The effect of paddles on pressure and force generation at the hand during front crawl

著者別名	高木 英樹
journal or publication title	Human movement science
volume	57
page range	409-416
year	2018-02
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URL	http://hdl.handle.net/2241/00151557

doi: 10.1016/j.humov.2017.10.002

Title:

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Abstract

Through pressure measurement, this study aimed to clarify the effects of hand paddle use on pressure and force generation around the hand during the front crawl. Eight male swimmers performed two trials of front crawl swimming with maximal effort, once using only their hands and once aided by hand paddles. During trials, pressure sensors and underwater motion capture cameras were used together to analyze hand kinematics and pressure forces acting on the hand. Six pressure sensors were attached to the right hand, and pressure forces acting on the right hand were estimated by multiplying the areas and the pressure differences between the palm side and dorsal side of the hand. Acting directions of pressure forces were analyzed using a normal vector perpendicular to the hand, calculated from coordinates of the right hand. As a result, using hand paddles decreases pressure differences between the palm and dorsal sides of hand related to the magnitude of pressure force. However, no difference was found in the mean value of resultant pressure forces compared with using hands alone, because the large surface area of the hand paddle compensated the decreased pressure differences due to decreased hand velocity. In addition, when hand paddles were used, the component of the pressure force acting in propulsive direction was significantly higher. Thus, the ratio of forces acting in the propulsive direction was higher than without hand paddles. These results suggest that the training loads with hand paddles are not high even if the swimming velocities increase because the power generated by upper limb motion didn’t increase.

Keywords

human swimming, propulsive force, hand paddle use, motion capture, pressure measurement

The Effect of Paddles on Pressure and Force Generation at the Hand during Front Crawl

1. Introduction

Hand paddles are used while training for competitive swimming to increase force and power generated by upper limb motion. In previous studies on the effects of hand paddles, kinematics, such as stroke length, stroke rate, hand velocity, coordination of upper limb motions and efficiency of propulsion and energy consumption using physiological methods have been reported. A study using image analysis (Gourgoulis, Aggelousis, Vezos, & Mavromatis, 2006) reported that stroke length and swimming velocity increased with increase in paddle size, despite reduction of the velocity of hand and stroke rate. Furthermore, a study measuring propelling efficiency reported that, in comparison with bare hand swimming at the same velocity, swimmers increased their propelling efficiency by about 7.8% with hand paddles (Toussaint, Janssen, & Kluft, 1991). Additionally, several investigations have shown that oxygen uptake in swimming with hand paddles was lower than without them at given submaximal velocities, due to increased propelling efficiency (Ogita, & Tabata, 1993; Ogita, Onodera, & Tabata, 1999).

The effects of hand paddles on the lift and drag forces during the front crawl were also estimated (Gourgoulis, Aggeloussis, Vezos, Kasimatis, Antoniou, & Mavromatis, 2008) based on kinematic data, using a quasi-static approach (Sanders, 1999). As a result, the surface area of the hand paddle caused an increased drag, lift, resultant forces, and propelling efficiency. However, the quasi-static approach applies drag and lift coefficients obtained under steady flow conditions to predict force acting on motion under unsteady flow conditions; this result in ignoring the effect of changes in acceleration and vortices around the body of swimmer. Since unsteady flow occurs around the hand during swimming (Toussaint, van den Berg, & Beek, 2002; Matsuuchi, Miwa, Nomura, Sakakibara, Shintani, & Ungerechts, 2009; Kudo, Vennell, & Wilson, 2013; Takagi, Nakashima, Ozaki, & Matsuuchi, 2013, 2014), it was reported that force estimated by the quasi-static approach (Schleihauf, Gray, & DeRose, 1983) became a large error (Pai & Hay, 1988; Lauder & Dabnichki, 2005).

To fulfil these requirements, a growing number of studies have focused on pressure forces during swimming. In these studies, pressure forces acting on the body of swimmer were estimated from the pressure of body surface while considering unsteady motion (Takagi & Wilson, 1999;

Kudo, Yanai, Wilson, Takagi, & Vennell, 2008; Tsunokawa, Nakashima, & Takagi, 2015). As swimmers move their hands through water, pressure forces acts in the normal direction, and frictional force in the tangential direction to the hand surface. Swimmers propel themselves by the sum of these forces in the propulsive direction. In a study using computational fluid dynamics (Marinho et al., 2009), the ratio of the pressure forces to total drag experiences during gliding position were 86.95 – 92.05%. Thus, frictional forces are considerably less than pressure forces. The use of pressure measurement can clarify the effects of hand paddle use on the propulsion during swimming. If these matters are clarified, the factors that increase propelling efficiency, velocity, and stroke length with the use of hand paddles become clear.

