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Swimming performance is reduced by reflective markers intended for the analysis of swimming kinematics

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ABSTRACT

The present study aimed to clarify whether swimming performance is affected by reflective markers being attached to the swimmer's body, as is required for a kinematic analysis of swimming. Fourteen well-trained male swimmers (21.1 ± 1.7 yrs) performed maximal 50 m front crawl swimming with (W) and without (WO) 25 reflective markers attached to their skin and swimwear. This number represents the minimum required to estimate the body's center of mass. Fifty meter swimming time, mid-pool swimming velocity, stroke rate, and stroke length were determined using video analysis. We found swimming time to be 3.9 ± 1.6% longer for W condition. Swimming velocity (3.3 ± 1.8%), stroke rate (1.2 ± 2.0%), and stroke length (2.1 ± 2.7%) were also significantly lower for W condition. To elucidate whether the observed reduction in performance was potentially owing to an additional drag force induced by the reflective markers, measured swimming velocity under W condition was compared to a predicted velocity that was calculated based on swimming velocity obtained under WO condition and an estimate of the additional drag force induced by the reflective markers. The mean prediction error and ICC (2,1) for this analysis of measured and predicted velocities was 0.014 m s^{-1} and 0.894, respectively. Reducing the drag force term led to a decrease in the degree of agreement between the velocities. Together, these results suggest that the reduction in swimming performance resulted, at least in part, from an additional drag force produced by the reflective markers.

1. Introduction

Measurements of human body kinematics can help with our understanding of sports performance. The kinematics of sports performed on land have generally been measured by means of three-dimensional motion capture, whereby retro-reflective markers define the location of skeletal landmarks. Motion capture has been developed further to enable measurement of limb motion underwater, for example, during competitive swimming (Kudo et al., 2017; Lauer et al., 2016; Matsuda et al., 2018; Olstad et al., 2017a, 2017b; Tsunokawa et al., 2017). Similar to traditional land-based motion capture systems, underwater motion capture systems measure the coordinates of multiple reflective markers attached to the body's skin and swimwear to calculate the position and orientation of limb segments. Olstad et al. (2017a, 2017b) previously measured swimming kinematics in four world-class competitive swimmers, however, we note that the maximal swimming velocities they report tend to be considerably lower than expected values. For example, the mean swimming velocity during 25 m of maximal breaststroke swimming was 1.30 m s^{-1} for the two male and two female world-class competitive swimmers (Olstad et al., 2017b), whereas the estimated swimming velocity during competition for 50 m breaststroke in accordance with the International Swimming Federation (FINA) point scoring is ~1.93 m s^{-1} and 1.69 m s^{-1} for male and female competitors, respectively (http://www.fina.org/content/fina-points). Since the density of water is much higher than that of air, drag force is a major factor that influences swimming performance (Toussaint and Truijens, 2005). Therefore, we speculate that reflective markers attached to the swimmer's body induce additional drag under-

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water, thereby impacting subsequent swimming performance. Accordingly, the purpose of this study was to determine the effect of reflective markers attached to the body on swimming spatiotemporal variables, including velocity, stroke rate, and stroke length. Moreover, we compared the measured velocity of swimming with reflective markers to a predicted velocity of swimming that was based on calculations of the extra drag force exerted by the markers, assuming a maximal effort, to elucidate whether the reduction in velocity was directly related to an increase in drag.

2. Methods

2.1. Subjects

Fourteen well-trained male swimmers participated in this study (age, 21.1 ± 1.7 yrs; height, 1.73 ± 0.07 m; body mass, 68.2 ± 7.2 kg; short course 100-m front crawl time, 53.7 ± 3.4 sec; mean ± SD). All subjects were informed about the experimental procedure and potential risks involved and gave informed consent. The study was approved by the ethics committee of the National Institute of Fitness and Sports in Kanoya.

