THREE-DIMENSIONAL FLOW FIELD AND LEG MOTION DURING UNDULATORY UNDERWATER SWIMMING

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This study described swimmers' leg motions and the three-dimensional flow field around their legs during undulatory underwater swimming (UUS). We used the particle image velocimetry (PIV) method and a three-dimensional motion capture system. Seven male swimmers participated and we acquired EMG data of one male swimmer during UUS after the previous experiment. After the downward kick motion that includes the legs' lateral rotation and the ankles' dorsal flexion, water's backward momentum was observed. During the upward kick motion, backward flow velocity decreased, but flow occurred in a vertical, upward direction. This suggested that UUS could demonstrate great propulsion power by generating jet flow through the downward kick motion that might be assisted by upstream flow from the upward kick motion.

KEYWORDS: PIV, motion capture, EMG, dolphin kick

INTRODUCTION: Swimming means moving in a complex environment, i.e. an invisible and unsteady flow field. Recently, during undulatory underwater swimming (UUS or 'dolphin kick'), the vortex around swimmers' legs has been focussed on as a propelling mechanism (Cohen, Cleary & Mason, 2012; Hochstein & Blickhan, 2011; Miwa, Matsuuchi, Shintani, Kamata & Nomura, 2006). Using the particle image velocimetry (PIV) method, we attempted to visualize the vortex in three dimensions (Shimojo et al., 2016). Some believe that a jet flow backward is generated during UUS and a doughnut-like vortex ring is formed around the jet flow (Cohen et al., 2012; Miwa et al., 2006). However, this phenomenon has not yet been observed in an actual swimmer.

Ankle motion is considered a critical factor for the UUS propelling mechanism. Willems, Cornelis, De Deurwaerder, Roelandt and De Mits (2014) reported that UUS velocity decreased after taping to restrict a swimmer's ankle flexibility—specifically, internal rotation and plantar flexion. Thus, the entire details of ankle joint motion should be observed to understand UUS. At present, however, no study has analysed swimmers' UUS leg motion three dimensionally. Therefore, this study's purpose was to visualize and describe the flow field and swimmers' UUS leg motion in three dimensions.

METHODS: Seven male college swimmers (age 22.0 ± 1.4 yr, height 1.77 ± 0.04 m, weight 70.9 ± 4.4 kg, FINA point 786.5 ± 71.2 pt) swam in a water flume channel. Active LED markers were attached to swimmers at 18 points (hip, lateral and medial knee, lateral and medial ankle, heel, MP5, MP1 and toe on both legs). We replicated a previous study's experimental setting (Fig. 1, Shimojo et al., 2016). A motion capture system (VENUS3D, Nobby Tech, Japan; 18 cameras) and a stereo PIV system (LaVision, KANOMAX JAPAN; 2 cameras) were used.

After the previous experiment, to understand UUS leg motion and muscle strategy, we acquired EMG data from one male college swimmer (age 20 yr, height 1.81 m, weight 73.0

kg, FINA point 837) during UUS at an indoor pool (25 m × 6 lanes, depth 1.4 m). Again, we replicated a previous study's experimental setting (see Martens, Figueiredo & Daly, 2015). The seven EMG data of the left leg (rectus abdominis [RA], erector spinae [ES], gluteus maximus [GMa], rectus femoris [RF], biceps femoris [BF], anterior tibialis [TA] and gastrocnemius [GAS]) were measured at a sampling freqneucy of 1000 Hz with waterproof wireless active electrodes (DL-510, S&ME corp., Japan). The EMG data were filtered by the band-pass filter between 10 Hz and 500 Hz using MATLAB software (Mathworks Inc., USA). By capturing UUS motion through an underwater window using a high-speed camera (EXILIM EX-FH20, CASIO, Japan; sampling frequency 300Hz), a two-dimensional motion analysis was conducted. The camera and the EMG system were synchronized.

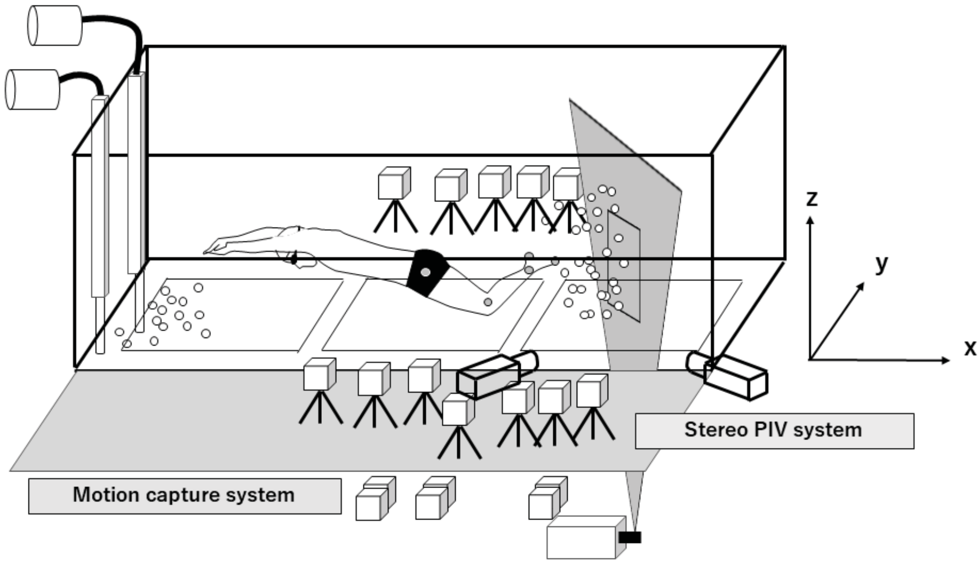

Figure 1: Experimental setting (see Shimojo et al., 2016)

