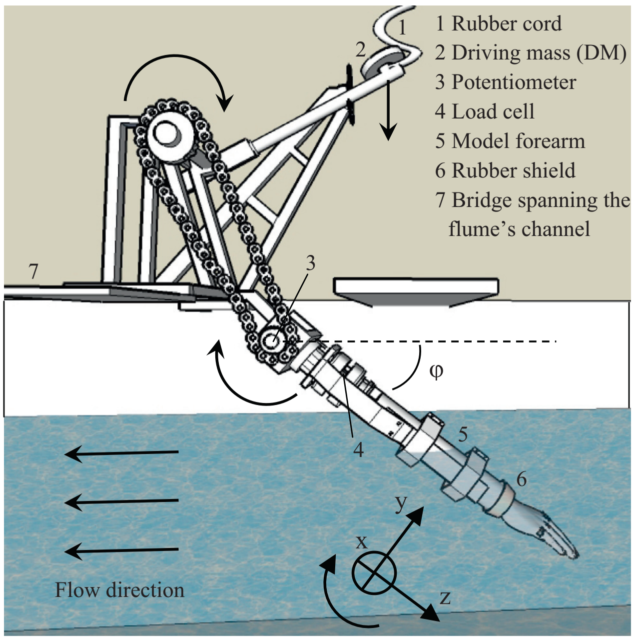

Fig. 1. Experimental set-up for accelerating hand-forearm model to measure hydrodynamic forces acting on the hand model. The accelerating hand-forearm model started rotating when a driving mass was released. The rotation plane was parallel to the constant flow direction in the flume. Angular position (φ) was defined as 0° when the longitudinal axis of the model was parallel to the flume flow with the finger tips pointing forward and 90° when the model was set vertically downward. There is no flow in the swimming flume during testing for the accelerating hand-forearm model in the non-flowing flume (angular motion). The rubber cord from the ceiling was attached to the driving mass for the measurement of general motion II so that the mode was decelerated in the late phase of the rotation while stretching the rubber code. The *y*-direction is tangential to the hand's arc of rotation, the *z*-direction is parallel to the longitudinal axis of the model, and the *x*-direction is perpendicular to the two axes.

For measurement of an accelerating hand, the model was attached to a rotating rig fixed to the bridge spanning the channel of the swimming flume with the ventral side of the hand perpendicular to the *y*-axis. The model was rotated and accelerated when a driving mass (DM) was released (Fig. 1). The angular position of the hand model (φ) was measured at 200 Hz by a potentiometer (Model 157, VISHAY, Selb, Germany). The angle of incidence of the flow to the hand (β) was defined as the angle between the *z*-axis and the direction of on-coming flow to the hand, which is expressed in the following (Fig. 2).

$$\mathbf{v_h} = \mathbf{v_f} - \mathbf{v_y} \tag{1}$$

where $\mathbf{v_h}$ is an on-coming flow's velocity to the hand, $\mathbf{v_f}$ is a flow velocity in the flume, and $\mathbf{v_y}$ is the hand velocity tangential to the model's arc of rotation.

To produce angular motion, the model was rotated in the non-flowing flume so that the direction of flow acceleration tangential to the hand's arc of rotation (a_y) was the same as the direction of $\mathbf{v_h}$ with β=90°. To produce general motion, the model was rotated in the flowing flume set at 1.0 and 1.5 m/s (general motion I and II), which were 50% and 75% of elite swimming speed during competition (Cappaert et al., 1995). A 10 kg DM was used for the three motions so as that a_y was similar to hand accelerations of the previous studies (Ohgi et al., 2000 and Rouboa et al., 2006). In the general motion II, a rubber cord from the ceiling was attached to the DM bar to produce deceleration of the hand. The length of the rubber cord was adjusted so that stretching occurred in the late phase of the model rotation and the elongation of the rubber cord caused force against the DM. Consequently, a_y was reduced and became greater negative (deceleration) than for the other trials. The preliminary testing for reliability, using the Agreement method (Bland and Altman, 1986), measured the resultant force on the hand model in 5 trials with 10 kg DM in the flowing flume set at 1.6 m/s (Lauder and Dabnichki, 2005). The agreement among the trials was $\pm$2 N which was 4% of the peak resultant force. Thus, the present study reports the single trial for angular and general motion.

