A FLOW VISUALIZATION OF UNDULATORY UNDERWATER SWIMMING -A PILOT STUDY OF THREE DEIMENTIONAL ANALYSIS-

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The purpose of this study was to visualize the flow characteristic behind a swimmer during undulatory underwater swimming (UUS). A male college swimmer performed dolphin kicks in a water flume channel (flow velocity was set at 0.8 $m \cdot s^{-1}$). By using the stereo PIV system, we captured the flow vector field in cross-sectional areas behind the swimmer and the swimmer's motions with a synchronized motion capture system. The vector fields were averaged for each kicking phase, and for spatial cross-sectional plane. This enabled visualization of the three dimensional flow field in UUS. The results showed that the swimmer created a counter vortex pair around the feet before the downward kick, and this appeared to assist the generation of thrust during the down kick motion.

KEY WORDS: PIV, vortex, dolphin kick, motion capture.

INTRODUCTION: Swimming mechanics is complex because hydrodynamic forces generated by unsteady flow fields act on the whole body from all directions. Recently, fluid characteristics of competitive swimming have been shown by using computer fluid dynamics (CFD) and particle image velocimetry (PIV). Takagi, Nakashima, Sato, Matsuuchi, & Sanders (2015) reported the merits of PIV as follows: (i) the method does not disturb the swimming motion owing to its contact free setup; (ii) instantaneous velocity, vorticity and heat-fluxrates can be measured; and (iii) multidimensional measurements are possible. Hence, the PIV is a powerful tool for explaining the relationship between hydrodynamic force and flow velocity.
Undulatory underwater swimming (UUS) is one of the techniques used to reduce race time. The kicking frequency has been observed to be related to UUS velocity (Arellano, Pardillo, & Gavilán, 2002). However, a kicking frequency threshold within subjects has also been observed (Shimojo, Sengoku, Miyoshi, Tsubakimoto, & Takagi, 2014). By using PIV, some studies of UUS have shown that a vortex ring is generated from lower limb whip-like kicking motions to produce thrust (Hochstein & Blickhan, 2011; Miwa, Matsuuchi, Shintani, Kamata, & Nomura, 2006). Therefore, to clarify the mechanism of the UUS technique, analysis of vortex generation is necessary. The purpose of this study was to visualize the three dimensional flow characteristics behind a swimmer during UUS.

METHODS: One male college swimmer (age 20 yr, weight 75 kg, height 1.72 m, FINA point 742 pt) participated in this study. The swimmer performed UUS in a water flume channel (height 2.0 m, width 1.5 m, length 5.0 m), and PIV system (LaVision) and a motion capture system (VENUS 3D) was used for measurement (Fig. 1). The sampling frequency was set at 10 Hz, and the PIV system and the motion capture system were synchronized.

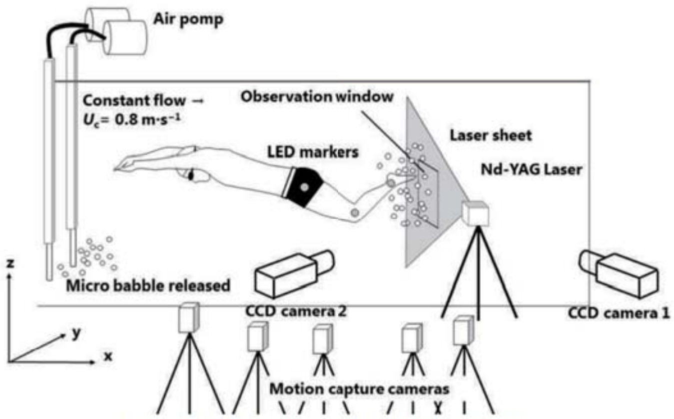

Fig. 1: The experimental settings.

The swimmer performed UUS in water flow set at 0.8 m·s^{-1} (*U*c) and was required to maintain constant position and depth. After fifteen kick cycles the swimmer rested for three minutes. For each of seven sessions the swimming position was incremented by 0.1 m in the swimming direction through a range of 0 m to 0.6 m.