RESULTS: The inner rotation angle of the ankle pattern and the EMG pattern are shown in Fig. 2. Ankle rotation at the beginning of the downward kick was observed and at the same time, RF and TA were activated. During one kick cycle, the order of EMG activity timing was 1) RF, 2) TA, 3) ES, 4) GMa, 5) BF, 6) GAS and 7) RA.

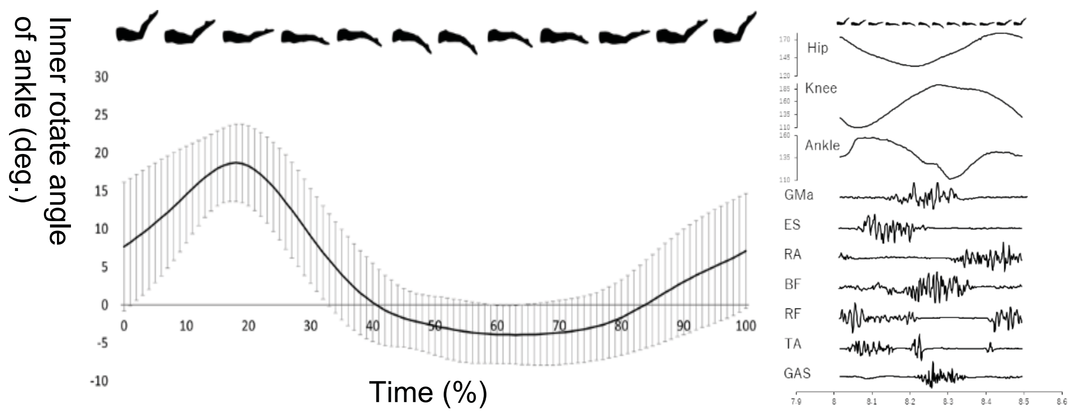

Figure 2: Inner rotated angle of one normalized kick cycle (left), joint angle and raw EMG pattern (right).

The flow field and typical vortices are shown in Fig. 3. At the end of the downward kick, jet flow was observed around the legs. Many vortices appeared in the middle of the upward kick.

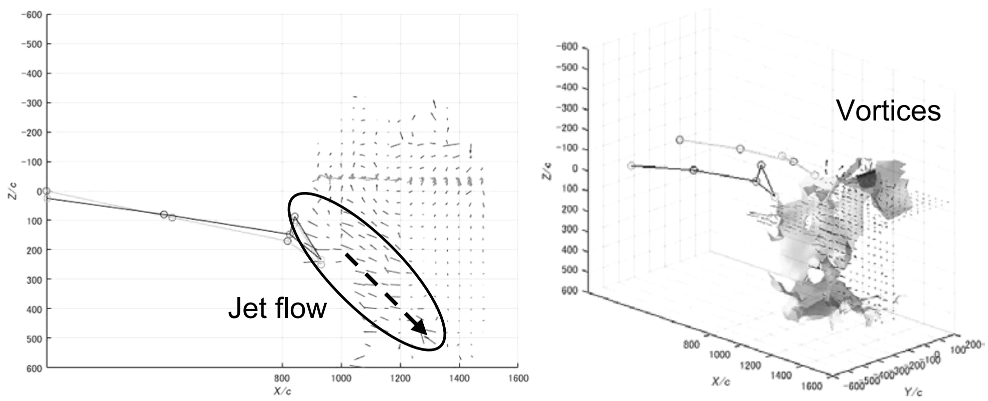

Figure 3: Flow field and swimmer's leg (stick imaged) viewed from the left side at the end of the downward kick (left) and vortices (coloured area) in the middle of the upward kick (right).

DISCUSSION: Results show that we were able to describe the flow field and leg motion in three dimensions during UUS. In addition, the EMG strategy of UUS was observed however note that the kick amplitude of UUS was 3%@height greater in the flume than in the pool (Shimojo et al., 2014). Swimmers rotated legs during the first phase of the downward kick (Fig. 2, left) and, at the same time, activated TA to dorsal flexion (Fig. 2, right). Then, swimmers were accelerated by the released jet flow (Fig. 3) during the end phase of the downward kick; therefore, these downward kick phase behaviours are the main factors for obtaining thrust force. This result supported previous studies (Cohen et al., 2012; Miwa et al., 2006).During the upward kick, many vortices were generated and upstream flow fields were observed. In our hypothesis of the UUS mechanism (Shimojo et al., 2016), upstream flow during the upward kick could assist thrust force incrementally when the downward kick followed. Thus, the role of the upward kick was to provide assistance to thrust force rather than working as a recovery motion.

CONCLUSION: During UUS, swimmers rotated their legs and flexed their ankles to the dorsal side in the downward kick motion; thrust was obtained after this motion, which reflects the jet flow at the end of the downward kick. These motions and their flow field connexion may explain the UUS propulsion mechanism.

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