Measurements of a non-accelerating hand (linear motion) were conducted for comparison with measurements of the accelerating hand so as to identify the effect of acceleration on hydrodynamic forces on the hand. The model was fixed to the bridge spanning the channel of the flume with the ventral side of the hand directed to the flow as rotated 180° about the *z*-axis. To obtain the range of β, because β is equal to φ in the non-accelerating hand, the model's φ was set by rotating and fixing the model at a new φ for each measurement condition. Test conditions for the non-accelerating hand were with three β (70°, 90°, and 110°) with flume velocities of 0.7, 1.4, 2.1, and 2.8 m/s, and for five β (30°, 50°, 60°, 120°, and 150°) with flume velocities of 0.7, 1.6, and 2.5 m/s. The testing was conducted once for each condition in the non-accelerating hand.

2.2. Hydrodynamic forces

The signals of the load cell were smoothed using a fourth order, zero lag, low-pass Butterworth filter (Winter, 1990) with a cut-off frequency of 14 $\pm$ 1 Hz so that 98 $\pm$ 2% of the power of the original signal was used in the present study. A Fourier analysis approach (Cappozzo et al., 1975; Wood, 1982) was used for smoothing and

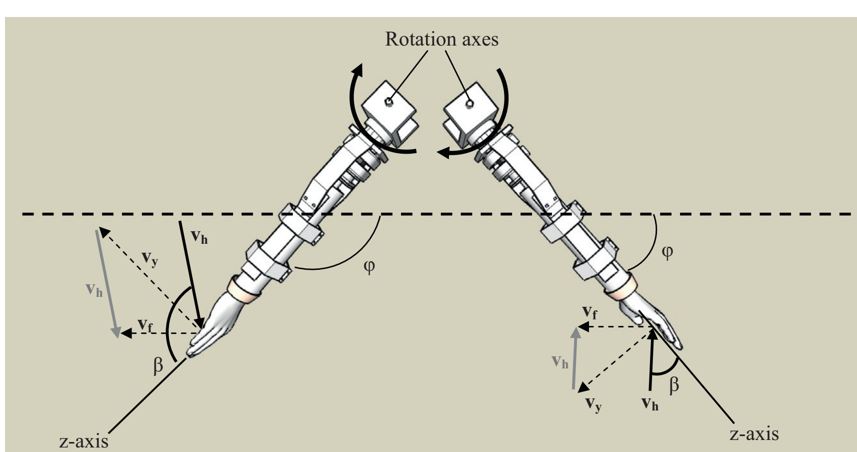

Fig. 2. The instantaneous angle of incidence of the flow to the hand (β) changed during a trial as the hand model rotated in the flowing flume (general motion). β was measured in the plane of rotation of the arm and depended on both the rotation rate of the arm and the flow in the flume. φ is the angular position of the hand model, $\mathbf{v_f}$ is a flow velocity in the flume, $\mathbf{v_y}$ is the hand velocity tangential to the model's arc of rotation, and $\mathbf{v_h}$ is the velocity of on-coming flow to the hand, which is the difference between $\mathbf{v_f}$ and $\mathbf{v_y}$. In the measurements of the accelerating hand in the non-flowing flume (angular motion), β was constant at 90° through the motion because $\mathbf{v_f}$ was zero. In the measurements of the non-accelerating hand model (linear motion), there was no rotation of the model ($\mathbf{v_y}$=0 m/s) and the ventral side of the hand model was directed toward $\mathbf{v_f}$. Thus, β was equal to φ.