Therefore, by using pressure measurement, this study aimed to clarify the effects of hand paddle use on pressure and force generation around the hand during the front crawl. It was hypothesized that swimming velocity and propulsive forces would increase when use hand paddles. This hypothesis may seem to be in contrast with the reports by previous studies that hand velocity decreases with the use of hand paddles. If the pressures and force generations processes are clarified, the reasons why swimming velocity and propulsive forces increase despite a reduction of hand velocity should become clear. In addition, we hope to clarify how much the pressure forces and propulsive forces change when use hand paddles. If propulsive forces increase without an increase in the resultant pressure forces, this would mean that the muscle power generated by the upper limbs does not increase but propelling efficiency improves.

2. Method

2.1. Participants

The study sample consisted of eight national-level male swimmers (age: 20.4 ± 1.3; height: 1.75 ± 0.06 m; mass: 69.2 ± 7.9 kg; area of hand: 0.0161 ± 0.0011 m^2; FINA point: 672.3 ± 25.1), with best performances in the 100-m front crawl between 52.9 and 55.0 s. Test procedures were fully explained to participants before they provided written consent to participate in the study, which was approved by the Ethics Committee of institute (approval number: 3–16).

2.2. Experimental trials

Experiments were conducted in an indoor pool (length: 50.0 m; width: 21.0 m; depth: 2.0 m;

water temperature: 27.5 °C). Each swimmer performed 16 m front crawl swimming with maximal effort starting with a push-off start at the wall. To clarify the effects of hand paddles, swimmers swam two trials in randomized order, once using only their hands (hand trials) and once aided by hand paddles on both hands (paddle trials). In both trials, swimmers performed only arm strokes while a buoy supported their legs. In paddle trials, plastic resin hand paddles were used (surface area: 0.0336 m^2; longitudinal: 0.21 m; width: 0.20 m; thickness: 3.0 mm).

2.3. Experimental design

In both trials, reflective markers were attached to each hip, and five markers were attached to landmark points on the right hand. Elastic medical tape made of cotton and strong magnets was used for attaching reflective markers. Positions of markers were determined according to previous studies (Gourgoulis, Aggeloussis, Vezos, Kasimatis, Antoniou, & Mavromatis, 2008; Monnet, Samson, Bernard, David, & Lacouture, 2014). In hand trials, five reflective markers on the right hand were attached on the tip of the third finger, the second (M2) and fifth (M5) metacarpophalangeal joints, the radial styloid and the ulnar styloid. In paddle trials, five reflective markers were attached at the five edge points of hand paddles (Fig. 1). A Qualisys motion capture system composed of 15 underwater cameras (Qualisys Opus Underwater, Qualisys, Sweden) was used. The markers reflected the light of the LEDs, so it could be captured by the CCD sensors of cameras. The 3D coordinates of markers were recorded with software for motion capture (Qualisys Track Manager, Qualisys, Sweden) at a frame rate of 200 Hz. In the present study, the horizontal direction was defined as the X axis, the swimming direction as the Y axis and the vertical direction as the Z axis; the measurement volume was 2.0 m in the X axis, 7.0 m in the Y axis, and 2.0 m in the Z axis. The measurement volume in the Y axis was set from 8.0 m to 15.0 m from the wall. For calibration of motion capture, a carbon fiber rod with reflective markers on both ends was moved underwater, and the distance between markers was analyzed. Using the ruler, the distance between the reflective markers attached to both ends was measured before calibration. Calibration confirmed that accuracy of underwater motion capture within the analysis range had less than 0.5% error. Fig. 2 shows a schematic representation of the experiment.