2.2. Experimental procedures

All tests were conducted in a 25 m indoor pool. After a routine warm-up, participants randomly performed 50 m of front crawl swimming at maximal effort with (W) and without (WO) reflective markers attached to their body. Participants were not given any instructions in relation to breathing when swimming in the motion capture volume. To minimize the effect of fatigue on swimming performance, one swimming trial was employed for each condition and at least 30 min of rest was provided between trials. Twenty five commercially-available, spherical reflective markers purpose-built for underwater motion capture (Qualisys, Göteborg, Sweden) were attached to the participant's body (Fig. 1) according to a standard procedure used to estimate the position of the body's center of mass (Ae et al., 1992). To minimize marker obstruction owing to arm movement, markers were attached to the front and rear of the head rather than the tragus. All markers were 19 mm in diameter (0.0095 m radius) to improve visibility underwater (Olstad et al., 2017a, 2017b). Each marker was attached to a flat magnetic base (diameter 10 mm, thickness 2 mm), which was attached to either the participant's skin or swimwear with adhesive waterproof tape. The mass of an individual marker and magnetic base was 7.0 and 1.9 g, respectively. The combined mass of the markers (7.0 g × 25 markers) and magnetic bases (1.9 g × 25 magnets) was equivalent to approximately 0.03% of participant body mass.

A digital video camera (GC-LJ20B, Logical Product Co., Japan, 640 × 360 pixels resolution, 120 frames per second) was positioned approximately 5 m above the water's surface and approximately 30 m away from the swimming lane. This video camera was used to determine 50 m swimming time, as well as swimming velocity, stroke rate, and stroke length for 10–20 m (between 10 m and 20 m markers) and 35–45 m segments (between 5 m and 15 m markers). Reference markers were placed at 5, 10, 15, and 20 m on each lane rope to calibrate swimming distance. The camera was panned to minimize parallax or perspective error. Participants started the swimming trial with a push off from the wall immediately after the sound of a starting pistol that also triggered lights for synchronization with the video camera.

Blood lactate concentration was measured from pin prick blood samples taken from the fingertip (Lactate Pro2, Arkray, Japan) both before and three-minutes after each trial to assess whether the physiological effort was similar for each condition.

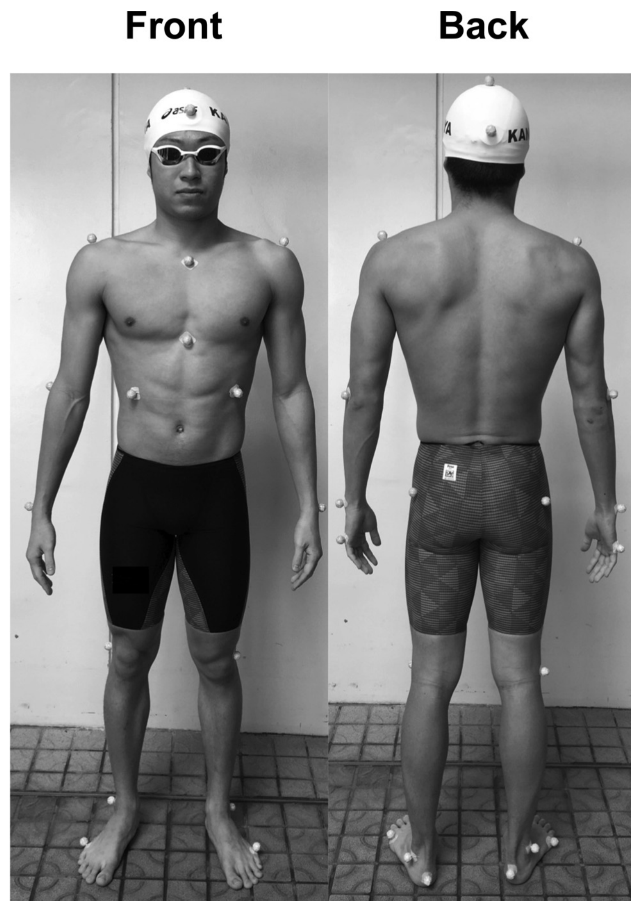

Fig. 1. Attachment position of the 25 reflective markers in W condition.

