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The effect of using paddles on hand propulsive forces and Froude efficiency in arm-stroke-only front-crawl swimming at various velocities

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ABSTRACT

Through pressure measurement and underwater motion capture analysis, this study aimed to elucidate the effects of hand paddles on hand propulsive forces, mechanical power, and Froude efficiency in arm-stroke-only front-crawl swimming at various velocities. Eight male swimmers swam under two conditions in randomized order, once using only their hands and once aided by hand paddles on both hands. Each participant swam 10 times a distance of 16 m in each condition, for a total of 20 trials. To elucidate the relationship between propulsive forces and swimming velocity, each participant was instructed to swim each of the two sets of 10 trials at an arbitrarily different swimming velocity. During the trials, pressure sensors and underwater motion capture cameras were used together to analyze the pressure forces acting on the hand and hand kinematics, respectively. Six pressure sensors were attached to the right hand, and pressure forces acting on the right hand were estimated by multiplying the areas with the pressure differences between the palm and dorsal side of the hand. Acting directions of pressure forces were analyzed using a normal vector perpendicular to the hand or hand paddle, calculated from coordinates obtained using underwater motion capture analysis. As a result, there were no differences in propulsive forces and mechanical power to overcome water resistance (P_D) with or without hand paddles at the same swimming velocities. However, the use of hand paddles decreased stroke rate and hand velocities, so mechanical power to push the water at the hand (P_K) decreased. Using hand paddles thus increased Froude efficiency (η_F). These results suggest that training load decreases when swimmers swim at the same velocities while using hand paddles. This insight could prove useful for coaches and swimmers when using hand paddles for training to help ensure that they are used in accordance with their intended training purpose. If swimmers use hand paddles increasing propulsive force or P_K, they should swim at a higher swimming velocity with hand paddles than without.

1. Introduction

Competitive swimmers use hand paddles while training to increase propulsive force and power generated by upper limb motion.

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Several studies have investigated the effects of hand paddles on swimming motion by using physiological or biomechanical methods. A study measuring propelling efficiency reported that, in comparison with bare hand swimming at the same velocity, swimmers increased their propelling efficiency by roughly 7.8% by using hand paddles (Toussaint, Janssen, & Kluft, 1991). In addition, several investigations have shown that oxygen uptake in swimming with hand paddles was lower than without them at given submaximal velocities, because of increased propelling efficiency (Ogita & Tabata, 1993; Ogita, Onodera, & Tabata, 1999). A study involving kinematic analysis reported that stroke length and swimming velocity increased for maximal swimming when paddle size increased, despite an accompanying reduction of hand velocity and stroke rate (Gourgoulis, Aggelousis, Vezos, & Mavromatis, 2006). Furthermore, a study using a quasi-static approach for estimating fluid force from image analysis reported that resultant fluid forces, propulsive forces, and propelling efficiencies increased when using hand paddles in maximal swimming (Gourgoulis et al., 2008). However, the quasi-static approach applies drag and lift coefficients obtained under steady flow conditions to predict fluid force acting on motion under unsteady flow conditions, resulting in a significant error in the estimated fluid force (Pai & Hay, 1988). As the unsteady flow around the hand during swimming is reflected in the pressure around the hand, the effects of the use of hand paddles on fluid forces should be investigated by means of pressure measurement (Tsunokawa, Tsuno, Mankyu, Takagi, & Ogita, 2018) while considering unsteady flow effects (Kudo, Vennell, & Wilson, 2013; Matsuuchi et al., 2009; Takagi, Nakashima, Ozaki, & Matsuuchi, 2013, 2014; Toussaint, Van den Berg, & Beek, 2002). As a result, using hand paddles decreases both the hand velocities and the pressure difference between the palm and dorsal side of the hand, but without affecting the resultant fluid forces because the increased area was nullified by a decreased pressure difference. In addition, since using hand paddles increases the ratio of the fluid force contributing as the propulsive force, the maximal swimming velocity also increases with hand paddles.

As described above, the effects of hand paddles on the propelling efficiency, oxygen uptake, kinematics, and fluid forces acting on a hand were investigated using various methods. However, all of these studies focused on maximal swimming. As hand paddles increase swimming velocity and propulsive forces at maximal swimming, mechanical power to overcome water resistance (P_D) inevitably increases compared with bare hand swimming. Because P_D is determined by propulsive force and swimming velocity, the effects of hand paddles on P_D at the same swimming velocity has not been elucidated. In addition, hand velocity and the resultant fluid force acting on the hand depend on the in swimming velocity. Therefore, the mechanical power to push the water at the hand (P_K) also depends on the swimming velocity. Because Froude efficiency (η_F) defined as the fraction of the external power produced by the swimmer's muscles that contributes to propulsion (Zamparo, Pendergast, Mollendorf, Termin, & Minetti, 2005; Zamparo, Pendergast, Termin, & Minetti, 2002) is determined by P_D and P_K, the effects of hand paddles on Froude efficiency at submaximal swimming have not been elucidated for arm-stroke-only front-crawl swimming (i.e. without kicking motion).

