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Effect of leg kick on active drag in front-crawl swimming: comparison of whole stroke and arms-only stroke during front-crawl and the streamlined position

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Abstract

The purpose of this study was to examine the effect of leg kick on the resistance force in front-crawl swimming. The active drag in front-crawl swimming with and without leg motion was evaluated using measured values of residual thrust (MRT method) and compared with the passive drag of the streamlined position (SP) for the same swimmers. Seven male competitive swimmers participated in this study, and the testing was conducted in a swimming flume. Each swimmer performed front-crawl under two conditions: using arms and legs (whole stroke: WS) and using arms only (arms-only stroke: AS). Active drag and passive drag were measured at swimming velocities of 1.1 and 1.3 m s^{-1} using load cells connected to the swimmer via wires. We calculated a drag coefficient to compare the resistances of the WS, AS and SP at each velocity. For both the WS and AS at both swimming velocities, active drag coefficient was found to be about 1.6 – 1.9 times larger than that in passive conditions. In contrast, although leg movement did not cause a difference in drag coefficient for front-crawl swimming, there was a large effect size (d = 1.43) at 1.3 m s^{-1}. Therefore, although upper and lower limb movements increase resistance compared to the passive condition, the effect of leg kick on drag may depend on swimming velocity.

1. Introduction

In front-crawl swimming, which is the fastest human swimming stroke among the four techniques used in swimming competitions, the arms and legs move repeatedly across the water surface, creating additional resistance from waves and splashes. Therefore, it is extremely difficult to evaluate the resistance force acting on a swimmer who propels the water surface with moving limbs.

The resistance force acting on a swimmer maintaining a streamlined position (SP), which is known as ‘passive drag’, has been widely measured and used as an index with which to evaluate swimmers (Chatard et al., 1990; Havriluk, 2005) and swimsuit performance (Gatta et al., 2013; Mollendorf et al., 2004). Passive drag remains similar regardless of measurement environment if swimmers maintain the same posture and shape (Havriluk, 2005, 2007). Measuring resistance force during swimming (known as ‘active drag’) is more difficult, and various methods have been suggested to estimate it.

Hollander et al. (1986) developed the measurement of active drag (MAD) approach and attempted to directly measure actual drag during swimming. The MAD approach measures the force of a swimmer pushing off fixed pads placed under the water surface. Active drag is then estimated based on the precondition that resistance force is equal to the force exerted on the pads by the swimmer's hands at constant swimming velocity. This means that only the arm stroke can be evaluated using the MAD approach. The values of active drag obtained using the MAD approach are reported to be similar to those of passive drag (Hollander et al., 1986; Van der Vaart et al., 1987). Previous studies that used trunk incline and projected frontal area to evaluate the active drag of front-crawl with kicking found it to be larger than passive drag (Gatta et al., 2015; Zamparo et al., 2009). Similar results were reported in studies using an energetics approach (Di Prampero et al., 1974; Zamparo et al., 2005). Narita et al. (2017) estimated drag during swimming using measured values of residual thrust (MRT) and found similar results. From data reported in previous studies, it is evident that the active drag in front-crawl swimming is larger than that in passive conditions, except when the data were obtained using the MAD approach. In MAD approach, the swimmer does not use leg movement unlike other studies. Therefore, the lack of leg movement is thought to be one of the reasons why the values of drag measured with the MAD approach were similar to those of passive drag (i.e. we assume that the kicking motion increases active drag). On the other hand, previous studies have reported that kicking during front-crawl reduced the resistive force acting on the whole body by elevating the legs and counteracting the sinking moment produced by the arm motion (Nakashima, 2007; Yanai, 2001). However, no studies have yet evaluated the influence of kicking on active drag using the same method and swimmers. Furthermore, it is unclear whether the differences in reported values are due to the addition of lower limb motion or to differences in methodology. To address these shortcomings, it is necessary to verify the effect of kicking on active drag by evaluating active drag with and without lower limb motion using the same method and swimmers. Moreover, by comparing the active drag evaluated using the MRT method with the passive drag, it is possible to evaluate the changes in the resistance force acting on the swimmer's body in response to any active movements due to self-propelling. These comparisons would promote understanding of the resistance forces that act on swimmers as they move their limbs to propel themselves through the water surface.

