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Unsteady hydrodynamic forces acting on a robotic arm and its flow field: Application to the crawl stroke

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ABSTRACT

This study aims to clarify the mechanisms by which unsteady hydrodynamic forces act on the hand of a swimmer during a crawl stroke. Measurements were performed for a hand attached to a robotic arm with five degrees of freedom independently controlled by a computer. The computer was programmed so the hand and arm mimicked a human performing the stroke. We directly measured forces on the hand and pressure distributions around it at 200 Hz; flow fields underwater near the hand were obtained via 2D particle image velocimetry (PIV). The data revealed two mechanisms that generate unsteady forces during a crawl stroke. One is the unsteady lift force generated when hand movement changes direction during the stroke, leading to vortex shedding and bound vortex created around it. This bound vortex circulation results in a lift that contributes to the thrust. The other occurs when the hand moves linearly with a large angle of attack, creating a Kármán vortex street. This street alternatively sheds clockwise and counterclockwise vortices, resulting in a quasi-steady drag contributing to the thrust. We presume that professional swimmers benefit from both mechanisms. Further studies are necessary in which 3D flow fields are measured using a 3D PIV system and a human swimmer.

1. Introduction

The importance of unsteady phenomena in human swimming has been emphasized in previous studies (Arellano et al., 2002; Sanders, 1999; Toussaint et al., 2002), hence we know that quasi-steady hydrodynamic theory is insufficient to describe the mechanisms by which humans propel themselves through water. To address such problems, computational fluid dynamics (CFD), including the effects of unsteady fluid flow, has been making a major contribution to understanding hydrodynamic phenomenon when the swimmer was moving actively either on the surface or underwater (Lecrivain et al., 2008; Von Loebbecke et al., 2009; Dabnichki, 2011). Particle image velocimetry (PIV) has also proven to be a powerful tool for measuring the actual flow fields around human swimmers. Based on PIV measurements, Matsuuchi et al. (2009) have reported that a pair of counter-rotating vortices might play an important role in generating unsteady fluid forces, and Hochstein and Blickhan (2011) have found that vortices generated in the region of strongly flexing joints are suitable to enhance propulsion; this process is known as vortex recapturing. Combining the results from CFD and PIV should help in visually and theoretically understanding complicated hydrodynamic mechanisms. However, actual experiment data, such as for forces and pressures, are also valuable for verifying CFD results and interpreting PIV images. Therefore, in a previous study, we conducted experiments in which we directly measured hydrodynamic forces, pressure distributions, and flow fields around a hand attached to a robotic arm (Takagi et al., 2013). In that work, simple 2D hand motions were the subject for study; nevertheless, a significant unsteady hydrodynamic phenomenon was observed that reveals the behavior of certain kinds of vortices play an essential role in generating substantial unsteady hydrodynamic forces. In this study, we used a robotic arm and PIV to clarify the mechanisms by which unsteady forces are generated during 3D crawl-stroke-motions. By analyzing the 3D motions, it is expected that actual propelling mechanisms can be elucidated and the findings will contribute to an improvement of swimmers' technique.

2. Methods

Since this study was based on the same methodology used in Takagi et al. (2013), we limit this section to introducing and discussing the main points.

2.1. Robotic arm and hand models

A robotic arm that consisted of a trunk, shoulder, upper arm, forearm, and hand (Takagi et al., 2013) was used. The robotic arm had five degrees of freedom (DOF),

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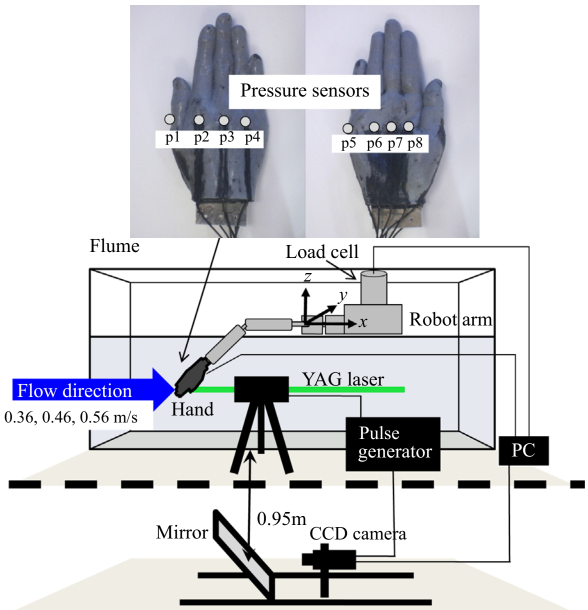

Fig. 1. Schematic of experimental devices and definition of the global coordination system. The origin of the global coordinate system was set at the center of the shoulder joint of the robotic arm. The x-direction was parallel to the main flow, the z-direction was perpendicular to and upward from the main flow, and the y-direction was normal to the x- and z-directions. Model hand (*Hand* 2) used for measuring pressure distributions and locations of pressure sensor attachments (right, palmar side; left, dorsal side).