During trials, six pressure sensors (PS05–KC Kyowa Electronic Instruments Co. Ltd., Japan) were attached to the right hand to measure pressure around the hand. Pressure sensors were small

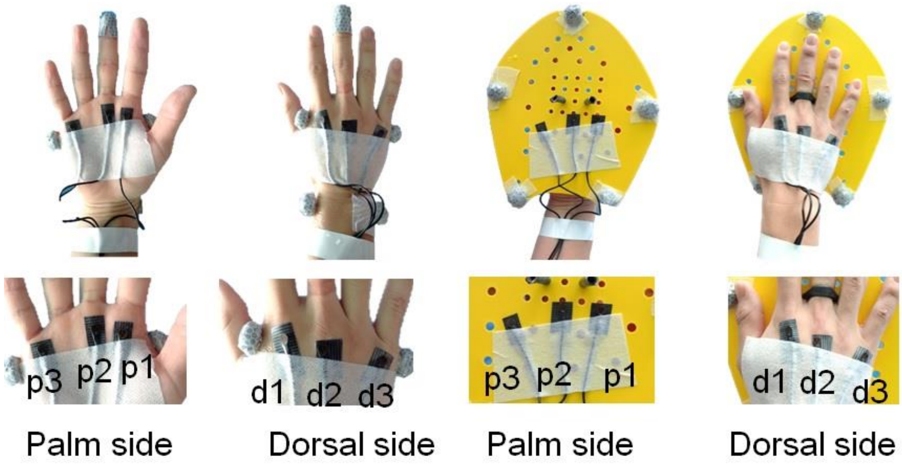

Fig. 1. Photographs of hands and paddles with reflecting markers and pressure sensors

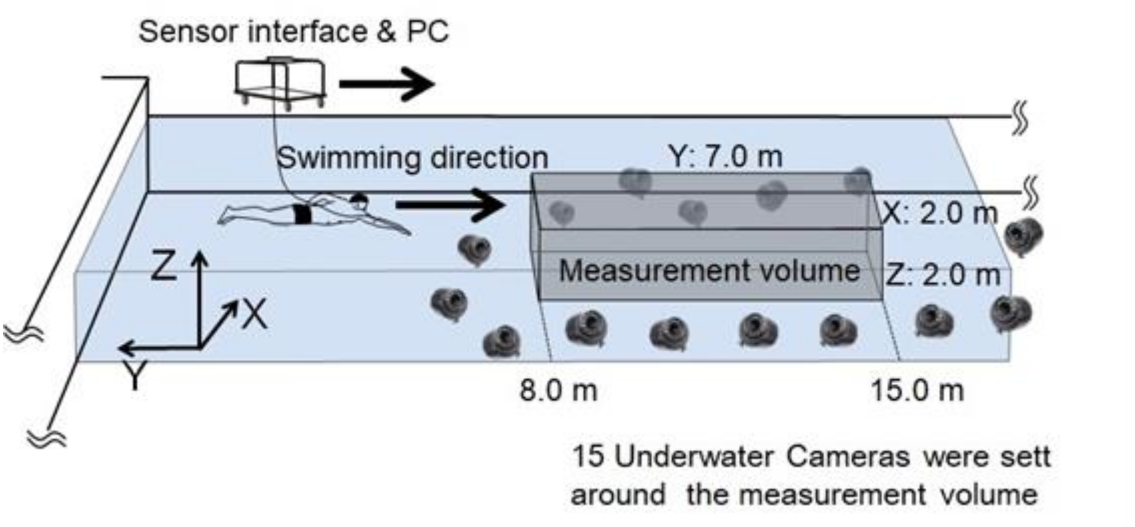

Fig. 2. Schematic representation of the experiment

(diameter 6.0 mm; thickness 0.6 mm) and waterproof. In hand trials, six pressure sensors on the right hand were attached at the palm and the dorsal sides of the second (p1, d1), third (p2, d2) and fifth (p3, d3) metacarpophalangeal joints. In paddle trials, six pressure sensors were attached at the same points as in hand trials; on the palm side, sensors were attached to the hand paddle. Fig. 1 shows photographs of hands and paddles with reflecting markers and pressure sensors attached.

The pressures were measured with wired pressure sensors with a sample rate of 200 Hz. Pressure data were processed with sensor interface (PCD330B-F Kyowa Electronic Instruments Co.

