A new method to evaluate breaststroke kicking technique using a pressure distribution analysis
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1. Introduction
The propulsive force produced by limbs is a key contributor to the velocity attained during human swimming. However, the swimming motion in the aquatic environment is very complex, being difficult to evaluate the propulsive forces. Although many researchers have developed direct method to measure active drag during human swimming (Hollander et al., 1986; Formosa, Mason, & Burkett, 2011), the situation differs from that in free swimming.

To circumvent these difficulties, a new method has been developed in which fluid forces are estimated from analysis of pressure distributions (Takagi & Wilson, 1999; Kudo et al., 2008). This method has been used to successfully measure the force acting on a hand over time. As swimmers move their hand through the water, the pressure fluid drag forces act perpendicularly to the hand surface. Swimmers are propelled by the reaction force that matches the sum of these fluid forces. Estimating fluid forces by analyzing pressure distributions confers a distinct advantage over conventional measures: swimming technique is undisturbed and, provided that the pressure drag is measured directly, errors in the estimated fluid forces appear to be reduced.

However, no methodology has been proposed for predicting the fluid forces acting on other parts of a swimmer’s body. Especially in the breaststroke, the propulsive forces produced by lower limb motions are more important than those produced by upper limb motions. Therefore, while an improved kicking technique would seem to be essential to performance of the breaststroke. If the fluid forces produced by breaststroke kicking could be measured precisely, coaches and swimmers would be better equipped to evaluate their technical training. In addition, if the reliability of a methodology for estimating the fluid forces acting on a foot during breaststroke kicking could verified, then coaches and swimmers could apply this information.

The purpose of this study was to develop a new method for evaluation of breaststroke kicking motion using a pressure distribution analysis around a foot.

2. Method
Experimental Design
To achieve the purpose, two experiments were carried out. In the first experiment, we investigated the reliability of estimated fluid forces by using a robotic leg to which a model foot was affixed. The robotic leg could reproduce breaststroke kicking motions. As a breaststroke kicking motion was generated, the pressure distribution around the model foot was measured. In the second experiment, to test the possibility of using this method to evaluate the kicking techniques of actual swimmers, eleven national-level male swimmers participated in this experiment. Swimmers performed the breaststroke kicking motion at maximal effort without upper limb motions. During the trial, kicking
techniques of actual swimmers were analyzed using the methodology tested in the first experiment. 

First Experiment
Experiments were conducted in a circulating water channel. The robotic leg comprised the trunk, hip, thigh, and shank of a human left leg (Figure 1). The robotic leg was designed by Nakashima and Takahashi and constructed at the Akishima Laboratory, Mitsui Zosen Inc., Japan. The hip joint has three degrees-of-freedom (DOF), and knee joint has a DOF. Breaststroke-kicking motions were reproduced by combinations of these four motions.

The robotic leg performed two types of breaststroke-kicking motions (standard and large) at two speeds of the joint angles (6.4 s/cycle and 8.0 s/cycle). The joint angles of the standard trial were based on kinematic swimming data from an international-level female swimmer. The ranges of joint angles in the large trial were adjusted to be larger than those in the standard trial. Additionally, to clarify the influence of fluid forces on the foot model alone, trials were conducted on the robotic leg that was not mounted to the model foot.

The robotic leg was fixed from above the water channel with a three-dimensional load cell (LSM-E Kyowa Electronic Instruments Co. Ltd., Japan). The forces measured by the load cell were processed using a sensor interface (PCD330B-F Kyowa Electronic Instruments Co. Ltd., Japan), sampled at 200 Hz and input to a personal computer.

The foot model (Figure 1) was 0.217 m long, 0.086 m wide, 0.080 m high, and weighed 0.804 kg. The projected areas on the horizontal and sagittal planes were 133.20 cm² and 122.75 cm², respectively. The foot model was constructed from silicone and was molded from the left foot of a female swimmer. Eight pressure sensors (PS05-KC Kyowa Electronic Instruments Co. Ltd., Japan) were embedded in a grooved chassis that conformed to the foot surface.

Fluid forces were estimated from pressure distributions and areas of the foot model using a modification of the methodology reported by Takagi and Wilson (1999). The sensors measured flow-induced hydrodynamic pressures, as well as hydrostatic pressures due to the depth of the sensors. Hydrostatic pressures were eliminated by subtracting dorsal pressures from those at the plantar sides, enabling values for effective hydrodynamic pressures to be obtained. In the present study, the toe end of the foot was divided into three segments, while the heel end was defined as a single segment (Figure 2). These four segments were divided according to six anatomical landmarks, and four pairs of pressure sensors were embedded into the dorsal and plantar sides of each segment. Hydrodynamic pressures were calculated as pressure differences between dorsal and plantar sides. These calculated pressure differences were assumed to represent the pressure differences at the segment. Multiplying those pressure differences by the area of each segment yields the fluid forces acting on each segment. The fluid forces acting across the entire foot model were obtained by summing the forces calculated at each segment. When calculating pressure differences, angles between pairs of pressure sensors were taken into account by measuring the angles at the sagittal plane between the dorsal and plantar sides of the foot model in the standing position. The pressure data collected from the pressure sensors were processed via a sensor interface linked to the loadcell,
Figure 2  Construction of the foot model, showing the four segments, and the points where pressure sensors were attached.

Figure 1  Robotic leg and foot model used in the first experiment.

sampled at 200 Hz and fed into a personal computer together with force data and joint angles.