Therefore, the purpose of this study was to investigate the effect of leg kick on resistance force in front-crawl swimming. Moreover, we compared active drag and passive drag in SP for the same swimmers. The active drag in front-crawl swimming with and without kicking was evaluated using the MRT method. We hypothesized that active drag in front-crawl swimming is larger than passive drag regardless of leg kicking because (i) the projected frontal area of the swimmer during front-crawl swimming is larger than that with SP and (□) the active movements of the upper and lower limbs cause additional resistance force owing to waves and splash. In addition, we hypothesized that the active drag with leg kicking is larger than that without because leg kicking creates additional drag. As Clarys (1979) reported, active drag is mainly influenced by changes in body shape and movements of the body segments; therefore, the use of the lower limbs would deform the streamlined posture of the lower limbs and increase resistance force.

2. Methods

2.1. Participants

Seven male competitive swimmers participated in this study. They all trained six days per week and had experience of participating in national competitions. The anthropometric data and long-course front-crawl performance of swimmers are given in Table 1. The test procedures were approved by the University of Tsukuba Ethics Committee (approval number: 25-57), and each participant signed an informed-consent form.

2.2. Experimental design

To compare active drag with and without kicking, each swimmer performed front-crawl using arms and legs (whole stroke: WS) and using arms only (arms-only stroke: AS). To restrict the movement of each swimmer’s legs during AS, swimmers were instructed to put a buoy between their thighs and fastened a band to their ankles. However, when measuring the resistance force in the streamlined position (SP), which is a prone position with raised arms, we did not use the buoy and band. In all experiments, the swimmer wore a snorkel to eliminate the influence of his breathing motion. Moreover, the swimmers wore the same type of swimsuit to eliminate the influence of swimsuit differences on resistance force (Gatta et al., 2013; Mollendorf et al., 2004).

2.3. Testing procedure

All tests were conducted in a water flume (Igarashi Industrial Works Co., Ltd., Japan; water temperature: 28.0 ± 0.3°C) of 5.5 m length, 2.0 m width, and 1.2 m depth, which had a control system that minimized an unbalanced flow distribution. We examined the three-dimensional flow distribution using a pitot tube, and the flow errors at 1.5 m s^{-1} ranged from –3.4 to +4.9%. Prior to the measurements, the swimmers underwent a preparation period to familiarize with the water flume.

To evaluate active drag, we used the MRT method developed by Narita et al. (2017). Prior to measuring the value of residual thrust, which is the difference between the propulsive force and the resistance force, to evaluate the active drag at the targeted swimming velocity V_{Si}, each swimmer self-propelled in the flume with the flow velocity U set to i m s^{-1} (i indicates an arbitrary velocity at which to evaluate active drag). Each swimmer was instructed to maintain the stroke motion and body position required to swim at V_{Si} even when U was varied. To make it easy for the swimmer to maintain his stroke at different values of U, the stroke time (seconds per stroke, s $stroke^{-1}$) that the swimmer used to propel himself at i m s^{-1} was beat using a small audible waterproof metronome (Tempo trainer Pro; FINIS, Inc., USA). To measure the residual thrust at each value of U, a belt wrapped around the swimmer's trunk was connected via wires to load cells attached at the front and back of the flume. The forward and backward towing forces were measured for 10 s, and the residual thrust was calculated from their difference. We measured the residual thrust at eight points within a range of ±0.2 m s^{-1} around V_{Si}, changing U by 0.05 m s^{-1} each time. Thereafter, we derived best-fit regression curves for the measured values of residual thrust and used them to calculate the active drag (for further details, see Narita et al. (2017)). We evaluated the active drag at i = 1.1 ($V_{S1.1}$) and 1.3 m s^{-1} ($V_{S1.3}$) using the above procedure, where $V_{S1.3}$ is the maximum speed that all of the swimmers could maintain under AS conditions.

