CHANGES OF KINEMATICS DURING UNDERWATER UNDULATORY SWIMMING WITH INCREASING SWIMMING VELOCITY

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The purpose of this study was to clarify about the changes of the kinematics during underwater undulatory swimming (UUS) with increasing the swimming velocity. Eight male collegiate swimmers performed three UUS trials at the 70%, 80% and 90% velocity of their maximum effort swimming velocity in a water flume. For motion analysis, a motion capture system was used to collect the three-dimensional coordinates. Using the collected coordinates, the kinematic parameters were analyzed in each trial. As the main results, the kick frequnecy increased and the relative duration of the un-propusive phase with hip extension and knee felxion decreased with increasing swimming velocity. Furtheremore, since the peak hip external roation velocity increased with increasing swimming velocity, it was considered that the hip external rotation velocity during the downward kicking related to controll the swimming velocity during underwater undulatory swimming.

KEYWORDS: motion capture, 3D motion analysis, joint angle, dolphin kicking.

INTRODUCTION: Underwater undulatory swimming (UUS), which is also called as underwater dolphin kicking or underwater butterfly kicking, is an underwater propelling technique in competitive swimming. The present international rules permit swimmers to use UUS maximum 15 m after start dive and turns. Since UUS have a potential to be faster than surface stroking (Vorontsov & Rumyantsev, 2000), elite swimmers used underwater swimming as long as possible in their race events (Veiga, Cala, G. Frutos, & Navarro, 2014; Veiga, Roig, & Gómez-Ruano, 2016).

As well as other swimming strokes, fatigue reduces UUS performance (Taladriz, Domínguez, Morales, & Arellano, 2015), and therefore it can be said that pacing strategy during UUS is one of factor to determine the total race performance. However, while the previous studies investigate about the relationship between the kinematic parameters and the swimming velocity in maximum effort swimming (Atkison, Dickey, Dragunas, & Nolte, 2014; Connaboy et al., 2016; Higgs, Pease, & Sanders, 2017; Houel, Elipot, André, & Hellard, 2013), it has not been reported about the changes of kinematics with changing swimming velocity in a same swimmer. Therefore, it was unclear about the information that how swimmers control the swimming velocity during UUS.

The purpose of this study was to clarify about the changes of the kinematics during UUS with increasing the swimming velocity.

METHODS: Eight male collegiate swimmers (age 21.1 ± 1.0 years, height 1.75 ± 0.06 m, weight 71.9 ± 7.2 kg, FINA point 800.4 ± 81.4 points) participated in this study. Before the experiment, the participants performed 25-m UUS at maximum effort in a 50 m indoor pool. The swim-time during the maximum effort swimming was measured using a manual stop watch, and the average swimming velocity between 15 m to 25 m were defined as the maximum swimming velocity (100%V). After the session of 100%V measurement, the participants performed three UUS trials in a water flume (Igarashi Industrial Works Co. Ltd.).

The flow velocities during each trial was set at relatively 70%, 80% and 90% velocity (70%V, 80%V and 90%V, respectively) of their 100%V.
For motion analysis, active LED markers were attached to swimmers at 13 points (right and left lowest ribs, right and left hip greater trochanters, right and left anterior superior iliac spines, left femur lateral and medial epicondyles, left ankle lateral and medial malleoluses, left epiphysis of first metatarsal, left epiphysis of fifth metatarsal and left calcanean tuberosity). A motion capture system (VENUS3D, Nobby Tech Inc., 18 cameras, 100 Hz) was used to collect the 3-D coordinates as Figure 1.
For joint angle analysis, the four local coordinate systems in trunk, thigh, leg and foot segments were defined, and the joint angles were calculated as Cardan angle using these coordinate systems (Robertson, 2004). In this study, one dolphin kick cycle was divided into four phases according to Matsuda et al. (2016): 1) the phase involves hip flexion with knee flexion (Phase A), 2) the phase involves hip flexion with knee extension (Phase B), 3) the phases involves hip extension with knee extension (Phase C) and 4) the phase involves hip extension with knee flexion (Phase D). The relative duration (%) normalized by the cycle duration in each phase were calculated. Swimming velocity was defined as the sum of the horizontal velocity at the mid-point between the coordinates of right and left hip greater trochanters and the flow velocity, and mean swimming velocity during one kick cycle was calculated. Furthermore, the kick frequency, kick amplitude, peak downward/upward toe velocity, body wave velocity, Froude efficiency, peak angle and peak angular velocity during each UUS trial were calculated referring to Yamakawa, Shimojo, Takagi, Tsubakimoto, and Sengoku (2017).
All parameters were reported as the mean and standard deviation (Mean ± SD). All parameters were compared between the three different velocities using a repeated one-way ANOVA, followed by Bonferroni's multiple comparison post-hoc tests. The statistical significance level was set at 5% in this study.

RESULTS: Table 1 shows the summary of kinematic parameters in 70%, 80%V and 90%V trials, and there was a significant effect of increasing swimming velocity in the 23 parameters (all F = 3.99—97.5, all p < .05) except the Froude efficiency, the relative duration of Phase A and B.