Fifty meter swimming time was defined as the time interval between the onset of the starting light signal and the swimmer's hand touching the wall. Velocity was calculated by dividing the 10 m segment distance by the time taken for the swimmer's head to pass between the relevant reference markers. Video data were analyzed by using Quick time player (version 7.6.6. Apple Inc., USA). Specifically, stroke rate was determined as the inverse of stroke time, which was calculated by averaging the time taken to complete three stroke cycles. A stroke cycle was defined as the period between two successive entries of the right hand into the water. Stroke length was calculated by dividing the mean 10 m segment velocity by the corresponding stroke rate (Chollet et al., 1997; Fernandes et al., 2011). An average measure of velocity, stroke rate and stroke length was determined from the measurements made at the 10–20 m and 35–45 m segments.

For simplicity, an estimate of the additional drag force (Da_{marker}) induced by the reflective markers was calculated according to the following equation (Gatta et al., 2015):

$$Da_{marker} = \frac{1}{2} p C_d A v^2 \quad (1)$$

where p is water density (997 kg m^{-3}), C_d is the drag coefficient of a sphere [0.47 (Hoerner, 1965)], A is the total reference area of the markers [π × square of radius (0.0095 m)] × 25, and v is the measured swimming velocity in WO condition ($v_{mea\text{-}wo}$). This estimate of drag was considered to represent an additional average value of drag applied to the swimmer's body in the opposite direction of travel. To validate this estimation, we predicted a swimming velocity based on our estimate of the additional drag force induced by the reflective markers (Da_{marker}) and the measured velocity in

WO ($v_{\text{mea-wo}}$). Predicted velocity was estimated as follows: first, the theoretical total drag force ($Da_{\text{total-wo}}$) applied to a swimmer in WO condition swimming at $v_{\text{mea-wo}}$ was calculated using Eq. (1). In this case, we assigned a value of 0.3 to the drag coefficient (C_d) according to Gatta et al. (2015), and A was calculated as [0.52–0.21 $v_{\text{mea-wo}}$] according to Zamparo et al. (2009). Second, we estimated the velocity ($v_{\text{est-w}}$) when Da_{marker} was applied to a swimmer with an exerted power output (P) equal to that estimated for WO condition. For a $v_{\text{mea-wo}}$ of 1.79 m s^{-1}, $Da_{\text{total-wo}}$ and P are estimated to be 69.05 N and 123.6 W (69.05 N × 1.79 m s^{-1}), respectively. We then obtained $v_{\text{est-w}}$ as follows:

$$Da_{\text{total}-w} = Da_{\text{marker}} + Da_{\text{swimmer}}$$

where Da_{swimmer} is a drag force that applies purely to the swimmer and calculated using Eq. (1) (i.e., $21.55 v^2_{\text{est-w}}$), and Da_{marker} is also calculated using Eq. (1) (i.e., $1.66 v^2_{\text{est-w}}$).

Thus,

$$P = 123.6\ \text{W} = Da_{\text{total - w}} \times v_{\text{est}-w} = (Da_{\text{marker}} + Da_{\text{swimmer}}) \times v_{\text{est}-w} = 23.21\, v^3_{\text{est}-w}$$

Hence, we calculate

$$v_{\text{est}-w} = 1.75\ \text{m s}^{-1}$$

Finally, we calculated the intraclass correlation coefficient (ICC) between the measured ($v_{\text{mea-w}}$) and predicted velocities ($v_{\text{est-w}}$) across all subjects to examine the validity of the estimate of Da_{marker}.