Ltd., Japan) and imported on computer, which were mounted on a carrier that moved along with a swimmer. For the calibration of the pressure sensors, all sensors were submerged in water to a depth of 1.2 m; from there, hydrostatic pressures were measured at intervals of 0.1 m to the surface. As a result, the error between the measured and the theoretical hydrostatic pressure was less than 2.5%. Motion capture and pressure measurement were synchronized with an electric signal to start simultaneously. Position and pressure data were filtered through a low pass Butterworth filter with net cut off frequency set at 20 Hz.

2.4. Data processing

In the present study, we analyzed one cycle of motion performed at the motion capture area. In particular, we analyzed duration from entry of reflective marker attached at the tip of the third finger to re-entry. In pressure measurement, when the tip of the third finger entered the water, since pressure sensors were still above the water, the duration of all reflective markers attached at the hand were in the water was analyzed. From coordinate data obtained with motion capture, Mean swimming velocity, Stroke length, Stroke rate and Hand velocity were calculated. Stroke length (m) was obtained from displacement of the hip during a stroke cycle, and Mean swimming velocity ($m \cdot s^{-1}$) was calculated by dividing Stroke length by time. Stroke rate ($stroke \cdot s^{-1}$) was calculated as the number of cycles per second. Hand velocity ($m \cdot s^{-1}$) during underwater motion was obtained from coordinates of the midpoint of reflective markers, attached to five points of the right hand.

Pressure sensors measured hydrodynamic pressures, as well as hydrostatic pressures due to depth of sensor. The depth of each pressure sensor was calculated from M2 and M5 coordinates during trials, and hydrostatic pressures were eliminated by subtracting them from total pressures. Therefore, reported pressure did not include hydrostatic pressures, but showed only hydrodynamic pressures. When swimmers move their hands under the water, pressures on the palm side of the hand increase, or pressures on the dorsal side decrease, thereby increasing pressure differences between palm side and dorsal side, related to the magnitude of pressure force. For these reasons, we reported mean pressure differences at each measurement point (p1 – d1, p2 – d2, p3 – d3).

2.5. Calculation of pressure forces

Pressure forces (N) were estimated by multiplying the projected areas (m^2) and the pressure differences ($N \cdot m^{-2}$) between the palm side and dorsal side of the right hand or hand paddle using the method reported in previous studies (Takagi & Wilson, 1999; Tsunokawa, Nakashima, & Takagi, 2015). Projected areas of the right hand or hand paddle were calculated from photographs using image processing software (NIH Image J, USA). And pressures differences were obtained by subtracting dorsal side pressures from those at the palm sides, enabling values of hydrodynamic pressures to be obtained. In the present study, the hand or hand paddle were divided into three segments, and three pairs of pressure sensors were attached on the dorsal and palm sides of each segments. Pressures differences were considered as the representative hydrodynamic pressure at each segment. The pressure forces acting on each segment were calculated by multiplying those pressure differences by the area of each segment. The pressure forces acting across the entire hand or hand paddle were obtained by summing the forces calculated at each segment.

Acting directions of pressure forces (X, Y, Z) were analyzed using a normal vector perpendicular to the hand, calculated from coordinates of the right hand or hand paddle. In the present study, pressure forces acting on the Y axis direction were defined as propulsive forces (Fig. 3).

2.6. Statistics

For statistical treatment of data, the assumption of normally distributed samples was verified with the Shapiro–Wilk test, and sphericity was verified with the Mauchly test. The paired *t*-test identified the effects of hand paddles. Since the sample size was relatively small, for each *t*-statistic, effect size was calculated with Cohen's *d*. Effect size was considered small if the absolute value of Cohen's *d* was less than 0.2, medium if it was between 0.2 and 0.5 and large if it was greater than 0.5 (Cohen, 1988). All statistical analyses were conducted with IBM SPSS statistics 22 for Windows at the $P < 0.05$ significance level.

