APPLICATION OF PRESSURE MEASURES TO PREDICT PROPULSIVE FORCES EXERTED BY THE HAND DURING SWIMMING

Shigetada Kudo[1], Ian Harris Sujae[1], and Khalid Jabbar[1]

Republic Polytechnic, Singapore[1]

The aim of this study is to investigate the validity of the pressure method to predict propulsive forces exerted by the hand during swimming. The use of pressure measures has been developed to predict hydrodynamic forces acting on the hand in swimming; however, the method has not been validated during swimming. Three swimmers were asked to swim without a kicking motion against a counter-weight in a towing system and to keep their position the same. The pressure method predicted the mean propulsive force by 25±12% differences from the known weights. The difference may be due to the propulsive force due to the forearm. This study estimated the hand propulsions due to drag and lift forces reliably, which can be useful information for a swimmer and coach.

KEY WORDS: propulsive drag and lift, dynamic pressure, towing system.

INTRODUCTION: Propulsive forces exerted by the arms have been shown to be important in the front crawl stroke since the force produced by the arm is the majority of the swimmer's propulsive force (Hollander, de Groot, van Ingen Schenau, Kahman, & Toussaint, 1988). The hand should be the single most important contributor to the propulsion in the arm stroke because the hand is the most distal end of the limb so that the hand reaches the fastest speed and acceleration during any swimming strokes. Additionally, unlike the upper arm or forearm, the hand can be manipulated through a range of orientations to maximize propulsive lift and drag. Thus, the quantification of propulsive forces exerted by the hand in swimming is necessary to provide swimmers and coaches the evidence on which to base improvement of swimmer's technique.

The use of multiple hand pressure measures has been developed to predict hydrodynamic forces acting on the hand in swimming to evaluate a swimmer's stroke technique (Havriluk, 1988; Kudo, Yanai, Wilson, Takagi, & Vennell, 2008). This method can take account of the effect of acceleration as well as vortices on hydrodynamic forces acting on the hand. Thus, this method should predict hydrodynamic forces on the hand more accurately than the quasi-static approach, which has been used in order to quantify propulsive force exerted by the hand during swimming (Shleihauf, Gray, & DeRose, 1983; Cappaert, Pease, & Troup, 1995). However, the pressure method has not been investigated the validity in a swimming stroke. Therefore, the aim of this study is to investigate the validity of the pressure method to predict propulsive force exerted by the hand during swimming.

METHODS: Three swimmers (two triathletes and one ex-college swimmer) participated in this study after they signed informed consent. The mean height, weight and hand area of the swimmers were 1.72 ±0.06 m, 69 ±9 kg, and 0.015 ±0.002 m^2, respectively.

Twelve pressure sensors with a portable data logger (MMT, Japan) were used to predict hydrodynamic force exerted by the swimmers. Twelve pressure sensors were attached on the swimmer's hand according to Kudo et al. (2008) and the data logger was attached on the back of the swimmer. The data logger was synchronized with an underwater motion capture system (Qualisys, Sweden), set up at the swimming pool (16 x 18 m), and the signals were recorded at 100 Hz. A right-handed Cartesian coordinate system was embedded at the bottom of the pool; the x-direction defined the direction of swimming, the y-direction defined the side-to-side direction, and the z-direction defined the vertical direction. Three reflective markers were attached on the right hand, the third finger tip, trapezium and pisiform, to determine hand motion and two reflective markers were attached on each iliac crest to determine swimming speed. The swimmers were asked to swim without a kicking motion