2.3. Statistical analysis

Statistical analyses were performed using SPSS (version 22.0, SPSS Inc., Japan). A Shapiro-Wilk's test was used to test for normality. Fifty meter swimming time, velocity, stroke rate, and stroke length were compared between W and WO conditions using a paired *t*-test. Blood lactate concentration was compared using a two-way ANOVA with repeated measures (2 measurement times × 2 conditions). ICC (2,1) was used to assess the relationship between measured ($v_{\text{mea-w}}$) and predicted velocities ($v_{\text{est-w}}$) in the W condition. Effect sizes were calculated as eta squared (η^2) for all *t*-tests outcomes and as partial eta squared (partial η^2) for ANOVA outcomes. $P \le 0.05$ was considered statistically significant. All values are expressed as means ± SD in the text.

3. Results

Adding reflective markers to the body reduced swimming performance. Fifty meter swimming time was significantly longer for W condition than for WO condition (W, 28.05 ± 1.41 s vs. WO, 26.97 ± 1.11 s; t (13) = 8.67, η^2 = 0.85, P < 0.001, Fig. 2A). Swimming velocity (W, 1.73 ± 0.09 m s^{-1} vs. WO, 1.79 ± 0.07 m s^{-1}; t (13) = 6.89, η^2 = 0.79, P = 0.001, Fig. 2B), stroke rate (W, 0.88 ± 0.10 Hz vs. WO, 0.89 ± 0.10 Hz; t (13) = 2.18, η^2 = 0.27, P = 0.048, Fig. 2C), and stroke length (W, 1.99 ± 0.21 m vs. WO, 2.04 ± 0.21 m; t (13) = 2.84, η^2 = 0.38, P = 0.014, Fig. 2D) were all significantly lower for W condition than for WO condition. With respect to blood lactate concentration, there was no interaction effect (F (1,13) = 0.25, partial η^2 = 0.019, P = 0.626) and no main effect of condition (W, 4.25 ± 1.40 mmol l^{-1} vs. WO, 4.52 ± 1.77 mmol l^{-1}; F (1,13) = 1.23, partial η^2 = 0.086, P = 0.287), but there was a main effect of time (before, 2.30 ± 0.91 mmol l^{-1} vs. after, 6.47 ± 2.25 mmol l^{-1}; F (1,13) = 99.3, partial η^2 = 0.88, P < 0.001). The additional drag force owing to the 25 reflective markers (Da_{marker}) was estimated to be 5.30 ± 0.42 N (0.212 ± 0.017 N marker^{-1}). This estimate gave rise to a predicted swimming velocity ($v_{\text{est-w}}$) of 1.74 ± 0.06 m s^{-1} and a mean prediction error of 0.014 m s^{-1}. The ICC (2,1) for measured ($v_{\text{mea-w}}$) and predicted ($v_{\text{est-w}}$) swimming velocities was 0.894 (P < 0.001; Fig. 3). Reducing the drag force estimate in our calculation by assuming that only 15 of the 25 reflective markers were directly exposed to water flow, thereby increasing the predicted swimming velocity, resulted in an increase in the mean prediction error (0.031 m s^{-1}) and a decrease in the ICC (0.851, P < 0.001, Fig. 3).

4. Discussion

The purpose of the current study was to determine if reflective markers intended for three-dimensional motion capture affect swimming performance when fixed to the swimmer's body. We show that mean mid-pool swimming velocity for 50 m front crawl is, in fact, 0.06 m s^{-1} (3.3%) slower when 25 commercially-available, purpose-built reflective markers are used. As swimming velocity predicted according to calculations of the extra drag force induced by the reflective markers was very similar to that measured in the experiment, we propose that the reduction in swimming performance may have resulted from an additional drag force produced by the reflective markers.