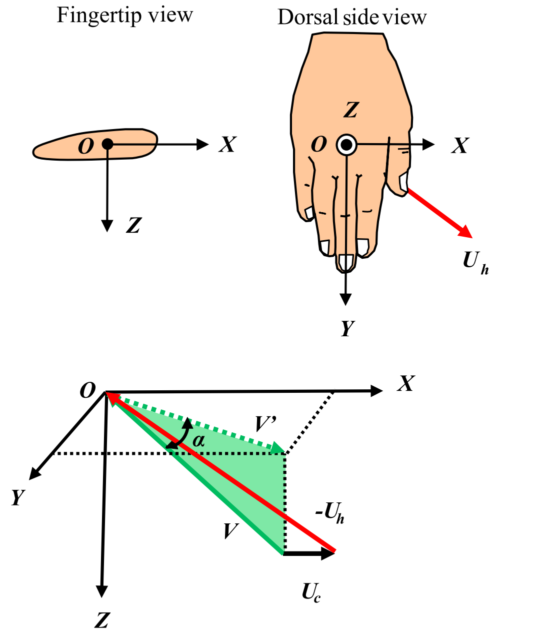

Fig. 2. Local coordinate system on the hand and definition of the angle of attack (α). The constant flow velocity vector of the main flow was $\boldsymbol{U_c}$ and the moving velocity vector of the center of the hand was $\boldsymbol{U_h}$. Therefore, the resultant flow vector relative to the hand ($\boldsymbol{V}$) was the vector sum of $\boldsymbol{U_c}$ and $-\boldsymbol{U_h}$. The angle of attack (α) was defined as the angle between $\boldsymbol{V}$ and its projection $\boldsymbol{V}'$ on the plane of the hand (the X–Y plane).

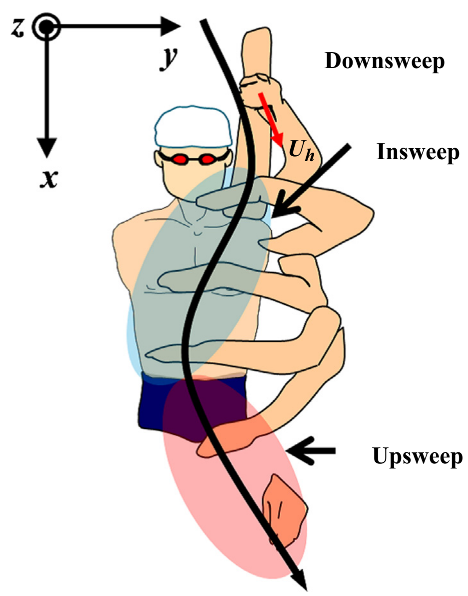

Fig. 3. Illustrations of three phases during one stroke. *Downsweep* is the phase during which the hand enters the water and moves outward/downward until the hand reaches the local maximal value of the y-coordinate. *Insweep* is the phase during which $\boldsymbol{U_h}$ changes direction to the centerline of the body, until the hand reaches the local maximal value of the z-coordinate. *Upsweep* is the phase during which $\boldsymbol{U_h}$ changes direction to outward/upward until the hand leaves the water.

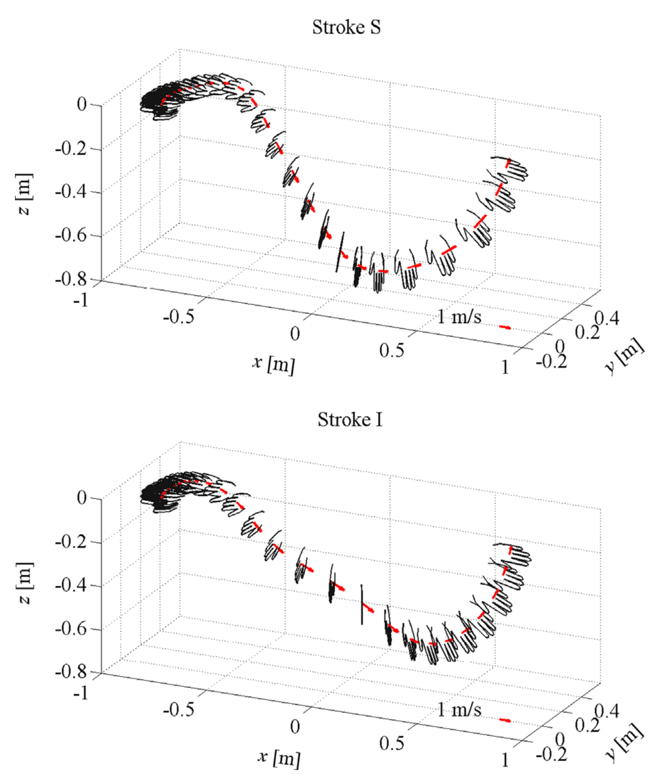

Fig. 4. 3D Hand trajectories for *Stroke S* (upper panel) and *Stroke I* (lower panel) at intervals of 125 ms. Red arrows represent the moving velocity vector ($\boldsymbol{U_h}$) of the center of the hand. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

which were driven by three motors housed in the trunk and two motors housed in the upper arm and forearm.

Two hand models were fabricated from a silicon-based material (Takagi et al., 2013). One hand (*Hand* 1) was used to measure hydrodynamic forces via flow visualization, and another (*Hand* 2) was used to measure pressure distributions during stroking motions. Eight pressure sensors were embedded in *Hand* 2 to measure the pressure distribution on its surface (Fig. 1).

2.2. Definitions of the coordinate system and technical terms

The origin of the global coordinate system was set at the center of the shoulder joint, as shown in Fig. 1. The x-direction was parallel to the main flow, the z-direction was upward and perpendicular to the main flow, and the y-direction