HYDRODYNAMIC RE-EXAMINATION OF UNDERWATER NON-PROPULSIVE PHASE IN FRONT CRAWL

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The purpose of this study was to re-examination of the hand propulsive force (F_P) during the entry and catch (*EC*) phase in a stroke of front crawl. The *EC* phase was defined as non-propulsive phase (Collet et al., 2000), which is until a hand starts moving backwards after it enters the water and moves forward. The other phases in the stroke was defined as propulsive phase. Twelve male swimmers performed a 20-m front crawl with maximal effort. For estimatinng the F_P, six pressure sensors were attched on their right hand and trials were recorded by three-dimentional motion capture system. We calculated *%EC* that was the ratio of the mean F_P in the *EC* phase to the mean F_P in the propulsive phase. As a result, the mean F_P in the *EC* phase was 22.4 ± 12.9 N and the *%EC* was 29.1%. Therefore, it was considered the *EC* phase is propulsive phase even though the hand moves forward.

KEYWORDS: Swimming, Propulsive force, Non-propulsive phase, Pressure.

INTRODUCTION: Several methods have been proposed for identifying the phases of a stroke in front crawl. Chollet et al. (2000) divided the underwater stroke movements into entry and catch (*EC* phase), the *Pull* and *Push* phases based on the back and forth movement of a hand. The *EC* phase was from when the hand entered the water until it started moving backward, and was considered to be a non-propulsive phase which the hand propulsive force (F_P) is not exerted because the hand moves to forward. The *Pull* phase was from the end of the *EC* phase until the point where the hand reached below the shoulder, and the *Push* phase was from the end of the *Push* phase until the hand exit from water. These two phases were defined as propulsive phases which the F_P is exerted because the hand moves to backward and push water. This method identifying the phases of the stroke was conducted by using video image analysis. However, in practice, unsteady flow was generated around the hand by swimming motion, which affects the magnitude of the F_P. Therefore, it is not possible to determine whether the F_P is exerted only by analysing the video image of the swimming motion. In fact, Kudo et al. (2017) reported data showing that the F_P is exerted during a part of non-propulsive phase by using the pressure distribution measurement. Therefore, the purpose of this study was to re-examine the F_P in the *EC* phase using the pressure distribution measurement.

METHODS: Twelve male swimmers participated in this study (age: 22.3 ± 3.3 years; height: 1.78 ± 0.07 m; mass: 75.8 ± 5.6 kg; FINA Point in 50 m front crawl: 610.5). Prior to experiments, all participants were briefed on the outline and safety of the experiment, and written informed consent was obtained from all participants. After self-selected warm-up, they performed maximal effort swimming in front crawl without breathing at 20 m. Seven active LED markers were attached to the subject's body (left and right greater trochanter, right acromion, right second and fifth metacarpophalangeal joints, right radial styloid process, right ulnar styloid process). In order to obtain the absolute coordinate values, three-dimensional motion capture system (*VENUS 3D, Nobby Tech. Ltd.*) was utilized with a sampling frequency of 100 Hz. The analysis range was 5 m between 12-m and 17-m. The right and left direction of the swimmer was set as the *X*-axis, the propulsive direction was set as the *Y*-axis, and the vertical direction was set as the *Z*-axis. To measure the pressure distribution on the surface of the hand, six pressure sensors (*PS-05KC*, *Kyowa Electronic Instruments Co., Ltd.*) were attached to the right hand. Positions where the pressure sensors were attached (P1, P2, P3, D1, D2, D3) were the second, third, and fifth metacarpophalangeal joints, which were almost at the same position on the palm and the dorsal of the hand (Figure 1) (Tsunokawa et al., 2018). The signal output by the pressure sensors were recorded at 100 Hz. The mean value of swimming velocity (*SV*), stroke frequency (*SF*), and stroke length (*SL*) were analysed from one stroke cycle performed within the analysis range. One cycle in front crawl was from when the hand entered the water until the hand on the same side entered the water again. The other variables were analysed at underwater stroke duration only because the motion capture camera was set only underwater. The method identifying the underwater stroke phases used Collet et al. (2000) method mentioned earlier. The hand velocity was calculated in each direction component (*X*-axis: V_{HX}, *Y*-axis: V_{HY}, *Z*-axis: V_{HZ}) respectively. The pressure value at each measurement point obtained by the pressure distribution measurement was filtered using a Low-pass Butterworth digital filter (10 Hz). Since each sensor measures the sum of hydrostatic- and dynamic-pressure, the hydrostatic pressure was calculated from the depth of the hand, and the dynamic pressure was calculated by subtracting the hydrostatic pressure from the total pressure. The mean palm and dorsal pressure values were calculated as *PP* and *PD* by averaging the pressure values of the three pressure sensors on the palm and dorsal respectively. The hand resultant force (F_{hand}) calculated by referring to the method of Tsunokawa et al. (2018), and the F_P was defined as F_{hand} of the Y-axis direction component. In order to show the magnitude of the F_P in the *EC* phase (*%EC*), the ratio of the mean F_P in the *EC* phase to the mean F_P in the propulsive phase (mean of *Pull* and *Push*) was calculated. No statistical analysis was conducted.