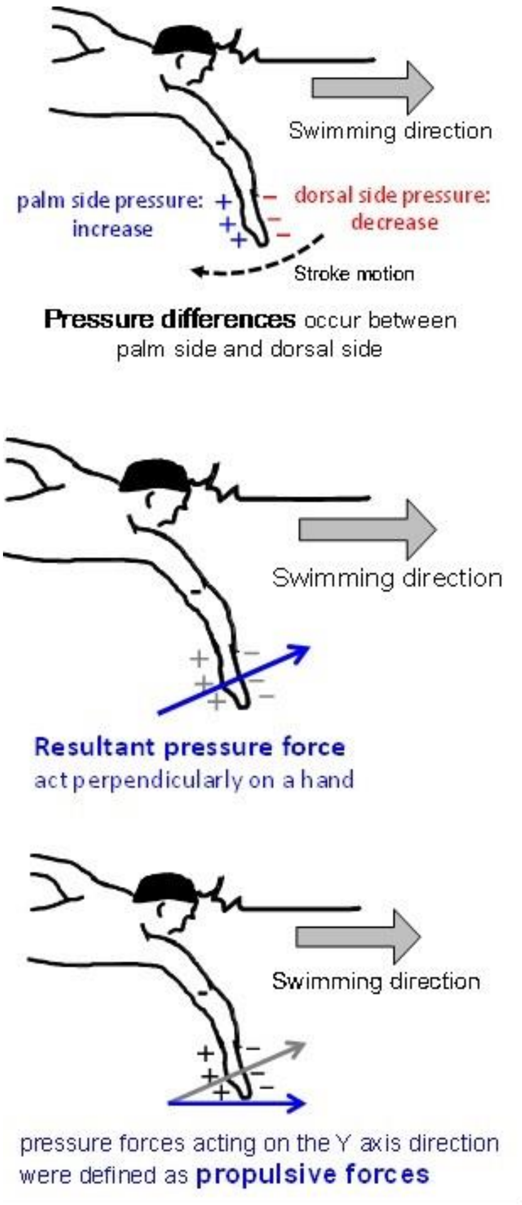

Fig. 3. Schematic of forces acting on a hand

3. Results

Fig. 4 and 5 show fluctuation of pressures and pressure forces during one stroke cycle of swimmer A. The swimmer A has the fastest best-record of 100-m freestyle among the participants, and the swimming velocity in the hand and paddle trials were highest. In both trials, the pressure on the palm side (p1–p3) showed positive values and the pressure on the dorsal side (d1–d3) showed negative values. Pressure forces acting on the hand or hand paddle consistently acted mainly in the propulsive direction (Y axis).

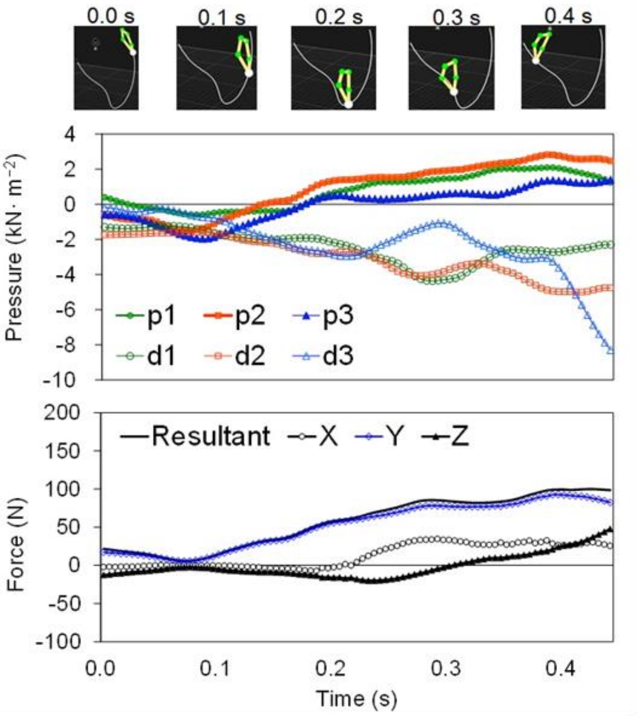

Fig. 4. Typical temporal profiles of pressure and pressure forces around a right hand during underwater phase at a hand trial (Swimmer A)