We measured passive drag using the same MRT apparatus as that for active drag. We did this for 5 s at U = 1.1 and 1.3 m s^{-1}. The measurement was repeated if the swimmer's position changed during the measurement.

2.4. Data processing

In the analysis of active drag, we used the velocity U_{Tre0} which was defined as the point at which the regression curve was equal to zero; this did not completely match $V_{\mathrm{S}i}$. In this regard, to assess the active drag at $V_{\mathrm{S}i}$, the swimmers were required to maintain their swimming movement at $V_{\mathrm{S}i}$ even if the flow velocities were different. Moreover, they were required to synchronise their stroke with the sound of the waterproof metronome. These factors may have caused differences between swimming freely at $V_{\mathrm{S}i}$ and swimming with constant stroke speed at different U. It is assumed that these elements have influenced the regression curve, which was derived from the relationship of residual thrust measured at each values of U. However, if the difference between U_{Tre0} and $V_{\mathrm{S}i}$ was 0.05 m s^{-1} or more, we re-examined the experiment.

Given that resistance force is influenced strongly by a swimmer's speed and body size, we calculated a drag coefficient (excluding these influences) to compare the resistances of WS, AS and SP at each $V_{\mathrm{S}i}$. The drag coefficient C_{D} is calculated as:

$$C_{\mathrm{D}} = \frac{2 \cdot D}{\rho \cdot A \cdot V^2} \qquad (1)$$

where D is the drag evaluated in this study, ρ is the water density (996.232 kg m^{-3} at 28.0°C), A is the representative area of the swimmer's body and V is the swimming velocity. In this study, we used the body surface area as A and calculated it using the method of Shuter and Aslani (2000).

To investigate the influence of stroke parameters on active drag for the WS and AS, we analysed the stroke rate and length. The stroke rate (in Hz) was calculated from the inverse of the stroke time (s stroke^{-1}), measured when U was set to i m s^{-1}. The stroke length was computed by dividing U_{Tre0} (m s^{-1}) by the stroke rate.

2.5. Statistical analysis

We compared the drag coefficient and swimming velocity (SP: U; WS and AS: U_{Tre0}) among the test conditions using one-way repeated-measures ANOVA, followed by Bonferroni post hoc tests, at each stage. We compared the stroke parameters for the WS and AS using a paired t-test. All statistical analyses were conducted at a significance level of $P < 0.05$ using SPSS (version 22.0; SPSS, Inc., Chicago, IL).

3. Results

The WS, AS and SP drag values of all swimmers at 1.1 and 1.3 m s^{-1} are given in Table 2. Active drag in WS and AS conditions was found to be 1.6 – 1.9 times larger than that in passive conditions at both swimming velocities. In addition, the values of U_{Tre0} (or U for the SP) and C_{D} for each condition are shown in the upper panel of Fig. 1. We found no main effect in the swimming velocity (U_{Tre0} for WS and AS or U for SP) at 1.1 or 1.3 m s^{-1} in each condition (at $V_{\mathrm{S1.1}}$: $F = 0.183$, $p = 0.84$; at $V_{\mathrm{S1.3}}$: $F = 0.925$, $p = 0.42$). In contrast, we did observe main effects on C_{D} at both 1.1 and 1.3 m s^{-1} (at $V_{\mathrm{S1.1}}$: $F = 27.0$, $p < 0.01$; at $V_{\mathrm{S1.3}}$: $F = 28.4$, $p < 0.01$). Moreover, the C_{D} values were found to differ significantly between WS and SP (at $V_{\mathrm{S1.1}}$: $p < 0.01$; at $V_{\mathrm{S1.3}}$: $p < 0.01$) and between AS and SP (at $V_{\mathrm{S1.1}}$: $p < 0.01$; at $V_{\mathrm{S1.3}}$: $p < 0.01$). On the other hand, there was no significant difference between WS and AS values of C_{D} (at $V_{\mathrm{S1.1}}$: $p = 1.00$; at $V_{\mathrm{S1.3}}$: $p = 0.34$). The changing ratios of C_{D} caused by additional movements were 158% and 166% for AS/SP and 102% and 118% for WS/AS, respectively, at $V_{\mathrm{S1.1}}$ and $V_{\mathrm{S1.3}}$.