Swimming velocity is the product of stroke rate and stroke length. In the current study, both stroke rate and length were reduced for W condition. Subsequent to confirming a negative impact of reflective markers on swimming performance, we attempted to identify a potential mechanism. Theoretically, additional resistance owing to the reflective markers was an obvious candidate. Accordingly, we set out to estimate the additional drag force produced by the reflective markers (Da_{marker}) according to Eq. (1), and then compared our measured swimming velocity to that which we predicted according to our estimate of marker resistance. We consider our estimate of additional drag to theoretically represent an average value that is applied to the swimmer's body in the opposite direction of travel throughout the trial. Reflective markers fixed to the swimmer's skin and swimwear might induce additional drag by turbulent flow (Kjendlie and Olstad, 2012), causing stroke rate to be reduced, despite the attempts of the swimmer to maximize stroke rate. Similarly, a smaller net propulsive force owing to an increase in resistive force may give rise to a shorter stroke length. Indeed, the mean prediction error for our analysis of measured and predicted velocities was only 0.014 m s^{-1}. Such a high degree of agreement supports the notion that an additional drag force arising from the reflective markers was an important factor in the observed reduction in swimming performance. In fact, that the predicted velocity was greater than the measured velocity for eleven of the fourteen participants suggests that we may have underestimated the true drag force contributed by the reflective markers. Alternatively, swimming performance might have also been compromised by other factors.

Changes in swimming action induced by the markers being attached to the swimmer may have contributed to the reduction in swimming velocity. It is possible that propulsive force might be reduced by a change in the angle of attack of the swimmer's upper limbs. In the current study, we employed competitive swimmers who had prior experience performing maximal swimming efforts with reflective markers attached to their body. Indeed, no swimmers reported discomfort or indicated that their performance was affected by the addition of reflective markers when interviewed after the W condition. There was also no difference in blood lactate concentration after swimming between conditions, indicating that the physiological effort was very similar for each condition. Taken together, we propose that the lower swimming performance in W condition was likely primarily the result of additional drag produced by the reflective markers.