against a counter-weight in a towing system for 20 to 30 seconds and to keep their position the same. During swimming, the swimmers used a pull buoy to float their legs. Two swimmers (S1 and S2) swam the front crawl with different counter-weights (44 N and 68 N for S1 as S1a and S1b, and 30 N for S2) and another swimmer (S3) conducted a sculling motion against a counter weight (44 N).
The signals of data logger and motion capture system for a right hand stoke of S1 and S2 and for both hand strokes of S3 were smoothed using a low-pass Butterworth filter. Propulsive forces exerted by the hand with the consideration of the hand area of each swimmer were predicted by the method of Kudo and Lee (2010), and propulsive forces due to drag and lift by the hand were also predicted. A swimming speed for each trial was computed using the displacement data of iliac crests. Data sets for one stroke of each swimmer were chosen as the representative trial for each condition when the swimming speed was close to 0. The swimming speed close to 0 indicated that a swimmer kept the position the same and the propulsive forces exerted by the swimmer for the one stroke was theoretically equal to the counter-weight. In the representative trials, the mean propulsive forces by the right hand of S1 and S2 were compared to the known counter-weights while the mean propulsive force by both hands of S3 were compared to the known counter-weight. Instantaneous values of propulsive drag for each representative trial were fitted using the square of the hand velocity in the x-direction (swimming direction), and instantaneous values of propulsive lift for each representative trail was fitted using the square of the hand velocity in the direction perpendicular to the x-direction (the y- and z-directions). The R^2 values of the fitted curves were computed to investigate the trend of instantaneous propulsive drag and lift forces exerted by the hand.

RESULTS AND DISCUSSION: Mean predicted propulsive forces exerted by the hand of three swimmers are shown in Table 1. The pressure method predicted the mean propulsive force by 25 ±12% of the known counter-weights. The difference might be because we only predicted the propulsion exerted by the hand while hydrodynamic forces exerted by the forearm during the trails could contribute to the propulsive forces (Rushall, Holt, Sprigings & Cappaert, 1994). The difference between the known counter-weight and the predicted propulsion increased from S1a to S1b. This can be because the contribution of forearm to hydrodynamic forces acting on the hand and forearm increased as the swimming speed increased (Rushall et al., 1994). The movement of hand and forearm during sculling motion was mainly in the lateral direction so that most of propulsive forces during sculling motion should result from lift forces and the shape of the forearm seems not to be able to generate much lift forces. Thus, the predicted hand propulsive force of 39 N by both hands was close to the known counter-weight of 44 N (11% difference).

Table 1: Mean and standard deviation of propulsive force exerted by the hand and swimming speed.

	Swimming style	Hand to predict	Known counter-weight (N)	Predicted propulsion (N)	Swimming speed for a stroke (m/s)
S1a	Front crawl	Right	44	33 ± 18	0.07 ± 0.13
S1b	Front crawl	Right	68	41 ± 19	0.02 ± 0.14
S2	Front crawl	Right	30	23 ± 9	0.11 ± 0.08
S3	Sculling	Right	44	21 ± 12	0.01 ± 0.06
		Left		18 ± 9	

The fitted curves of the predicted propulsive drag and lift forces by the hand against the hand velocities are shown with the R^2 values in Figures 1 and 2. The R^2 values were high in the most trials, indicating that the trend of propulsive drag and lift forces exerted by the hand was predicted well. Drag and lift forces acting an object moving in fluid are proportional to the square of the object's velocity. This was true for the propulsive drag in the present study, except for propulsive drag of S3 (R^2=0.01), and for the propulsive lift indicating that the pressure method predicted the trend of instantaneous drag and lift forces for the stroke. The R^2 value of propulsive drag for S3 was small; however, the magnitude of propulsive drag was small and approximately5 N at the hand velocity in the x-direction of 2 m/s because of hand sculling motion. When S1 swam against the counter-weight of 68 N, S1 changed swimming technique and exerted more propulsive lift by the hand than for swimming against the counter-weight of 44 N while the propulsive drag by the hand did not change much between the two conditions (the coefficients of S1a and S1b in Figure 2). According to the marker data on the S1's hand, the maximum hand velocity in the yz-plane during the insweep phase was 1.9 m/s in the swimming against 68 N counter-weight whereas the maximum hand velocity in the yz-plane during the insweep phase was 1.6 m/s in the swimming against 44 N counter-weight. This hand kinematics support that S1 exerted more propulsive lift by the hand during swimming against 68 N counter-weight than for swimming against 44 N counter-weight, and the hand motion in the insweep phase is likely to exert lift force.