Underwater motion capture analysis has underwent a rapid development and is currently being applied in swimming research (Ceccon et al., 2013; Dubois, Thiel, & James, 2012; Monnet, Samson, Bernard, David, & Lacouture, 2014). Since this method has drastically reduced the time and labor involved in kinematic analysis, many trials can now be used to analyze both maximal swimming and submaximal swimming. Via simultaneous analysis using pressure measurement and underwater motion capture analysis, P_D, P_K, and Froude efficiency can now be analyzed at various velocities. Additionally, swimmers do not always swim at maximal effort, and training programs may consist of various swimming velocities depending on their training purpose. By analyzing at various swimming velocities, it is possible to quantify the effects of hand paddles on the training load during swimming training.

Therefore, through pressure measurement and underwater motion capture analysis, this study aimed to elucidate the effects of using hand paddles on hand propulsive forces, P_D, P_K, and Froude efficiency in arm-stroke-only front-crawl swimming at various velocities. We hypothesized that the hand paddles would have no effect on propulsive forces and P_D at submaximal swimming, but that P_K would decrease and Froude efficiency would increase, because the use of hand paddles decreases the velocity of the hand.

2. Method

2.1. Participants

The study sample consisted of eight national-level male swimmers (age: 20.4 ± 1.3 years; 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, mean ± standard deviation), 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.

2.2. Experimental trials

The experimental trials were conducted in an indoor pool (length: 50.0 m; width: 21.0 m; depth: 2.0 m; water temperature: 27.5 °C). To elucidate the effects of using hand paddles, participants swam under two conditions in randomized order, once using only their hands (Hand condition) and once aided by hand paddles on both hands (Paddle condition). In the Paddle condition, plastic resin hand paddles were used (surface area: 0.0336 m^2; longitudinal: 0.21 m; width: 0.20 m; thickness: 3.0 mm). Each participant swam 10 times a distance of 16 m in each condition with a push-off start at the wall, for a total of 20 trials. To elucidate the relationship between propulsive forces and swimming velocity, each participant was instructed to swim 10 trials at a self-selected, arbitrarily different swimming velocity. Participants gradually increased the swimming velocity in each trial from a velocity slower than 1.0 $m \cdot s^{-1}$, and then swam the final trial at maximal effort. In all trials, participants performed only arm strokes with a buoy (buoyancy: 22.5 N, ARN100, ARENA, Japan) between their legs.

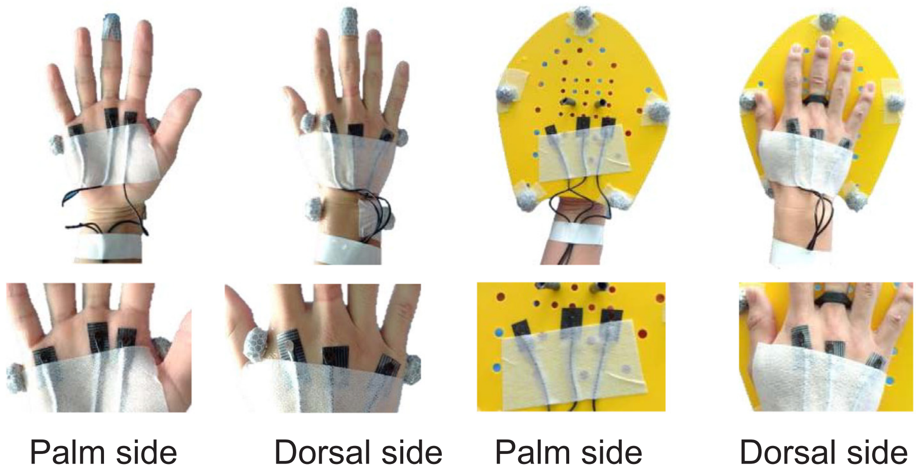

Fig. 1. Photographs of hands and paddles with reflecting markers and pressure sensors.

2.3. Experimental design

During this study, pressure measurement and underwater motion capture analysis were performed simultaneously. Pressure measurement was used to estimate the pressure forces acting on the right hand and the underwater motion capture analysis was used to analyze the direction of the pressure force, hand kinematics, and hip velocity.

In both conditions, reflective markers were attached to each hip, and five markers were attached to landmark points on the right hand or the right hand paddle. Strong magnets and elastic medical tape made of cotton were used for attaching reflective markers, the positions of which were determined according to previous studies (Gourgoulis et al., 2008; Monnet et al., 2014). In the Hand condition, 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 the Paddle condition, five reflective markers were attached at the five edge points of the hand paddles. Fig. 1 shows photographs of the right hand and paddle with reflecting markers and pressure sensors attached.

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 that it could be captured by the CCD camera sensors. The 3D coordinates of the markers were recorded with motion capture software (Qualisys Track Manager, Qualisys, Sweden) at a frame rate of 200 Hz. For the purpose of the present study, the transverse 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 to 15.0 m from the wall. To calibrate the motion capture, a carbon fiber rod with reflective markers on both ends was moved underwater, and the distance between the markers was analyzed. The distance between the reflective markers attached to both ends was measured with a ruler before calibration, which confirmed that the accuracy of the underwater motion capture within the analysis range had an error of less than 0.5%. Fig. 2 shows a schematic representation of the experiment.