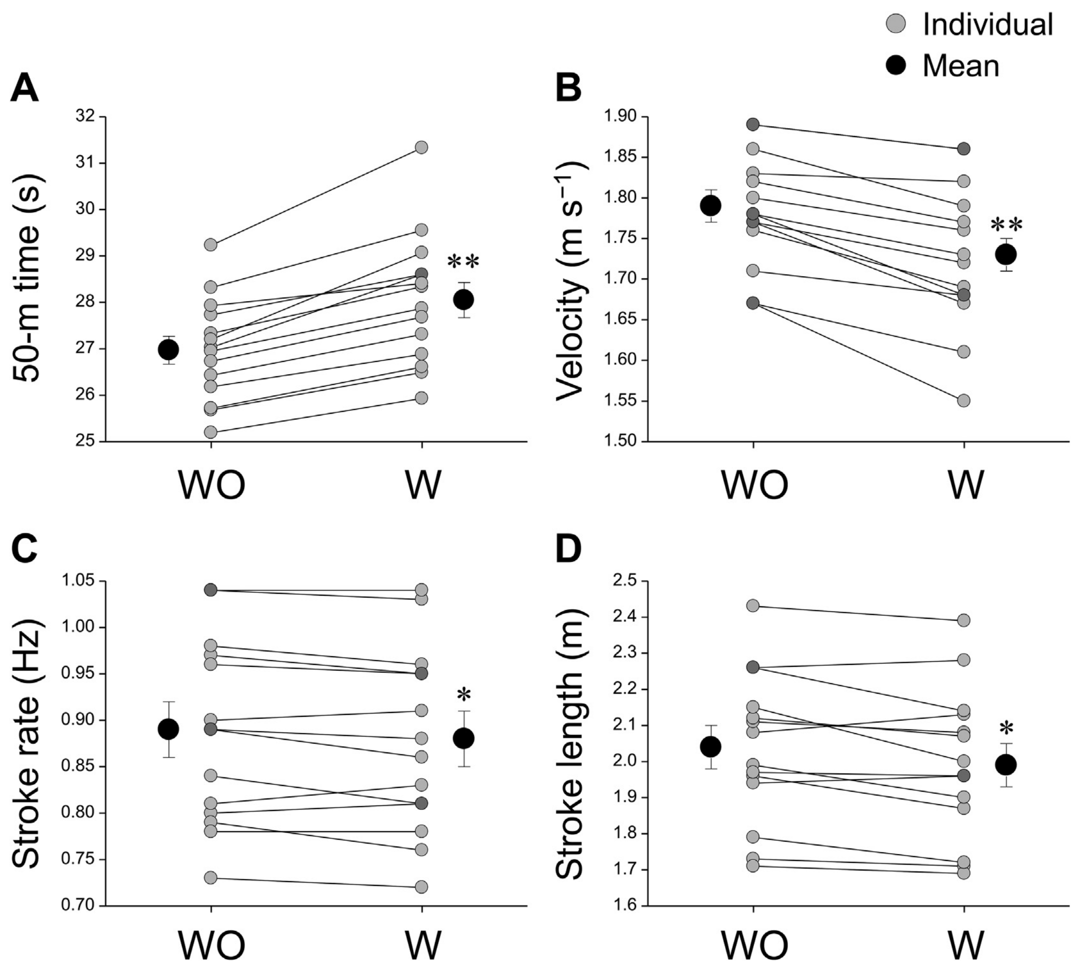

Fig. 2. Mean (filled circle) and individual (open circle) data of 50 m swimming time (**A**), velocity (**B**), stroke rate (**C**), and stroke length (**D**) for W and WO trials. Velocity, stroke rate, and stroke length were averaged across the 10–20 m and 35–45 m intervals. * and ** denote main effect of condition at $P < 0.05$ and $P < 0.01$, respectively.

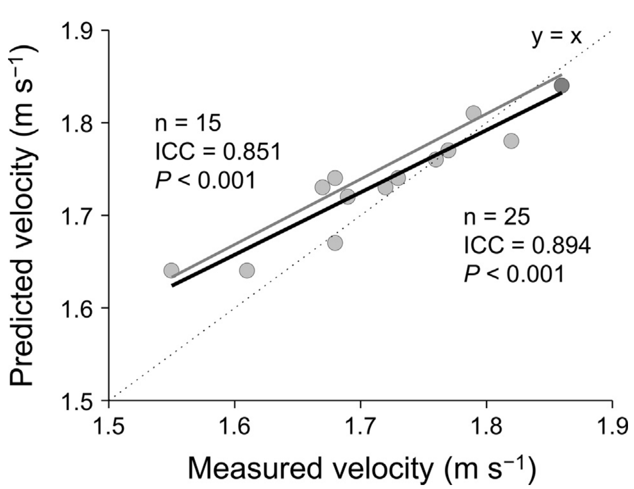

Fig. 3. Scatterplot illustrating the degree of agreement between measured and predicted velocities for swimming with reflective markers for all participants. Dotted line: line of identity; solid black and grey lines: linear regression between measured and predicted velocity calculated based on that number of reflective markers was 25 and 15, respectively.

As discussed earlier, we consider our estimate of additional drag produced by the reflective markers to represent an average drag that is theoretically applied to the swimmer's body in the opposite direction of travel. For simplicity, we have assumed that the swimmer's centre of mass velocity and projected frontal area were constant, whereas, in fact, both fluctuate within a stroke cycle. We also assumed that each marker was equally exposed to flow, and did not factor in the duration for which the arms were outside the water and, therefore, not contributing to a water-based drag force. Importantly, when we predicted swimming velocity assuming that only a subset (15) of the 25 reflective markers were directly exposed to the water flow, thereby reducing the drag force term, the mean prediction error increased by 0.017 m s^{-1}, shifting the slope of the relationship between measured and predicted velocities further away from the line of identity. This result suggests that it is unlikely that we have overestimated the effect of additional drag on swimming performance. Nonetheless, these limitations preclude a conclusion to be reached as to the exact degree to which swimming performance would be affected by a change in the number or size of the attached markers. As such, we stress that additional measurements are required to replicate our finding and reveal the exact effect of reflective markers on drag force and swimming performance.