Table 1: Summary of kinematic parameters in 70%V, 80%V and 90%V trials

Variables	70%V	80%V	90%V	ANOVA *F*-value
Mean swimming velocity ($m·s^{-1}$)	1.12±0.10	1.26±0.09^{a}	1.42±0.12^{b,c}	97.15*
Kick frequency (Hz)	1.47±0.19	1.75±0.26^{a}	2.13±0.33^{b,c}	94.74*
Kick amplitude (m)	0.60±0.04	0.58±0.06	0.54±0.06^{c}	10.31*
Body wave velocity ($m·s^{-1}$)	3.14±0.25	3.48±0.27^{a}	4.00±0.41^{b,c}	83.29*
Froude efficiency	0.68±0.01	0.68±0.01	0.68±0.01	0.71
Peak downward toe velocity ($m·s^{-1}$)	-3.59±0.27	-3.76±0.32	-4.07±0.19^{b,c}	25.17*
Peak upward toe velocity (m·s-1)	2.56±0.31	2.83±0.38^{a}	3.16±0.28^{b,c}	31.17*
Relative duration of Phase A (%)	17.4±2.7	17.0±2.7	17.9±2.2	1.14
Relative duration of Phase B (%)	32.2±5.0	33.4±4.3	33.1±4.4	1.13
Relative duration of Phase C (%)	9.8±2.8	10.8±2.8	12.1±4.2^{b}	7.56*
Relative duration of Phase D (%)	40.6±4.5	38.7±5.4	36.9±4.7^{b,c}	16.73*
Peak hip extension angle (deg)	13.0±4.4	13.0±4.3	11.5±5.0	4.27*
Peak hip flexion angle (deg)	-22.8±7.1	-21.0±8.1^{a}	-21.0±7.9^{b}	5.78*
Peak knee varus angle (deg)	-4.1±2.8	-4.2±2.6	-6.1±1.7	3.99*

Peak ankle planter flexion angle (deg)	63.3±7.4	64.6±7.6	66.0±8.7[b]	4.91*
Peak hip extension velocity ($deg \cdot s^{-1}$)	174.3±41.5	194.6±49.8[a]	215.5±47.5[b,c]	50.36*
Peak hip flexion velocity($deg \cdot s^{-1}$)	-181.5±34.6	-188.2±44.2	-210.2±47.1[b,c]	6.93*
Peak hip internal rotation velocity ($deg \cdot s^{-1}$)	181.9±56.0	206.2±32.6	251.1±42.8[b]	8.97*
Peak hip external rotation velocity ($deg \cdot s^{-1}$)	-219.1±68.9	-242.1±78.5	-309.3±98.7[b,c]	24.41*
Peak knee flexion velocity ($deg \cdot s^{-1}$)	333.2±76.2	409.0±97.7[a]	498.4±90.6[b,c]	73.48*
Peak knee extension velocity ($deg \cdot s^{-1}$)	-446.6±39.8	-454.6±62.6	-526.1±57.8[b,c]	12.53*
Peak knee valgus velocity ($deg \cdot s^{-1}$)	68.9±31.3	70.9±30.8	116.1±32.4[b,c]	15.08*
Peak knee varus velocity ($deg \cdot s^{-1}$)	-59.7±15.2	-82.5±36.3	-117.0±43.1[b,c]	12.57*
Peak ankle planter flexion velocity ($deg \cdot s^{-1}$)	239.3±52.3	300.7±106.3	354.1±113.4[b]	12.05*
Peak ankle dorsal flexion velocity ($deg \cdot s^{-1}$)	-185.4±34.0	-209.0±66.9	-279.3±103.0[b,c]	9.00*

* Significant main effect in ANOVA, $p < .05$

[a] Significant difference between 70%V and 80%V, $p < .05$

[b] Significant difference between 70%V and 90%V, $p < .05$

[c] Significant difference between 80%V and 90%V, $p < .05$

DISCUSSION:

Several UUS studies indicated that higher kick frequency related to higher swimming velocity (Arellano, Pardillo, & Gavilán, 2002; Houel et al., 2013), and Cohen, Cleary, and Mason (2012) used a computational simulation of the UUS to demonstrate that the mean of the net stream wise forces increases linearly with kick frequency. In this study, the kick frequency was increased with increasing swimming velocity (Table 1), and this result was similar to the results of the previous simulation study. Furthermore, the peak downward/upward toe velocity and peak hip flexion/extension velocity, peak knee flexion/extension velocity and peak ankle planter/dorsal flexion velocity were increased with increasing the kick frequency. These results mean that both the downward and upward kicks during UUS got to be quick with increasing kick frequency.

In 90V trial, it was shown that the relative duration of Phase C was increased and the relative duration of D was decreased. Arellano et al. (2002) reported that the first upward kick which mainly involved knee extension was a propulsive phase with increasing swimming velocity and the second upward kick phase which mainly involved knee flexion was a recovery phase with decreasing swimming velocity. The Phase C and D of this study correspond to the first upward kick and second upward kick respectively, and it was considered that the Phase C was a propulsive phase and the Phase D was an un-propulsive phase. In a breaststroke swimming study of Olstad, Vaz, Zinner, Cabri, and Kjendlie (2017), it was reported that the swimmers during breaststroke kicking decreased the duration of the un-propulsive phase with increasing their effort. As well as the breaststroke swimming, it was considered that the participants of this study decreased the duration of the un-propulsive phase to increase swimming velocity in 90%V trial.

In the results of the angular velocity, it was observed that the peak hip external rotation velocity increased with increasing swimming velocity. Shimojo et al. (2019) visualized the quasi 3-D flow fields in wake region during UUS and demonstrated that the external rotation of the lower limbs during downward kicking related to a strong cluster of vortices and jet flow in the wake resulting in thrust. Furthermore, Yamakawa et al. (2017) reported that the maximum hip external rotation velocity during UUS correlated positively to the average swimming velocity. Therefore, it was speculated that the increment of the hip external rotation velocity induced the lower limbs external rotation and contributed to increase the thrust of the downward kicking.

CONCLUSION: When swimmers increased the swimming velocity during UUS, they increased the kick frequency and decreased the un-propulsive phase which involved the hip extension and knee flexion. Furthermore, it was found that the velocity of the lower limbs external rotation relates to control the swimming velocity during UUS.

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