The stroke rate and length for the WS and AS are shown in the lower panel of Fig. 1. Significant differences were observed in the stroke rate at both stages (at $V_{\mathrm{S1.1}}$: $p = 0.02$; at $V_{\mathrm{S1.3}}$: $p = 0.01$). In contrast, a significant difference in stroke length was not observed at $V_{\mathrm{S1.1}}$ but was seen at $V_{\mathrm{S1.3}}$ (at $V_{\mathrm{S1.1}}$: $p = 0.06$; at $V_{\mathrm{S1.3}}$: $p < 0.01$).

4. Discussion

4.1. Effects of leg motion on active drag in front-crawl swimming

The present study is the first to examine the drag caused by leg motion during front-crawl swimming. We achieved this using the same swimmers and methodology throughout. The results indicate no significant differences between the WS and AS values of C_D for the $V_{S1.1}$ and $V_{S1.3}$ trials.

Previous studies reported that kicking in front-crawl reduced the resistive force acting on the whole body by elevating the legs and counteracting the sinking moment produced by the arm motion (Nakashima, 2007; Yanai, 2001). In the present study, swimmers used buoys that allowed their legs to float while restricting their lower limbs movement were used, as was performed in other studies (Gourgoulis et al., 2014; Morris et al., 2016; Toussaint et al., 1988). As such, a swimmer performing the AS could prevent his resistance from increasing because he was just able to maintain his horizontal attitude by means of buoyancy. Therefore, although we observed no significant difference between the WS and AS values of C_D, we assume that a difference would have been evident if the swimmer was to stop kicking and not use a buoy.

On the other hand, since the legs in front-crawl move perpendicular to the direction of propulsion, excessive kicking may increase resistance by deforming the streamlined shape of the swimmer and promoting flow separation in the unsteady state (Clarys, 1979; Maglischo, 2003; Zamparo et al., 2009). Even though there was no significant difference in this study, six of the seven swimmers tended to have WS C_D values at $V_{S1.3}$ that were higher than their respective values for the AS; moreover, the effect size for C_D at $V_{S1.3}$ was large (d = 1.43). Gatta et al. (2012) reported that the resistance produced by flutter kicking was larger than that produced by propulsive kicking at velocities greater than 1.27 m s^{-1}. From the above, we assume that leg motion in the 1.1 m s^{-1} trial ($V_{S1.1}$) could increase propulsion without becoming a factor in resistance, whereas leg motion in the

1.3 m s^{-1} trial ($V_{S1.3}$) might increase both resistance and propulsion; hence, the effect of leg kick on drag may depend on swimming velocity.

At the same swimming velocity, the WS stroke rate was 11% and 17% lower than the AS stroke rate at $V_{S1.1}$ and $V_{S1.3}$, respectively. These results indicate that swimmers must increase their stroke rate during the AS to achieve the same velocity as that of the WS (i.e. with kicking). Silveira et al. (2016) reported that WS swimming velocity was higher than AS swimming velocity at the same stroke rate. From results of previous studies (Deschodt et al., 1999; Gourgoulis et al., 2014; Morris et al., 2016; Silveira et al., 2016), it is apparent that kicking during front-crawl contributes to swimming speed by approximately 10%. On the other hand, the use of a kicking motion is inefficient (Zamparo et al., 2002) and affects energy consumption (Holmér, 1974; Morris et al., 2016; Ogita et al., 1996; Ribeiro et al., 2015; Rodriguez et al., 2015). Therefore, if a swimmer could float his or her legs and reduce his or her resistance, then minimal leg movement (e.g. two- or four-beat kicking) could save energy, which may improve performance, especially in long-distance events.

4.2. Comparison of drag in front-crawl swimming and SP

The active drag of the WS and AS, as estimated using the MRT method, showed higher values than the passive drags with the SP. These results support our hypothesis that active drag in front-crawl swimming is larger than passive drag, irrespective of the use of leg kicking.