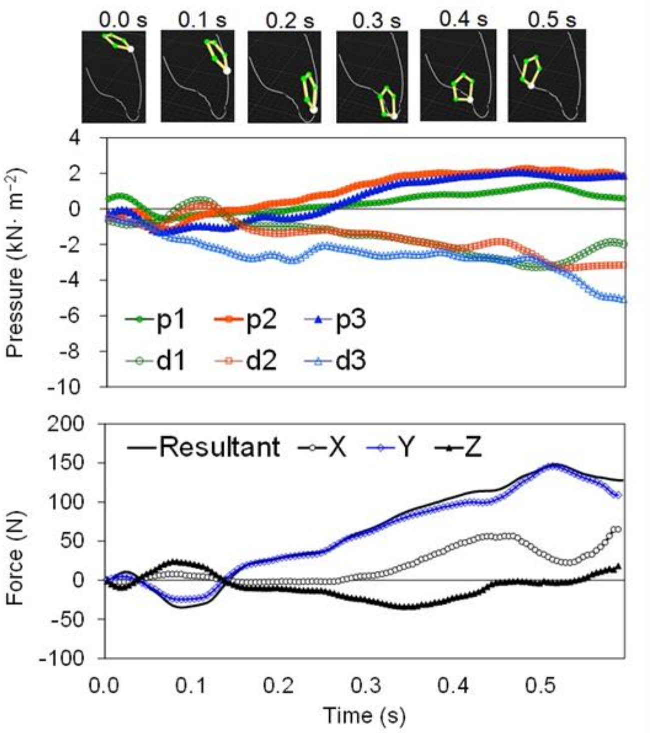

Fig. 5. Typical temporal profiles of pressure and pressure forces around a right hand during underwater phase at a paddle trial (Swimmer A)

Table 1 Means ± s, t–value and effect size of the kinematic parameters, pressure differences and pressure forces during underwater phase

	hand trials	paddle trials	*t* –value	*P*	Cohen's d (effect size)
Kinematic parameters					
Mean swimming velocity ($m\cdot s^{-1}$)	1.58 ± 0.06	1.67 ± 0.07	6.34*	0.00	1.52
Stroke length (m)	1.80 ± 0.16	1.99 ± 0.18	3.46*	0.01	1.08
Stroke rate ($stroke\cdot s^{-1}$)	0.88 ± 0.10	0.85 ± 0.10	1.05	0.31	0.31
Mean hand velocity ($m\cdot s^{-1}$)	2.29 ± 0.14	1.95 ± 0.13	7.00*	0.00	2.50
Maximum hand velocity ($m\cdot s^{-1}$)	3.35 ± 0.24	3.06 ± 0.35	2.71*	0.03	0.97
Mean pressure differences					
p1 − d1 ($kN\cdot m^{-2}$)	3.20 ± 0.62	1.57 ± 0.53	7.95*	0.00	2.83
p2 − d2 ($kN\cdot m^{-2}$)	3.74 ± 0.65	1.50 ± 0.23	10.12*	0.00	4.61
p3 − d3 ($kN\cdot m^{-2}$)	3.81 ± 0.66	2.47 ± 0.70	4.04*	0.01	1.98
Pressure forces					
Mean resultant pressure force (N)	56.74 ± 10.64	59.10 ± 11.20	0.61	0.56	0.22
Mean propulsive force (N)	44.86 ± 9.06	51.07 ± 9.36	2.92*	0.02	0.67

Note : *Significant differences

Table 2 The comparison of parameters

Parameter	bare hand	paddle hand
Mean swimming velocity ($m\cdot s^{-1}$)		+
Stroke length (m)		+
Mean hand velocity ($m\cdot s^{-1}$)	+	
Mean pressure difference ($kN\cdot m^{-2}$)	+	
Surface area (m^2)		+
Mean resultant pressure force (N)	Non difference	Non difference
Mean propulsive force (N)		+

Table 1 shows mean values, standard deviations, *t*–values, *P*–values and Cohen's *d*–values of each variable for hand and paddle trials. And, Table 2 shows the comparison of parameters. In paddle trials, Mean swimming velocity was significantly higher than in hand trials, and Stroke length was longer. Both the Mean and Maximum of hand velocities were significantly lower in paddle trials than in hand trials. And, at all measurement points, significant differences were also observed in mean pressure differences between trials. There was no significant difference in the mean value of the resultant pressure force between trials, but in paddle trials, mean values of the propulsive force were significantly higher than in hand trials.