During the 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 (diameter 6.0 mm; thickness 0.6 mm) and waterproof. In the Hand

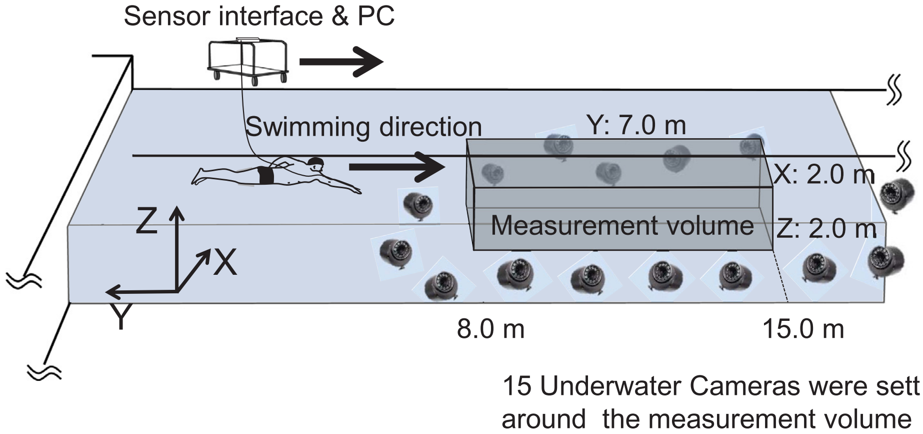

Fig. 2. Schematic representation of the experiment.

condition, six pressure sensors on the right hand were attached at the palm and dorsal sides of the second, third and fifth metacarpophalangeal joints. In the Paddle condition, six pressure sensors were attached at the same points as in the hand trials; on the palm side, sensors were attached to the hand paddle (Fig. 1).

Pressure was measured with wired pressure sensors at a sampling rate of 200 Hz. Pressure data were processed with a sensor interface (PCD330B-F, Kyowa Electronic Instruments Co. Ltd., Japan) and imported into a computer mounted on a carrier that moved along with the participants. 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 to start simultaneously with an electric signal. Position and pressure data were filtered through a low pass Butterworth filter with net cut off frequency set at 6 Hz for position data and 20 Hz for pressure data that was defined after residual analysis for a wide range of cut-off frequencies.

2.4. Data processing

In the present study, we analyzed one complete stroke cycle performed at the motion capture area. We defined the one stroke cycle as the duration between the entry to re-entry into the water of the reflective marker attached at the tip of the third finger. We calculated mean swimming velocity, stroke length, stroke rate, and mean hand velocity from coordinate data obtained with motion capture. Stroke length (m) was obtained from displacement of the midpoint of both hips 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. Mean 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.

We estimated the resultant pressure forces (N) by multiplying the projected areas (m^2) with the pressure differences ($N \cdot m^{-2}$) between the palm side and dorsal side of the right hand or hand paddle using a method reported in previous studies (Takagi & Wilson, 1999; Tsunokawa, Nakashima, & Takagi, 2015). The projected areas of the right hand or hand paddles were the projected areas on the coronal anatomic plane, which were different from the surface area. Projected areas were determined by using binary image analysis which was based upon the luminance level of the pixel of the photograph of the hand or hand paddles taken on a blank sheet before trials using image processing software (Image J, NIH, USA). In the binary image analysis, we used a shot image of the right hand or the hand paddle as shown in Fig. 1 to determine the projected area of the palm of each participant's hand or the hand paddle. 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 was divided into three segments, and three pairs of pressure sensors were attached on the dorsal and palm sides of each segments. We considered pressures differences as the representative hydrodynamic pressure at each segment, and we obtained the pressure forces acting on each segment by multiplying those pressure differences by the projected 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, and z) were analyzed using a normal vector perpendicular to the hand or hand paddle, calculated from coordinates obtained using underwater motion capture analysis. In the present study, pressure forces acting on the y-axis were defined as propulsive forces, and pressure forces that did not take the acting direction into account were defined as resultant forces (Fig. 3).

After calculating the propulsive forces, we determined the relationship between mean swimming velocity and mean propulsive forces generated by the hand during one complete arm-stroke obtained at every trial (10 times) using the least squares method as shown in the following formula:

$$F_P = A \cdot v^n \tag{1}$$

where F_P represents mean propulsive force, v equals mean swimming velocity, and coefficient A and degree n are parameters of the power function.