Regarding the relationship between active drag and passive drag, some studies have reported that active drag was larger than passive drag, whereas others have reported that active drag was equivalent to passive drag. A swimmer adopts the SP to minimize deceleration in the high-speed phases after the start and after the turn. On the other hand, during front-crawl swimming, the swimmer must break from the SP to self-propel by moving their limbs. Clarys (1979) reported that active drag was mainly influenced by changes in body shape and movements of the body segments. Moreover, it is likely that active drag is increased by the 'pushing drag' caused by moving the arms and legs forward against the water (Maglischo, 2003). From the standpoint of projected frontal area, it is somewhat obvious that the SP resistance should be lower than the active drag; however, this was the first study that compared the drag between SP and front-crawl techniques using the same testing equipment and condition. It is considered that differences noted in previous studies regarding the relationship between active drag and passive drag could be attributed to differences in methodology rather than to the influence of lower limbs movement.

4.3. Comparison with previous values of active drag

The C_D values obtained in the present study for the WS, AS and SP (together with those of previous studies) are plotted in Fig. 2. Also shown are C_D values calculated from active drag data reported in the literature; these were obtained according to Eq. 1 by calculating body surface area (as proposed by Shuter and Aslani (2000)) either from the height and weight of individual swimmers or from reported average values.

The AS C_D values of the present study (grey marks in Fig. 2) tend to be higher than those obtained using the MAD approach in previous studies (Toussaint et al., 2004; Van der Vaart et al., 1987). In the MAD approach, since swimmers propel themselves by pushing against a fixed pad, force is measured only when the swimmers touch the pads, not before or after. Therefore, we assume that the drag in the MAD approach is smaller than that observed in the present study because the MAD approach potentially underestimates drag owing to the measurement structure.

The WS C_D values of the present study (black marks in Fig. 2) tended to be higher than those of Gatta et al. (2015), who used the planimetric frontal area method. Gatta et al. (2015) estimated the resistance force by measuring the projected frontal area of swimmers during swimming and then substituting this value into the equation for steady-state pressure resistance. Furthermore, Zamparo et al. (2009) estimated active drag based on the assumption that the difference in trunk inclination between front-crawl swimming and SP is related to frontal area and hence resistance force. However, Taïar et al. (1999) pointed out the necessity of considering not only the static frontal area but also the dynamic movement speed when evaluating active drag in actual swimming. In addition, the resistance acting on the swimmer includes unsteady influences (Ungerechts and Arellano, 2011) and wave drag (Toussaint et al., 2002; Vennell et al., 2006). In fact, Gatta et al. (2015) suggested that the active drag that they calculated was a minimum value since they did not take into consideration the components of wave and friction drag.

Fig.2 shows smaller C_D values at high than low velocities, while we obtained opposite results in the present study. This may be attributed to differences in the methodologies used to evaluate active drag at each measuring velocity. Furthermore, the C_D values at $V_{S1.3}$ for the WS and AS indicated higher values than those at $V_{S1.1}$. Therefore, it will be necessary to evaluate C_D using the same method when investigating its changes according to swimming velocity. Also, if we attempt to accurately evaluate the difference in active drag, it will be necessary to analyse the same swimmers, as in several previous studies (Formosa et al., 2012; Toussaint et al., 2004), because active drag is considered to differ not only because of physical characteristics but also because of swimming technique, which is swimmer dependent (Kolmogorov et al., 1997). Doing so will shed light on the features of each methodology and help considerably in constructing a theoretical system governing drag in human swimming.