In summary, we have demonstrated that swimming performance is reduced by reflective markers intended for a kinematic analysis of swimming. Our findings suggest that this reduction in swimming performance is primarily the result of an additional drag force produced by the reflective markers. The outcomes of this study are of relevance to analyses of swimming technique that are derived from three-dimensional motion capture. Considerable reductions in marker number and or size might sufficiently reduce the effect of marker-based drag on swimming performance.

Although a markerless motion capture system is likely the best solution, this technology has yet to be developed for underwater activities.

Declaration of Competing Interest

The authors acknowledge no conflict of interest.

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References

Ae, M., Tang, H.P., Yokoi, T., 1992. Estimation of inertia properties of the body segments in Japanese athletes (in Japanese with English abstract). Soc. Biomech. Japan 11, 23–33.

Chollet, D., Delaplace, C., Pelayo, P., Tourny, C., Sidney, M., 1997. Stroking characteristic variations in the 100-M freestyle for male swimmers of differing skill. Percept. Motor Skills 85, 167–177.

Fernandes, R.J., Sousa, M., MacHado, L., Vilas-Boas, J.P., 2011. Step length and individual anaerobic threshold assessment in swimming. Int. J. Sports Med. 32, 940–946.

Gatta, G., Cortesi, M., Fantozzi, S., Zamparo, P., 2015. Planimetric frontal area in the four swimming strokes: implications for drag, energetics and speed. Human Move. Sci. 39, 41–54.

Hoerner, S.F., 1965. Fluid-Dynamic Drag: Theoretical, Experimental and Statistical Information. Hoerner Fluid Dynamics, Bricktown, pp. 3–8.

Kjendlie, P.-L., Olstad, B.H., 2012. Automatic 3D motion capture of swimming: marker resistance. Med. Sci. Sports Exe. 44 (5S), 476.

Kudo, S., Sakurai, Y., Miwa, T., Matsuda, Y., 2017. Relationship between shoulder roll and hand propulsion in the front crawl stroke. J. Sports Sci. 35, 945–952.

Lauer, J., Hélène, A., Vilas-boas, J.P., 2016. Upper limb joint forces and moments during underwater cyclical movements. J. Biomech. 49, 3355–3361.

Matsuda, Y., Sakurai, Y., Akashi, K., Kubo, Y., 2018. A practical estimation method for center of mass velocity in swimming direction during front crawl swimming. J. Appl. Biomech. 34, 342–347.

Olstad, B.H., Vaz, J.R., Zinner, C., Cabri, J.M.H., Kjendlie, P.-L., 2017a. Muscle coordination, activation and kinematics of world-class and elite breaststroke swimmers during submaximal and maximal efforts swimmers during submaximal and maximal efforts. J. Sports Sci. 35, 1107–1117.

Olstad, B.H., Zinner, C., Vaz, J.R., Cabri, J.M.H., Kjendlie, P.-L., 2017b. Muscle activation in world-champion, world-class, and national breaststroke swimmers. Int. J. Sports Physiol. Perform. 12, 538–547.

Toussaint, H., Truijens, M., 2005. Biomechanical aspects of peak performance in human swimming. Anim. Biol. 55, 17–40.

Tsunokawa, T., Tsuno, T., Mankyu, H., Takagi, H., Ogita, F., 2017. The effect of paddles on pressure and force generation at the hand during front crawl. Human Move. Sci. 57, 409–416.

Zamparo, P., Gatta, G., Pendergast, D., Capelli, C., 2009. Active and passive drag: the role of trunk incline. Euro. J. Appl. Physiol. 106, 195–205.