We calculated Froude efficiency (η_F) defined as the fraction of the external power produced by the swimmer's muscles that contributes to the propulsion (Zamparo et al., 2002, 2005) according to the methodology described in previous studies (Gourgoulis et al., 2014):

$$\eta_F = \frac{P_D}{P_D + P_K} = \frac{F_P \bullet v_{\text{body velocity}}}{(F_P \bullet v_{\text{body velocity}}) + [F_R \bullet v_{\text{hand velocity}} \bullet \cos(\alpha)]} \tag{2}$$

where P_D is the mechanical power to overcome water resistance, P_K is the mechanical power to push the water at the hand, F_P the mean propulsive force, F_R the resultant force at the right hand, $v_{\text{hand velocity}}$ the resultant velocity of the hand, and $v_{\text{body velocity}}$ is the mean swimming velocity. In order to take into account the difference between the direction of the vector of the resultant force produced by the hand and the vector of the resultant velocity of the hand, the calculation of P_K includes the cos (α) between the vector of the resultant force at the right hand and the vector of the resultant velocity of the right hand. Due to experimental limitations, we analyzed the pressure forces and propulsive forces only at the right hand. Therefore, it was assumed that the forces were not exerted on the other arm while the right arm was exerting, and forces were acting only on the hand part.

Additionally, the relationship between mean swimming velocity and P_K, P_D in each condition were analyzed using the least squares method as shown in the following formula:

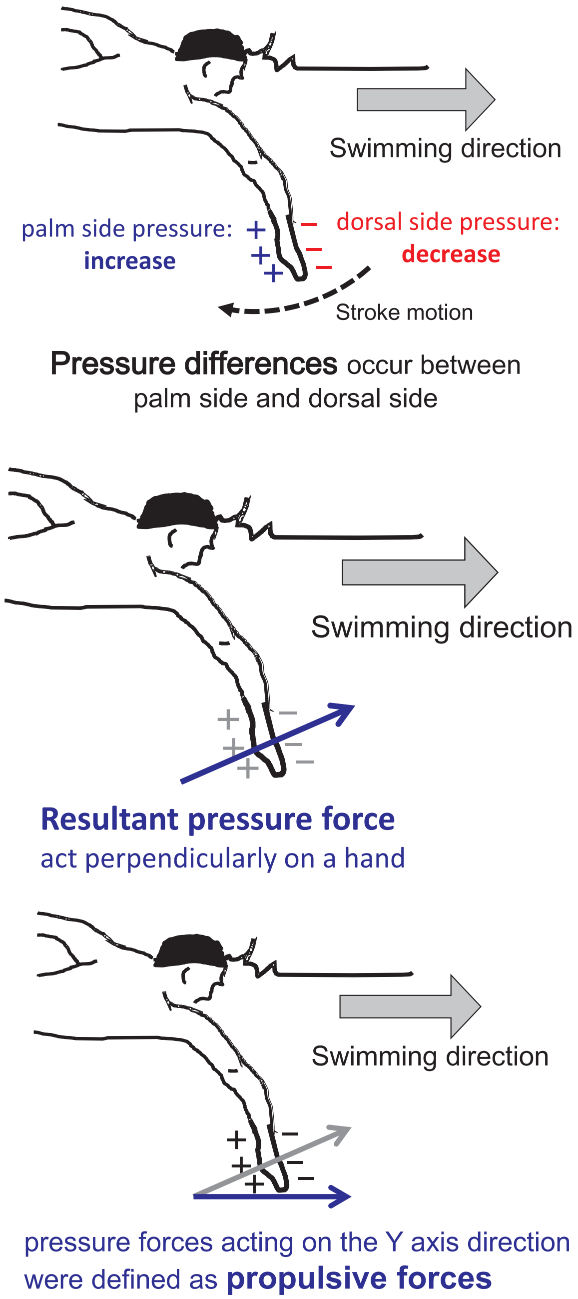

Fig. 3. Schematic of forces acting on a hand.

$$P_K = A \bullet v^n \quad (3)$$

$$P_D = A \bullet v^n \quad (4)$$

The paired *t*-test identified the differences between conditions in coefficient *A* and degree *n*. For statistical treatment of data, the assumption of normally distributed samples was verified using the Shapiro–Wilk test, while sphericity was verified using the Mauchly test. All statistical analyses and regression analyses were conducted using IBM SPSS Statistics 25 for windows (IBM, USA).

3. Results

Table 1 shows parameters of the power function on propulsive force for each participant while Fig. 4 shows the relationship between mean swimming velocity and mean resultant force, mean propulsive force generated by the hand during one complete arm-stroke for each participant. As a result, mean propulsive force increased exponentially with the increase of mean swimming velocity

Table 1
Parameters of the power function (1) on propulsive force for each participant.

Participant	Propulsive force on Hand condition				Propulsive force on Paddle condition			
	A	n	R^2	p	A	n	R^2	p
1	15.06	2.09	0.92	0.00	15.14	2.12	0.87	0.00
2	14.77	2.58	0.99	0.00	16.70	2.52	0.98	0.00
3	14.66	2.92	0.91	0.00	19.86	1.60	0.96	0.00
4	8.31	2.89	0.96	0.00	11.76	2.32	0.98	0.00
5	9.39	3.08	0.87	0.00	13.39	2.72	0.97	0.00
6	14.04	2.45	0.97	0.00	13.07	2.37	0.97	0.00
7	13.97	2.22	0.96	0.00	15.33	2.24	0.94	0.00
8	14.03	2.18	0.96	0.00	15.77	1.86	0.95	0.00
Mean	13.03*	2.55			15.13*	2.22		
SD	2.62	0.38			2.50	0.36		

* Significant difference between conditions.

for all participants. In the Paddle condition, coefficient A was significantly higher than in the Hand condition ($df = 7$, $t = 2.90$, $p = .02$).