4.4. Limitations and future prospects

We observed that active drag evaluated with the MRT method was about 1.6 – 1.9 times larger than passive drag in the same swimmers. Moreover, although leg movement did not cause a significant difference in active drag for the WS and AS for front-crawl swimming, the effect of leg kicking in front-crawl swimming on active drag may depend on swimming velocity. However, it would be difficult to directly apply the results of this research to improving race performance. For example, to investigate the role of leg motion under the same velocities in this study, we had to adopt a velocity under 1.3 m s^{-1} for the WS and AS conditions because not all swimmers could swim at a velocity above 1.4 m s^{-1}. However, if we focus only on estimating the resistance force for the WS, we can estimate a velocity close to actual race conditions. Besides, when we estimate active drag using the MRT method, we need to use a flume, belt and metronome. Guignard et al. (2017) noted the necessity to perform measurements that are representative of a competition context. The flume used in the present study has a control system to minimize the wave on the water surface and unequal flow distribution. Nevertheless, the environment of flume and pool, e.g. an influence of reflective waves from walls or a difference of perceiving visual information, cannot be the same perfectly, hence, this is the limitation of using MRT method. However, the MRT method has the advantage that it is possible to evaluate resistance force for various swimming styles and speeds. Therefore, even if the MRT method has such restrictions as described above, the accumulation of investigations using the MRT method will play an important role in deepening our understanding of active drag.

Since the present study investigated the effects of only stroke rate and stroke length on active drag, other potential factors may require future consideration (e.g. trunk incline and swimming technique). Moreover, it is necessary to consider the characteristics of each swimmer in relation to the contribution of leg kicking (Gourgoulis et al., 2014; Silveira et al., 2016). For example, in this study, one swimmer showed a larger drag coefficient for the AS than that for the WS in the $V_{S1.3}$ trial, whereas the other swimmers showed the opposite trend. However, no specific characteristics were observed in terms of stroke rate and stroke length in this swimmer. Therefore, in the future, it would be useful to evaluate the resistance forces in swimming using the MRT method combined with three-dimensional motion analysis (as with Gourgoulis et al., 2014; McCabe et al., 2015), pressure-distribution analysis (as with Takagi et al., 2014; Tsunokawa et al., 2015) and energy-consumption measurements (as with Ribeiro et al., 2015; Rodriguez et al., 2015) to deepen our understanding of the role of leg motion in front-crawl swimming.

Conflict of interest statement

There are no conflicts of interest to declare.

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Table 1. The anthropometric details of each swimmers and his personal best time for the 200-m front-crawl (in a long-course pool).

Swimmer	Age (year)	Height (m)	Mass (kg)	Body surface area (m^2)	200 m-Freestyle Best record (min'sec")
A	19	1.74	77.5	1.89	1'52"2
B	21	1.69	70.5	1.78	1'53"2
C	19	1.69	63.0	1.70	1'53"7
D	21	1.70	59.5	1.66	1'54"2
E	19	1.77	72.0	1.86	1'55"5
F	21	1.70	63.0	1.70	1'57"3
G	20	1.71	72.5	1.82	2'02"0
Mean	20.0	1.71	68.3	1.77	1'55"5
SD	0.9	0.03	6.0	0.08	3"0

Table 2. Active drag for the whole stroke and arms only stroke, and passive drag in a streamlined position at $V_{S1.1}$ and $V_{S1.3}$.

Swimmer	Whole stroke		Arms-only stroke		Passive drag	
	$V_{S1.1}$	$V_{S1.3}$	$V_{S1.1}$	$V_{S1.3}$	$V_{S1.1}$	$V_{S1.3}$
A	43.7	70.3	45.8	89.3	36.3	46.1
B	50.4	75.3	50.7	66.0	28.9	41.9
C	34.5	75.0	43.0	55.8	25.3	39.2
D	57.8	99.1	49.3	67.6	25.4	37.6
E	40.8	73.2	37.1	68.6	23.2	35.3
F	42.9	70.3	38.3	56.3	28.5	38.0
G	40.9	78.0	43.5	59.1	29.6	45.2
Mean	44.4	77.3	44.0	66.1	28.2	40.5
SD	7.0	9.3	4.7	10.7	4.0	3.8

(Unit: N)