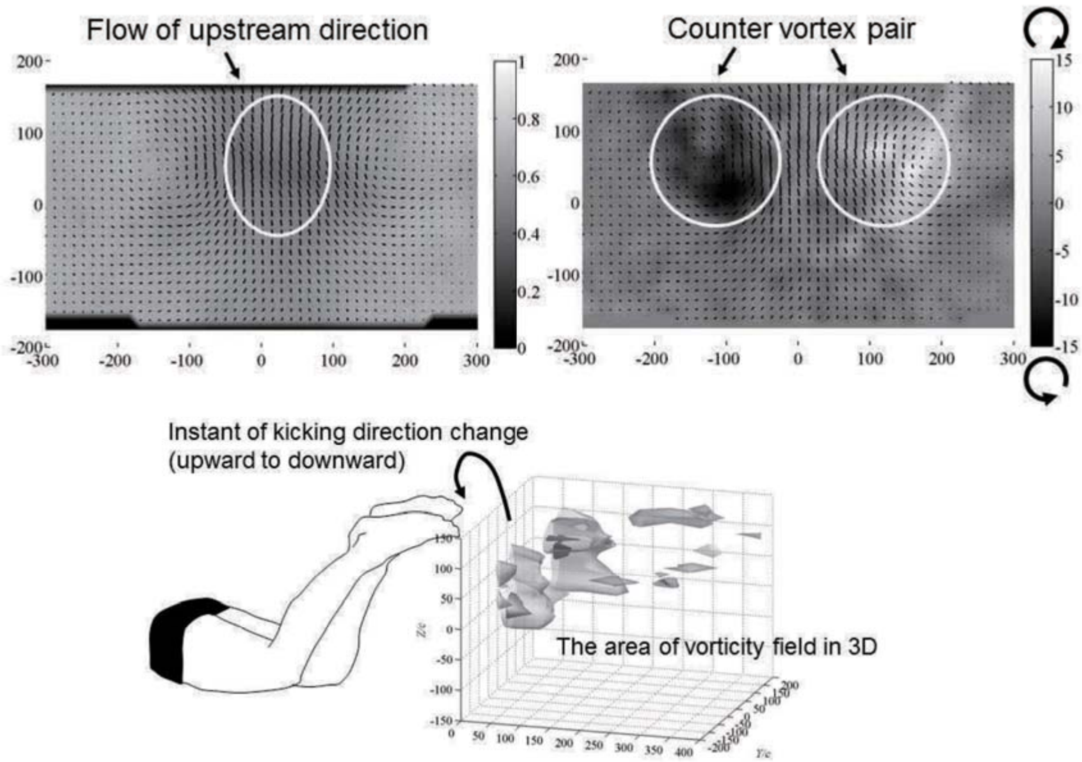

Fig. 2: Typical vector field (upper left; background shows propulsive direction vector), vorticity field (upper right; back ground shows vorticity field), and vorticity field in 3D (lower).

RESULTS: The result of typical flow field (vector of u, v, and w component), vorticity (dimensionless vorticity [ω/*U*c]), and vorticity field in three dimensional area (ω/*U*c > 8 areas are given gray, ω/*U*c > 10 areas are given black) are shown in figure 2. The resultant vectors of v, w (i.e. horizontal and vertical direction shown in Fig.2 as arrows) around center space are trend in upward direction (white circle in Fig.2 upper left), and a counter vortex pair is observed (white circle in Fig.2 upper right).

DISCUSSION: We attempted visualizing of flow characteristic from the vector data. Miwa et al. (2006), and Hochstein & Blickhan (2011) showed sagittal plane flow field during UUS using 2C-PIV, and Miwa et al. (2006) noted some pairs of small vortices and the jet flow were also confirmed after upward kicking motion. Our result is similar but visualization of these flow field in 3D is first time ever. In UUS study, Hochstein & Blickhan (2011) proposed re-capturing technique that is competitive swimmer using shedding vortex from their body to enhance propulsion by kicking motion pedally. In our results, the swimmer would do kick to downward after the instance in Fig.2 shows, and their foot would be into the pair vortices. This flow characteristic seem to be supported the re-capturing technique.

CONCLUSION: The swimmer generated vortex pair after upward kick, and this flow characteristic seem to be enhance propulsion (re-capturing).

REFERENCES:

Arellano, R., Pardillo, S., & Gavilán, A. (2002). Underwater undulatory swimming: kinematic characteristics, vortex generation and application during the start, turn and swimming strokes. In E. K. Gianikellis (Ed.), *Proceedings of the XXth International Symposium on Biomechanics in Sports*. Caceras, Spain.

Hochstein, S., & Blickhan, R. (2011). Vortex re-capturing and kinematics in human underwater undulatory swimming. *Human Movement Science*, *30*(5), 998–1007.

Miwa, T., Matsuuchi, K., Shintani, H., Kamata, E., & Nomura, T. (2006). Unsteady flow measurement of dolphin kicking wake in sagittal plane using 2C-PIV. In J. P. Vilas-Boas, F. Alves, & A. Marques (Eds.), *Proceedings of the Xth Congress of Biomechanics and Medicine in Swimming* (pp. 66–68).

Shimojo, H., Sengoku, Y., Miyoshi, T., Tsubakimoto, S., & Takagi, H. (2014). Effect of imposing changes in kick frequency on kinematics during undulatory underwater swimming at maximal effort in male swimmers. *Human Movement Science*, *38*, 94–105.

Takagi, H., Nakashima, M., Sato, Y., Matsuuchi, K., & Sanders, R. H. (2015). Numerical and experimental investigations of human swimming motions. *Journal of Sports Sciences*, 1–17.

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