Figs. 5 and 6 respectively show the stroke rate and mean hand velocity at each swimming velocity for all trials. As can be seen, the stroke rate tended to become higher when swimming velocity exceeded roughly 1.3 $m{\cdot}s^{-1}$. Compared with the Hand condition, the Paddle condition tended to show a lower stroke rate and a lower hand velocity at all swimming velocities. Fig. 7 shows the mean resultant force at each hand velocity for all trials. As can be seen, the Paddle condition tended to show higher mean resultant forces than in the Hand condition at the same hand velocities (see Fig. 7).

Figs. 8–10 respectively show P_K, P_D, and Froude efficiency (η_F) for each trial at each swimming velocity. Table 2 shows the parameters of the power function for P_K for each participant. In the Hand condition, the degree n was significantly higher than in the Paddle condition ($df = 7$, $t = 5.68$, $p = .00$). There was no significant difference in the coefficient A between the two conditions for P_K, but the degree n showed a significantly higher value in the Hand condition than in the Paddle condition for P_K. Therefore, the gap between the two regression curves increased as the swimming velocity increased, and the regression values in the Hand condition at the higher swimming velocities were larger than in the Paddle condition (see Fig. 8). Table 3 shows the parameters of the power function for P_D for each participant. In the Paddle condition, the coefficient A was significantly higher than in the Hand condition ($df = 7$, $t = 2.90$, $p = .02$). Although the degree n in the Hand condition showed higher values than in the Paddle condition, this difference was not statistically significant ($df = 7$, $t = 2.08$, $p = .08$). Due to such results the regression curves of the respective conditions were close to each other (see Fig. 9). At the fastest trial, P_D and swimming velocities in the Paddle condition were both higher than in the Hand condition. Since the swimming velocities in each condition were different, it was impossible to evaluate the difference statistically for the Froude efficiencies at the same swimming velocities. However, the Froude efficiencies tended to be higher in the Paddle condition than in the Hand condition (see Fig. 10).

4. Discussion

Through pressure measurement and underwater motion capture analysis, this study aimed to elucidate the effects of using hand paddles on hand propulsive forces, mechanical power, and Froude efficiency in arm-stroke-only front-crawl swimming at various velocities. As hypothesized, the regression curves of the two conditions were close to each other for P_D, and there were little differences between the conditions (see Fig. 9). However, using hand paddles decreased the stroke rate and the mean hand velocity, rendering P_K lower than in the Hand condition. The use of hand paddles caused no changes in P_D while P_K decreased, thus increasing Froude efficiency.

As shown in Table 1 and Fig. 4, the propulsive forces increased exponentially with the increase of swimming velocity in both the Hand and Paddle condition. The mean value of the coefficient A was significantly higher in the Paddle condition (15.13) than in the Hand condition (13.03). In contrast, the mean value of the degree n was only slightly higher in the Hand condition (2.55) than in the Paddle condition (2.22). Overall, the regression curves of the respective conditions were close to each other.

As can be appreciated from Figs. 5 and 6, stroke rate and mean hand velocity tended to be lower in the Paddle condition than in the Hand condition at the same swimming velocities. Comparing the mean resultant force of each condition at the same hand velocity, Fig. 7 shows that the mean resultant force tended to be larger in the Paddle condition than in the Hand condition, suggesting that by using hand paddles, even if the hand velocity is low, a commensurate resultant force acts on the hand when using paddles as without paddles. A previous study investigating the effect of hand paddles on hand propulsive forces by using pressure measurement and underwater motion capture at maximal swimming (Tsunokawa et al., 2018) reported that using hand paddles decreases the pressure differences between the palm and dorsal sides of the hand related to the magnitude of fluid force but that there were no differences in the mean resultant forces compared with swimming with hands alone because the large surface area of the hand paddle compensated for the decreased pressure differences due to decreased hand velocity. Also in the present study, the Paddle condition showed a lower hand velocity, seemingly decreasing the pressure differences between palm and dorsal sides of hand, but there were no differences in the mean resultant forces at the same swimming velocities, thus replicating the results of the study by Tsunokawa