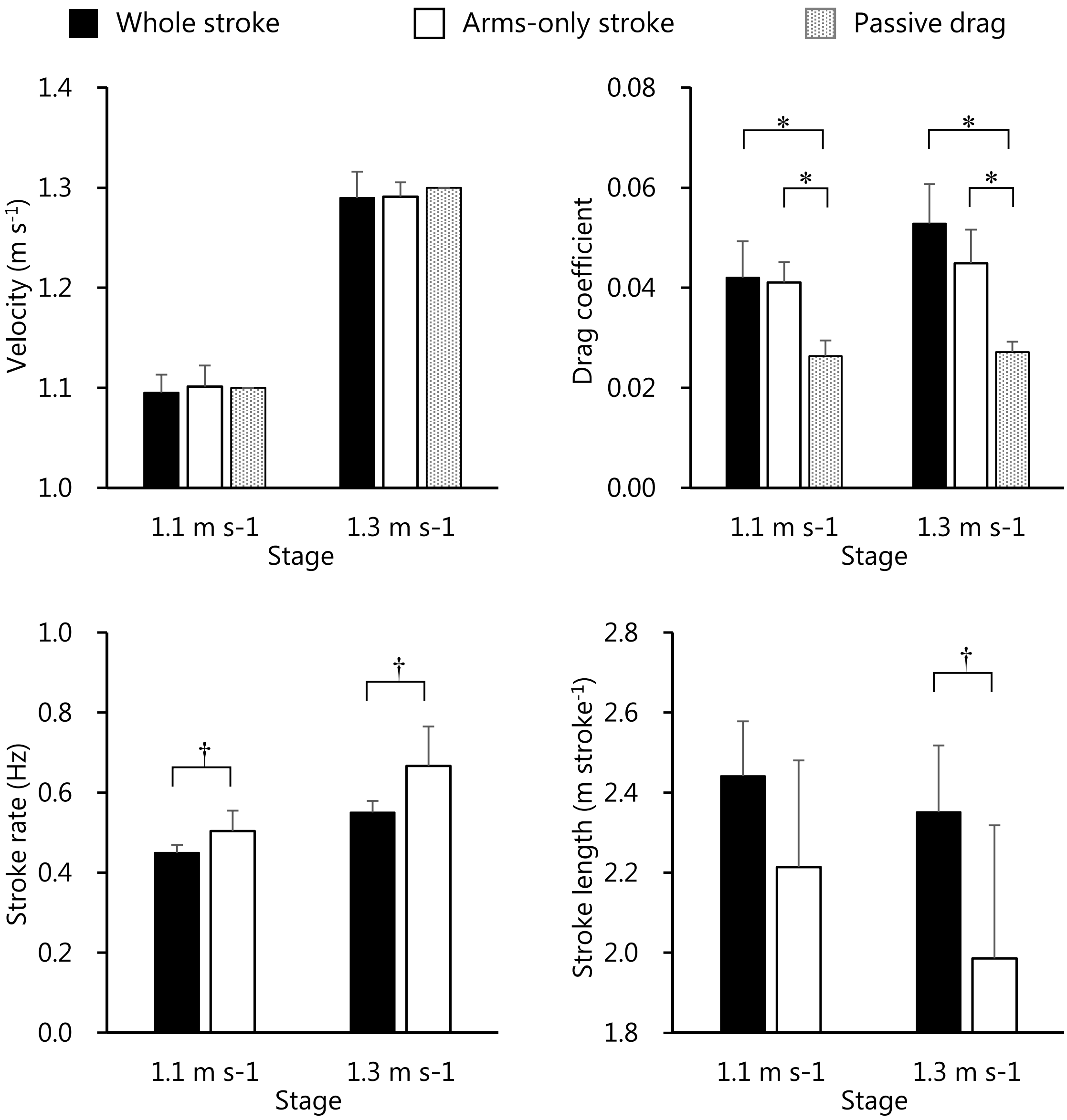

Fig. 1. Mean value of each variable at each stage. In the upper panel, significant differences for passive drag are indicated by asterisks (∗). In the lower panel, significant differences for arms-only stroke (AS) are indicated by daggers (†).