The breaststroke-kicking motion involves non-propulsive glide and recovery motions as well as propulsive motion. Here we focused, not only on the cycle of kicking motion, but also on the propulsive phase of fluid forces. The relationship between estimated fluid forces from pressure distribution analysis and the fluid forces measured by the load cell was quantified by Pearson’s correlation coefficient ($r$).

Second Experiment
To test the possibility of using this method to evaluate the kicking techniques of actual swimmers, seven male swimmers (age: $21.3 \pm 2.2$ year, height: $1.79 \pm 0.06$ m, mass: $71.9 \pm 7.1$ kg, 100 m breaststroke best record: $62.27 \pm 0.86$ s) participated in this study. The protocol was fully explained to the participants before they provided written consent to participate in the study, which was approved by the university ethics committee. Each swimmer performed the breaststroke kicking motion for ten seconds again without upper limb motions but using kickboard at maximal effort.

During the trial, swimmers were connected to a load cell via a polyethylene rope and a belt for measurement of tethered force at 200 Hz. Eight pressure sensors were attached to the right foot to measure the pressure distribution around the foot in the same manner as was used on the foot model attached to the robotic leg. Fluid forces acting on the foot during trials were estimated using the same procedure described at the method of first experiment. The trials were recorded by two backward underwater cameras and a lateral camera (frequency: 60 Hz, shutter speed: 1/500 s). Using
coordinates of the right foot calculated using the 3D-DLT method, estimated fluid forces were resolved into propulsive force, vertical force, and lateral force. The competitive swimming velocity (v50, v100 and v200) was calculated based on the personal best time over 50m, 100 m and 200 m breaststroke respectively. Pearson’s correlation coefficient (r) was used to investigate relationship among the estimated fluid forces, mean of tethered forces, and competitive swimming velocity.

3. Results
In the first experiment which used the robotic leg, Pearson’s correlation coefficient (r) revealed significant correlations between the estimated fluid forces from pressure distribution analysis and the fluid forces measured by the load cell (Table 1). These correlations can be seen in temporal profiles of the estimated fluid forces from pressure distribution analysis and the fluid forces measured by the load cell over one kicking cycle for each trial (Figure 3).

Table 1 Pearson’s correlation coefficient (r) between \( F_{\text{pressure}} \) and \( F_{\text{loadcell}} \). \( F_{\text{pressure}} \) is the fluid force estimated by using pressure distribution analysis. \( F_{\text{loadcell}} \) is the fluid force measured by a load cell.

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<thead>
<tr>
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<th>( F_{\text{loadcell}} )</th>
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<tr>
<td></td>
<td>Maximum F(_{\text{pressure}}) (N)</td>
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<tr>
<td>Maximum F(_{\text{pressure}}) (N)</td>
<td>0.77(*)</td>
</tr>
<tr>
<td>Impulse of F(_{\text{pressure}}) (N-s)</td>
<td>0.79(**)</td>
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<td>Impulse of F(_{\text{pressure}}) at propulsive phase (N-s)</td>
<td>0.82(**)</td>
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* : \( p < .05 \)  ** : \( p < .01 \)

![Figure 3](image-url) Temporal profiles of \( F_{\text{pressure}} \) and \( F_{\text{loadcell}} \) during one kicking cycle for each trial.
In the second experiment, competitive swimming velocity, mean of tethered forces, and variables of the estimated fluid forces for each swimmer were shown in Table 2. Pearson’s correlation coefficient (r) revealed significant correlations among the estimated fluid forces, the propulsive forces, mean of tethered forces, and competitive swimming velocity (Table 3). During the trial, the propulsive force, the vertical force, and the lateral forces corresponded to the kicking motions (Figure 4). In propulsive force, positive values mean the fluid forces acting backward of a swimmer. In vertical force, positive values mean the fluid forces acting upward of a swimmer. In lateral force, positive values mean the fluid forces acting toward left direction of a swimmer. And below graph shows pressure differences measured in each point where pressure sensors were attached.

4. Discussion
The estimated fluid forces acting on the foot model determined from pressure distribution analysis correlated significantly with the fluid forces measured by the load cell. The possibility of using pressure distribution analysis to evaluate the breaststroke technique of swimmers was evaluated in a series of experiments involving actual swimmers. The estimated fluid forces acting on a foot correlated significantly with actual competitive swimming velocities and mean of tethered forces. Characteristics of the kicking technique could be monitored from fluctuations in the propulsive forces, vertical forces, and lateral forces.
The present methodology, which estimated fluid forces during breaststroke kicking by pressure distribution analyses, could be applied to actual swimmers, and we could use those estimates to monitor the kicking techniques. Although the maximum and mean values of tethered forces correlate significantly with competitive swimming velocity, when the cable becomes slack the tethered force goes zero. Thus, tethered swimming can be used to evaluate propulsive force, but it cannot provide intra-cycle fluctuations in forces. In contrast, since pressure distribution analysis can monitor such fluctuations, swimmers and their coaches can identify more detailed and specific technical problems. In the present method, the hydrostatic pressure was eliminated by attaching pressure sensors in pair, which simplified the determination of estimates for fluid forces. Thus, fluid forces can be estimated more easily and conveniently than the method reported by Kudo et al. (2008). We conclude that the present methodology can be used to evaluate breaststroke-kicking motions qualitatively and quantitatively, thereby assisting swimmers and their coaches in evaluating and improving their training.

5. References