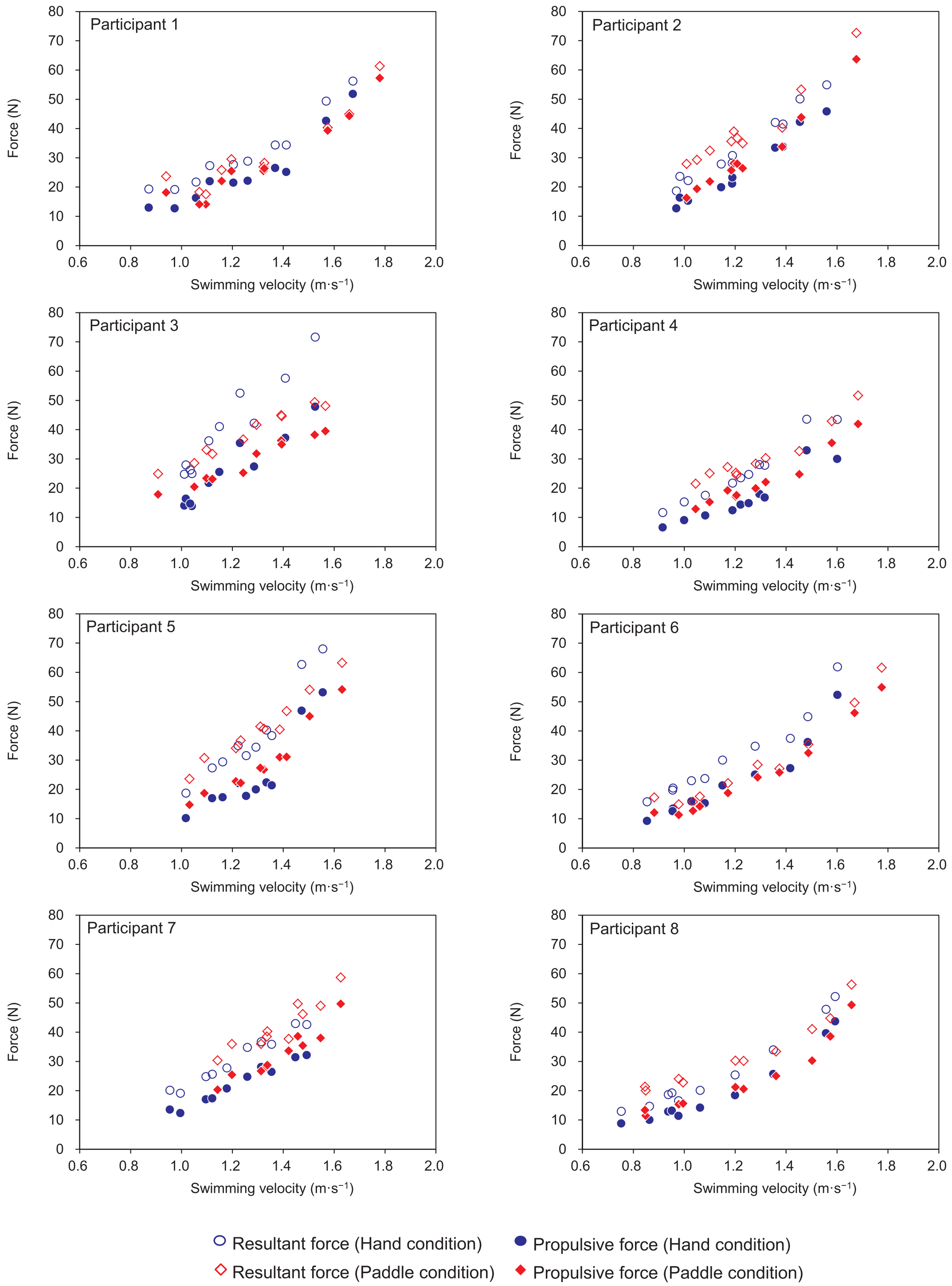

Fig. 4. Mean resultant forces and mean propulsive forces at each swimming velocity in both conditions for each participant.

et al. (2018). However, since P_K was determined by the product of the resultant forces acting on the hand and the mean hand velocity, and not only by the magnitude of the resultant forces, P_K is lower even with the same resultant force when resultant hand velocity is low. As shown in Fig. 8, P_K in the Paddle condition was lower than in the Hand condition at the higher swimming velocity, and the degree n was significantly lower in the Paddle condition. The present results could have been caused by the fact that the mean hand velocity in the Paddle condition was lower than in the Hand condition at the same swimming velocity. In other words, using hand paddles decreased the mean hand velocity, thereby decreased the mechanical power to push the water at the hand (P_K).

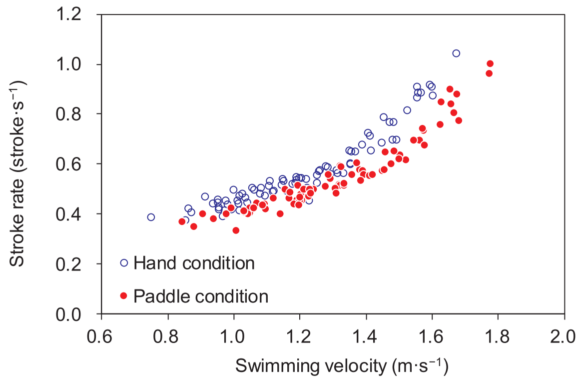

Fig. 5. Stroke rate at each swimming velocity for all trials.