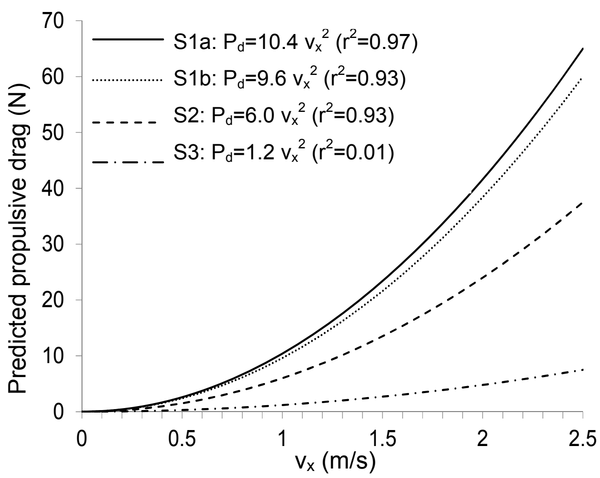

Figure 1: Propulsive drag (P_d) against hand velocity in the x-direction (swimming direction).

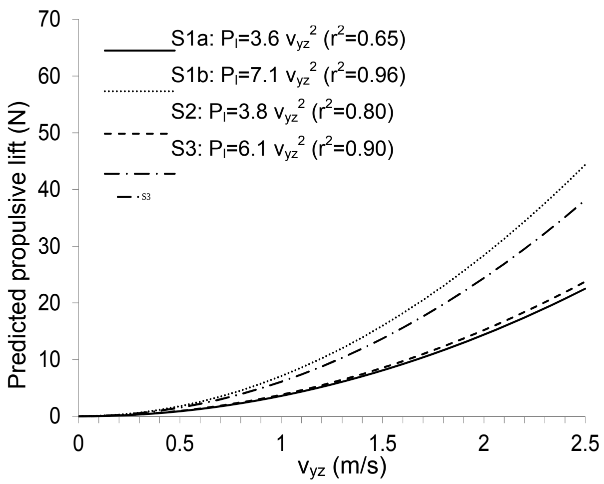

Figure 2: Propulsive lift (P_l) against hand velocity in the yz-direction perpendicular to the x-axis.

Figure 3 shows the typical trial of propulsive forces exerted by the hand during the front crawl. The maximum propulsive force by the hand was approximately 35 N when the propulsive drag reached the maximum. The propulsive lift reached the maximum in the insweep phase of the stroke and decreased in the upsweep phase. That is, the swimmer exerted the propulsive forces by the hand using both drag and lift forces until the end of insweep phase and then mainly used drag forces to propel in the upsweep phase.

CONCLUSION: This study suggests that the pressure method can feasibly provide useful feedback with certain validity for swimmers and coaches of when and how propulsive forces are generated by the hands. The feedback will facilitate swimmers and coaches to improve the stroke technique using relevant information such as propulsive drag and lift forces by the hand, the hand movement, and the swimming speed. Further studies should consider the hydrodynamic forces acting on the forearm to validate the pressure method for predicting propulsions exerted by the swimmer's hand.