RESULTS: *SV* was 1.74 ± 0.07 m/s, *SF* was 0.93 ± 0.05 stroke/s, and *SL* was 1.82 ± 0.14 m/stroke. Table 1 shows mean value of F_{hand}, F_P, *PP*, and *PD* for whole underwater stroke and each underwater stroke phase. The *%EC* representing the ratio of the F_P of the *EC* phase to the F_P of the propulsive phase was 29.1%. The temporal change from when the hand entered the water until when it exited the water of V_{HX}, V_{HY} and V_{HZ} (Figure 2), P1, P2, P3, D1, D2, and D3 (Figure 3), and F_{hand} and F_P (Figure 4) were showed.

Table 1. Mean F_{hand}, F_P, *PP* and *PD* at whole underwater stroke and three phases.

	whole	*EC*	*Pull*	*Push*
F_{hand} (N)	71.8 ± 16.8	44.2 ± 18.6	92.7 ± 16.1	89.6 ± 23.1
F_P (N)	53.1 ± 12.8	22.4 ± 12.9	77.6 ± 18.3	70.6 ± 18.3
PP (kpa)	3.6 ± 2.3	3.2 ± 2.3	6.0 ± 2.4	2.3 ± 3.0
PD (kpa)	-8.5 ± 1.5	-3.9 ± 1.6	-9.9 ± 1.3	-13.4 ± 2.1

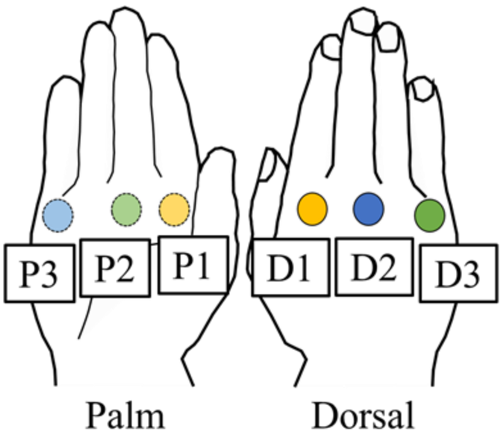

Figure 1. A Schematic diagram of positions where the pressure sensors was attached.

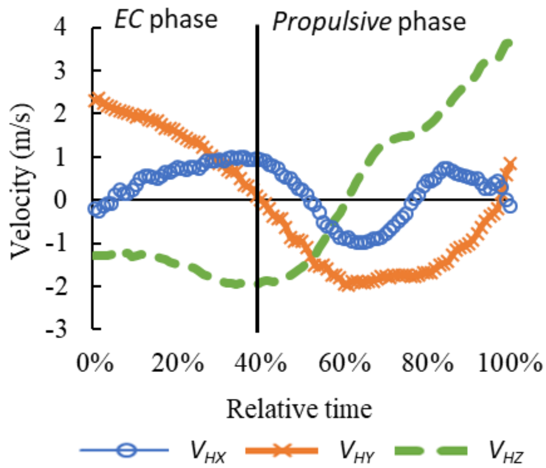

Figure 2. Temporal change of V_{HV}, V_{HY} and V_{HZ}. The vertical line is the boundary between the *EC* and the propulsive phase.