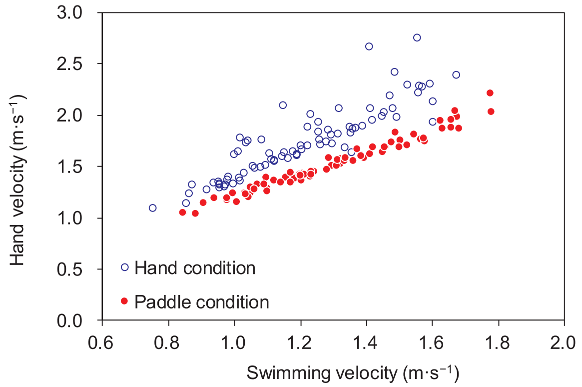

Fig. 6. Mean hand velocity at each swimming velocity for all trials.

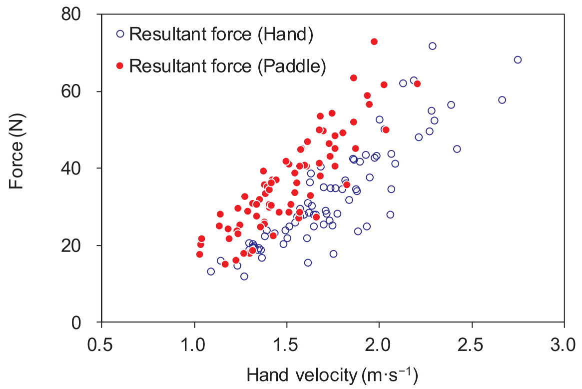

Fig. 7. Mean resultant force at each hand velocity for all trials.

Additionally, in order to evaluate the power contributing to the propulsion, we calculated P_D from the mean propulsive forces and the mean swimming velocity. As a result, coefficient A was significantly higher in the Paddle condition, but there was no significant difference in the degree n. As a result, the regression curves of the respective condition were close to each other (see Fig. 9). As shown in Fig. 4, this could have been caused by the fact that there was no marked difference in the propulsive force at the same swimming velocity between conditions. For the magnitude of P_D, then, there are no resultant effects of hand paddles at the same swimming velocity.

In this study, we calculate the Froude efficiency from P_D and P_K. As shown in Fig. 10, Froude efficiencies tended to be higher in the Paddle condition than in the Hand condition. In swimming motions, not all powers contribute to propulsion and there are also wasteful powers (Zamparo et al., 2002, 2005). When swimmers swim with hand paddles, as the ratio of the power contributing to propulsion increases, swimmers can expend less P_K than without hand paddles at the same swimming velocity. In previous studies investigating the effects of hand paddles on oxygen uptake and propelling efficiency at various swimming velocities, it was reported that by using hand paddles, swimmers reduced their oxygen uptake and increased their propelling efficiency (Ogita & Tabata, 1993;

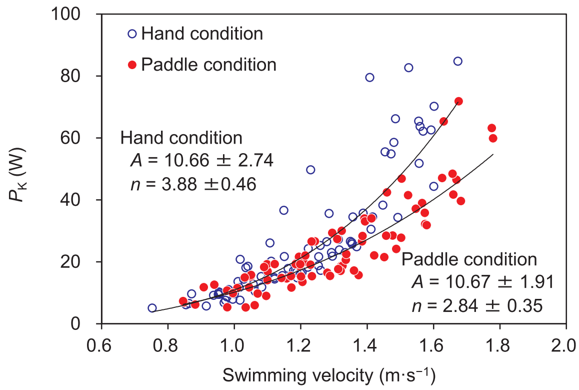

Fig. 8. P_K at each swimming velocity for all trials.

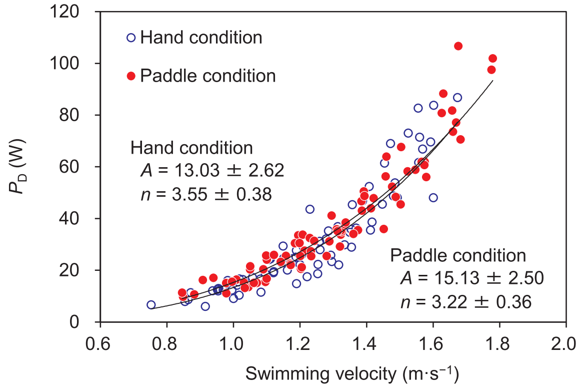

Fig. 9. P_D at each swimming velocity for all trials.

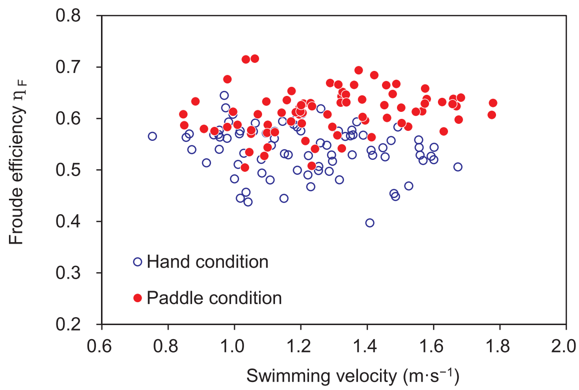

Fig. 10. Froude efficiency (η_F) at each swimming velocity for all trials.