4. Discussion

Through pressure measurement, this study proposed to clarify the effects of hand paddle use on pressure and force generation around the hand during the front crawl. Results revealed significant differences in pressure differences measured at each point, and it is thought that hand paddle use also affected pressure around the hands. When swimmers move their hands under the water, pressures on the palm side increase, or pressures on the dorsal side decrease, thereby are increasing pressure differences between palm side and dorsal side related to the magnitude of pressure force. In contrast, no difference was found in mean value of the resultant pressure forces between trials. In addition, when hand paddles were used, propulsive forces and swimming velocities increased more than in bare hand trials. The area of hand paddle was about twice the mean value of the area of hands of subjects, so that in paddle trials, pressure forces acting on hand paddles increased due to increased area. It is well established that forces acting on the hand are proportional to the area of hand and to the square of relative velocity between water and hand (Berger, de Groot, & Hollander, 1995). Thus, no difference was inferred in mean resultant pressure force, since increased area supplemented the reduction of pressure differences due to hand velocity reduction.

In addition, in paddle trials, the mean values of propulsive forces were significantly higher so that the ratio of forces acting in the propulsive direction was higher than in bare hand swimming. In the past, it was thought that using hand paddles increased the muscle power generated by upper limb motion and the training load, but the results of present study contradict this. On the other hand, increased ratio of force acting in the propulsive direction, longer stroke length and lower hand velocity showed improved propelling efficiency; these results align with previous studies (Toussaint, Janssen, & Kluft, 1991), indicating that using hand paddles might improve propelling efficiency and reduce training load in some cases. Coaches and swimmers should pay attention to these points when using hand paddles for training, ensuring that they use them according to the training purpose.

A previous study analyzing tufts movements and pressure around the upper limbs (Toussaint, van den Berg, & Beek, 2002) confirmed that unsteady flows occur around the upper limbs and that pressure differences between palm side and dorsal side of the hand increased as swimming velocity increased. In addition, previous studies using PIV (Matsuuchi, Miwa, Nomura, Sakakibara, Shintani, & Ungerechts, 2009; Takagi, Nakashima, Ozaki, & Matsuuchi, 2013, 2014) reported that unsteady flow accompanied by vortices occurs on the dorsal side during swimming. In the present study, pressures showed lower values on the dorsal side than on the palm side, suggesting that unsteady flows occur on the dorsal side. Furthermore, since pressures consistently fluctuated during underwater stroke motion, the difficulty of accurately estimating forces acting on the hand, considering the unsteady flow from kinematic data with the quasi-static approach, was reconfirmed. In fact, since the errors of quasi-static approach were indicated in previous studies (Pai & Hay, 1988; Lauder & Dabnichki, 2005), considering unsteady flow is necessary to accurately estimate forces on the body during swimming.

In the present study, pressure measurement and underwater motion capture were used together to analyze hand kinematics and acting direction of pressure forces. In recent years, motion capture technique, which can analyze body landmark points automatically, has been applied to swimming research (Ceccon, Ceseracciu, Sawacha, Gatta, Cortesi, Cobelli, & Fantozzi, 2013; Dubois, Thiel, & James, 2013; Monnet, Samson, Bernard, David, & Lacouture, 2014) and is expected to be used in the future. Compared to conventional manual digitization, innovative motion capture techniques make it possible. In addition, the study confirmed that even in an experimental setting using motion capture and pressure measurement, analysis can be conducted without disturbing movement of swimmers. Thus, henceforth, research using such measurement will reveal information on swimming mechanisms and knowledge useful for improving competitive skills.

In the present study, we analyzed only the right hand so as not to encumber swimming motions by attaching too many pressure sensors and cables. However, differences between left and right motions are thought to occur. Additionally, research on stroke coordination has reported that in some cases, left and right propulsive phases may overlap. Therefore, propulsive forces acting on the right hand as calculated in the present study, do not represent propulsive forces of the entire swimming motion. In future, if pressure measurement can be conducted wirelessly, clarifying propulsive forces acting on each hand without encumbering swimming motions will be possible.

5. Conclusion

This research clarified that using hand paddles decreases pressure differences between palm and dorsal sides of the hand related to the magnitude of pressure force. However, no difference was found in the mean value of resultant pressure forces compared with that of bare hand swimming, because increased area supplemented decreased pressure differences due to decreased hand velocity. In addition, when hand paddles were used, mean values of propulsive forces were significantly higher, so the ratio of forces acting in the propulsive direction was higher than without hand paddles. These results suggest that the use of hand paddles increased swimming velocity and propelling efficiency, but did not increase the muscle power generated by the upper limb motion.

Conflict of interest

None

Acknowledgment

This work was supported by JSPS KAKENHI Grant Number JP17K13139.

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