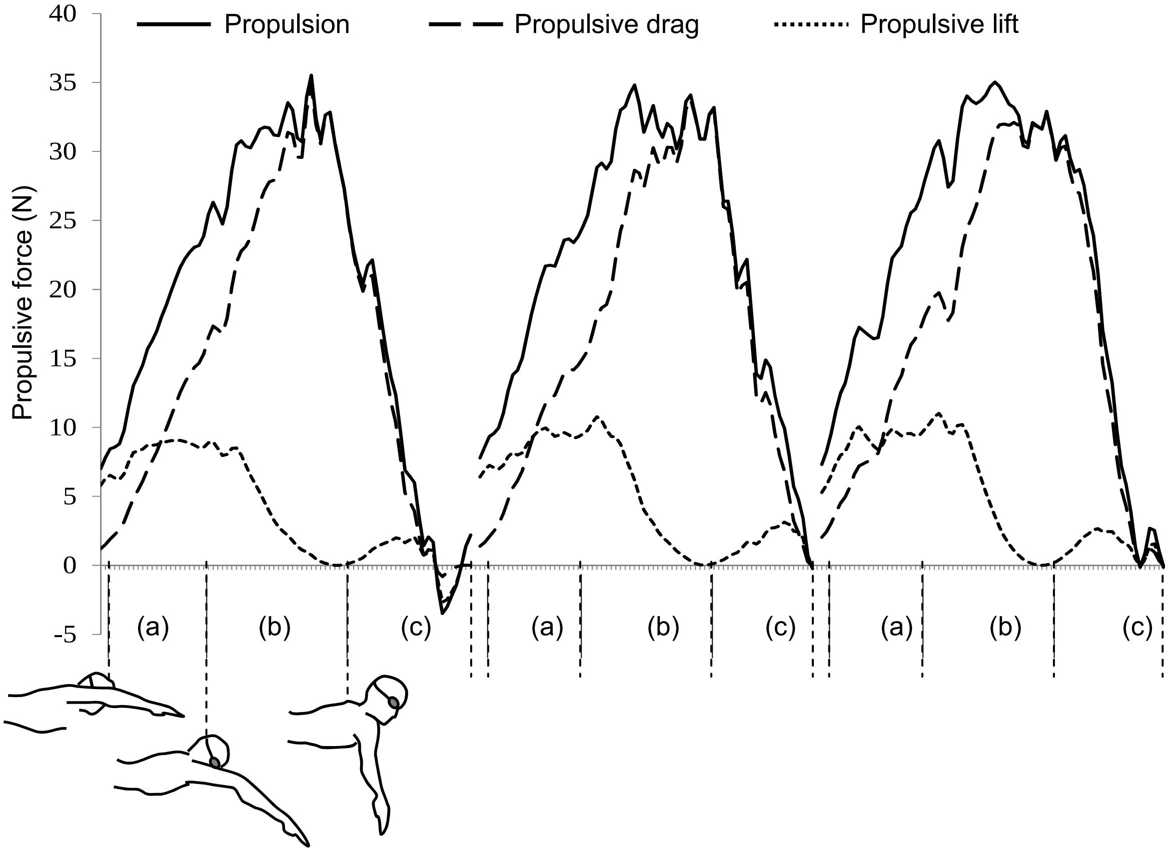

Figure 3: Typical example of propulsive forces by the swimmer (S2) for three strokes; (a) stretch and downsweep phase, (b) insweep phase, (c) upsweep phase.

REFERENCES:

Cappaert, J. M., Pease, D. L., & Troup, J. P. (1995). Three-dimensional analysis of the men's 100-m freestyle during the 1992 Olympic games. *Journal of Applied Biomechanics*, 11, 103-112.

Havriluk, R. (1988). Validation of a criterion measure for swimming technique. *Journal of Swimming Research*, 4, 11-16.

Hollander, A. P., de Groot, G., van Ingen Schenau, G. J., Kahman, R., & Toussaint, H. M. (1988). Contribution of the legs to propulsion in front crawl swimming. In B. E. Ungerechts, Wilke, K., Reischle, K. (Eds.), *Swimming Science V* (pp 39-43). Champaign, IL: Human Kinetics Publishers.

Kudo, S. & Lee, M. K. (2010). Prediction of propulsive force exerted by the hand in swimming. In P. L. Kjendlie, R. K. Stallman, and J. Cabri (Eds.), *Biomechanics and Medicine in Swimming XI* (pp112-114). Oslo: Norwegian School of Sport Science.

Kudo, S., Yanai, T., Wilson, B., Takagi, H., & Vennell, R. (2008). Prediction of fluid forces acting on a hand model in unsteady flow conditions. *Journal of Biomechanics*, 41, 1131-1136.

Rushall, B.S, Holt, L. E., Sprigings, E. J. & Cappaert, J. M. (1994). A re-evaluation of forces in swimming. *Journal of Swimming Research*, 10, 6-30.

Schleihauf, R., Gray, L., & DeRose, J. (1983). Three-dimensional analysis of hand propulsion in the sprint front crawl stroke. In P. A. Hollander, Huijing, P. A., and de Groot, G. (Eds.), *Biomechanics and Medicine in Swimming* (pp173-184). Champaign, IL.: Human Kinetics.