Ogita et al., 1999; Toussaint et al., 1991). In light of the present results, a decrease in P_K and an increase in Froude efficiency are considered to be related effects of using hand paddles on the oxygen uptake and the propelling efficiency reported in previous studies.

In competitive swim training, swimmers and coaches often use hand paddles with the aim of increasing the propulsive force acting on the hand and upper limb power expended in giving masses of water pushed away. Contrary to their intended purpose, we did not find that hand paddles caused any significant difference between conditions for propulsive forces at the same swimming velocities. Further, the use of hand paddles decreased the mean resultant hand velocity, increased Froude efficiency and reduced P_K. So if swimmers swim at the same velocity with and without hand paddles, they may reduce their training load as their P_K decreases when using hand paddles. Also, as reported in previous studies (Gourgoulis et al., 2006; Tsunokawa et al., 2018), using hand paddles increases swimming velocity at maximal effort because if swimmers generate the same P_K combined with higher Froude efficiency in the Paddle condition, a higher swimming velocity can be achieved. Therefore, if swimmers use hand paddles increasing propulsive force or P_K, they should swim at a higher swimming velocity with hand paddles than without. Swimmers and coaches should pay

Table 2
Parameters of the power function (3) on P_K for each participant.

Participant	P_K on Hand condition				P_K on Paddle condition			
	A	n	R^2	p	A	n	R^2	p
1	10.67	3.45	0.92	0.00	9.70	2.79	0.87	0.00
2	9.45	4.28	0.96	0.00	11.31	3.31	0.95	0.00
3	16.64	4.13	0.91	0.00	14.96	2.37	0.98	0.00
4	8.41	3.94	0.94	0.00	9.69	2.45	0.92	0.00
5	7.77	4.64	0.93	0.00	11.08	2.98	0.94	0.00
6	11.77	3.78	0.98	0.00	9.05	3.22	0.93	0.00
7	9.88	3.45	0.96	0.00	9.32	2.99	0.87	0.00
8	10.66	3.35	0.97	0.00	10.22	2.57	0.95	0.00
Mean	10.66	3.88*			10.67	2.84*		
SD	2.74	0.46			1.91	0.35		

* Significant difference between conditions.

Table 3
Parameters of the power function (4) on P_D for each participant.

Participant	P_D on Hand condition				P_D on Paddle condition			
	A	n	R^2	p	A	n	R^2	p
1	15.06	3.09	0.96	0.00	15.14	3.12	0.94	0.00
2	14.77	3.58	0.99	0.00	16.70	3.52	0.99	0.00
3	14.66	3.92	0.94	0.00	19.86	2.60	0.98	0.00
4	8.31	3.89	0.98	0.00	11.76	3.32	0.98	0.00
5	9.39	4.08	0.91	0.00	13.39	3.72	0.98	0.00
6	14.04	3.45	0.98	0.00	13.07	3.37	0.99	0.00
7	13.97	3.22	0.98	0.00	15.33	3.24	0.97	0.00
8	14.03	3.18	0.98	0.00	15.77	2.86	0.98	0.00
Mean	13.03*	3.55			15.13*	3.22		
SD	2.62	0.38			2.50	0.36		

* Significant difference between conditions.

attention to these points when using hand paddles for training and ensure that they use them according to their intended training purpose.

In this study, we analyzed the propulsive forces, P_D, P_K, and Froude efficiency, by means of a simultaneous analysis of pressure measurement and underwater motion capture analysis. However, these analyses could only be performed on the right hand. We could not analyze any other parts. When analyzing arm stroke motions, forces act not only on the hand but also on other parts of the limb such as the forearm. Therefore, since we calculated propulsive forces acting on the right hand and not active drag, we cannot compare propulsive forces or P_D with whole body (active) drag values reported in previous studies. Additionally, in this study, since each participant was instructed to swim at a self-selected different swimming velocity, the swimming velocities at each condition were different. Therefore, it was impossible to statistically evaluate the difference for stroke rates, mean hand velocities, and Froude efficiencies at the same swimming velocities. For the same reason, since the hand velocities at each condition were also different, it was impossible to evaluate the difference statistically for the mean resultant forces at the same hand velocities. Therefore, the differences between the two conditions in these parameters were only evaluating trends from the figures.

5. Conclusion

The present study revealed that there were no significant differences in propulsive forces and mechanical power to overcome water resistance (P_D) depending on whether or not swimmers swam with hand paddles at the same swimming velocities. However, using hand paddles decreased stroke rate and hand velocity, thereby decreasing the mechanical power to push the water at the hand (P_K). Therefore, using hand paddles increased Froude efficiency. These results suggest that training loads decreases when swimmers swim at the same velocities using hand paddles.

Conflict of interest

None.

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