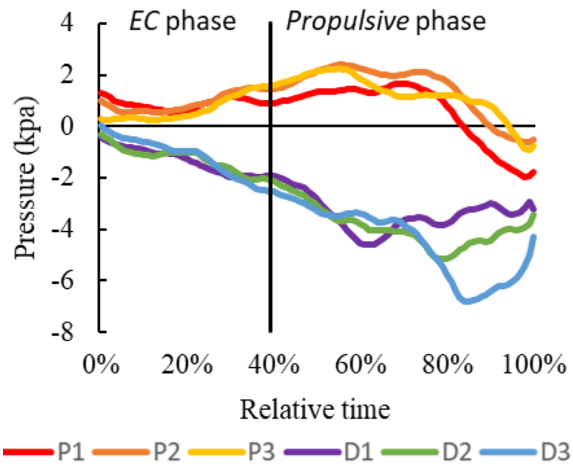

Figure 3. Temporal change of each pressure value on the hand.

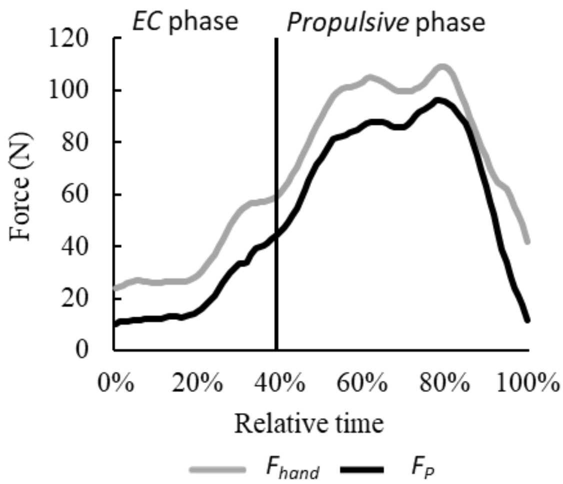

Figure 4. Temporal change of F_{hand} and F_P.

DISCUSSION: The purpose of this study was to re-examine the F_P of the *EC* phase using the pressure distribution measurement. The mean F_P in the *EC* phase was 22.4 ± 12.9 N, and the *%EC* indicating the magnitude of the mean F_P in the *EC* phase to the mean F_P in the propulsive phase was 29.1%. A previous study using the same methodology also showed the F_P of about 10-30 N in the *downsweep* phase, which is recognized as a part of the non-propulsive phase (Kudo et al., 2017). From these results, it became clear that about 30% of the F_P is exerted in the *EC* phase. Therefore, the *EC* phase is not non-propulsive phase but propulsive phase, and the definition of stroke phase must be re-considered.

However, the ratio of F_P to the F_{hand} was about 50% in the *EC* phase and about 80% in both the *Pull* and the *Push* phases. Therefore, although the *EC* phase was not the non-propulsive phase, it is necessary to recognize that the ratio of the F_{hand} acting in the propulsion direction was lower in the *EC* phase than in the *Pull* and *Push* phases. In addition, since the trial in this study was performed with maximal effort, it is considered that the swimmers immediately tried to make the F_{hand} act to the propulsion direction after the hand entered the water, and the F_P was exerted during the entire *EC* phase. Therefore, it is necessary to pay attention that the timing at which the F_P begins to be exerted may be different depending on the pace of the trial.

The pressure difference between the palm and the dorsal side contributes to the F_P. This is because the F_P is a propulsion direction component of the F_{hand}, and the F_{hand} is determined by the product of the pressure difference and the hand area. In the *EC* phase, the pressure on the palm and the dorsal side were positive and negative respectively, causing the pressure difference (Table 1). It is considered the positive pressure on the palm side was due to the counteraction from water by the hand movement to the rightward and downward (Figure 2). On the other hand, it was considered the negative pressure on the dorsal side was caused by the faster water flow on the dorsal due to adjusting the angle between the hand plane and the direction of hand movement. If the angle was too large, a positive pressure would be measured on the dorsal side due to the counteraction from water because the hand moved forward and the dorsal side was the leading side. Therefore, there would be an optimal range of the angle to exert the F_P in the *EC* phase. However, the actual relationship between the angle and the water flow speed is not clear. In the future, it may be possible to clarify by observing changes in the flow of water around the hand by visualizing the flow field.

CONCLUSION: The purpose of this study was to re-examine the F_P in the *EC* phase, which is considered to be non-propulsive phase. From the results, the *EC* phase was considered to be the propulsive phase, and the method identifying the underwater stroke phase needs to be re-considered. In addition, it is necessary to identify a technique for exerting higher F_P in the *EC* phase in order to swim faster.

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