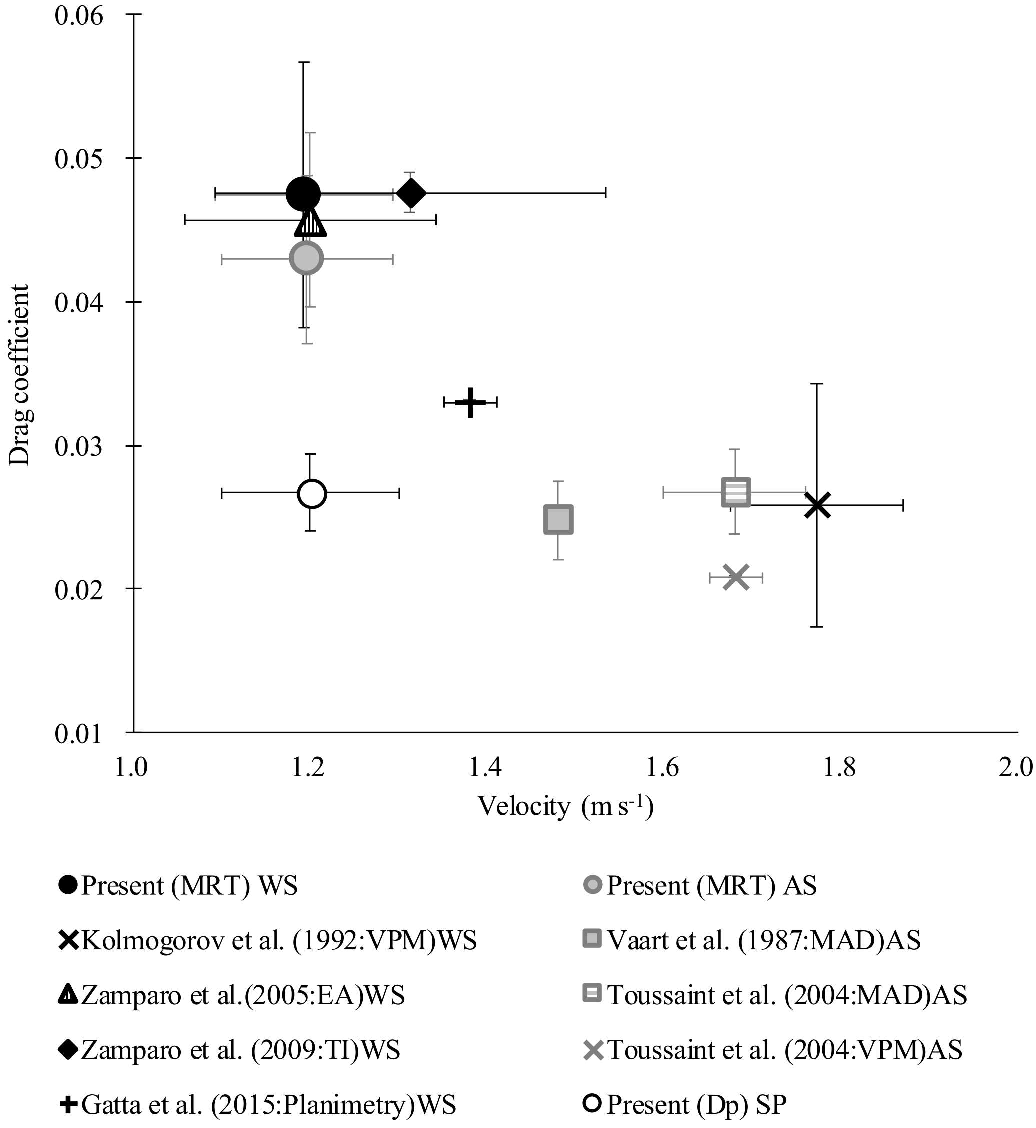

Fig. 2. Values of active drag coefficient from present and previous studies. These data were indicated as mean values and SD. Black and grey marks represent whole stroke (WS) and arms-only stroke (AS), respectively.

Circle (○): present study—MRT method (MRT) or passive drag; triangle (△): energetics approach (EA); square (□): MAD approach (MAD); cross (×): VPM approach (VPM); diamond (◇): calculated from relationship between trunk incline while swimming and that in the streamlined position (TI); plus (+): planimetic method (Planimetry).