Estimating Hydrodynamic Forces Acting on the Hand during Sculling in Synchronized Swimming

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The characteristics of the hydrodynamic forces acting on the hand at different loads during sculling in synchronized swimming was estimated using a pressure distribution measuring method. One cycle of flat scull in a back layout position and support scull in a vertical position for one female national-level synchronized swimmer were analyzed. Results showed, at small loads in the flat scull, larger hydrodynamic force was observed during out-scull. As load increased, the hydrodynamic force increased during in-scull, and the values were observed to equalize between in-scull and out-scull. At all loads in the support scull, the larger value was observed during in-scull. It was apparent that in both sculls, the hydrodynamic force increased as the load increased, and the pressure on the dorsum of the hand decreased when large hydrodynamic force was generated.

KEY WORDS: Synchronized swimming, sculling, pressure distribution measurement.

INTRODUCTION: Synchronized swimming is a competitive sport requiring the exposure of a portion of the body above the water surface. When a portion of the body is exposed above the water surface, buoyancy is reduced in proportion to the volume above the water surface; and therefore, to maintain a steady position in the water, a load-bearing capacity comparable to the reduced buoyancy must be generated. In synchronized swimming, a propulsion technique such as sculling is used to generate upward propulsive force, so as to maintain a portion of the body above the water surface and perform the various movements. Earlier studies measuring the load above the water surface for basic performance positions reported that different positions produce different loads. For example, for a swimmer with a weight of 52 kg, the load is approximately 145 N in the vertical position with both legs raised above the water surface and the torso and head underwater, and approximately 83 N in the ballet leg position where one leg is lifted straight up in the back layout position; and synchronized swimmers choose the most suitable and efficient sculling methods for different loads (Homma 2000).
While sculling is the most basic technique in synchronized swimming, it is also an important technique, and considered the most difficult even for elite swimmers. Previous studies (Homma 2006, Homma et al. 2006, Homma et al. 2007) have investigated the movement characteristics of sculling by world-class synchronized swimmers and provided practical suggestions for efficient sculling. However, the hydrodynamic forces involved in actual synchronized swimming movements remain unclear.
Currently, several studies are using pressure sensors to directly measure the pressure on the swimmer's hand, in order to estimate the hydrodynamic forces acting on the hand (Ozaki et al., 2009). Because the hydrodynamic force created by the hand will be reflected in the distribution of pressure on the surface of the hand, methods utilizing pressure sensors to collect real-time measurements of the pressure working on the hand are considered to be effective.
The purpose of this study was to estimate the characteristics of the hydrodynamic forces acting on the hand at different loads during sculling in synchronized swimming using a pressure distribution measuring method.

METHODS: One female national-level synchronized swimmer participated in this study. The swimmer was asked to perform a flat scull in a stationary back layout position (Figure 1), and a support scull in a stationary vertical position (Figure 2), under the following four conditions, for five seconds each: with no load, and with 1, 2, or 3 kg of weight attached to the waist. The swimmer was instructed to maintain the most elevated position possible, in a stable position.

Figure 1 (left): Flat scull in a back layout position

Figure 2 (right): Support scull in a vertical position

Small pressure sensors (PS-05KC, Kyowa Electronic Instruments Co., Ltd.) were attached to six places on the subject's left hand, and pressure distribution was measured during the demonstrations using a sampling frequency of 200 Hz. With reference to Ozaki et al. (2009), the left hand was divided in a longitudinal direction into three areas, from the thumb to the space between the index finger and the middle finger (hereinafter the "thumb"), from the space between the index finger and the middle finger to the space between the middle finger and the ring finger (hereinafter the "middle"), and from the space between the middle finger and the ring finger to the little finger (hereinafter the "little"). The sensors were attached to each of these areas on the palm and the dorsum of the hand. The parts of the hand to which the sensors were attached. P1, P2, and P3 were attached to the index finger, the middle finger, and the ring finger of the dorsum of the hand, respectively, and P4, P5, and P6 were attached to the ring finger, the middle finger, and the index finger of the palm of the hand, respectively, near the metacarpophalangeal joint.

The sculling movement during the demonstrations was recorded by a total of four cameras (with a shutter speed of 1/500 sec and a sampling frequency of 60 Hz). Two underwater cameras were installed on the bottom of the pool (CPT-30A-H2A, Fujifilm Co., Ltd.), one video camera (TK-C1381, VC KENWOOD Corporation) was installed at the viewing window on the sidewall of the pool, and one wireless video camera (WUC-265, Nihon Jimukoki Co., Ltd.) capable of recording underwater/above water shots at the same time was installed on the pool wall opposite the viewing window.

As sculling is a repetitive movement, one cycle of sculling was extracted from the stable demonstration and analyzed in this study. For the purpose of the study, a sculling cycle was considered to begin at the moment when the hands were closest to each other. The phase in which the hands move away from each other is called the out scull, and that in which the hands move towards each other is called the in scull.

The dynamic pressure acting on the hand was estimated by subtracting the static pressure on the pressure sensors from the pressure value measured during sculling, and by calculating the difference in the pressure value between the sensors on the palm and the dorsum of the hand for each sensor on the index finger, middle finger, and ring finger. The hydrodynamic force was computed by considering the pressure measured in each area as a representative value, and by multiplying the estimated dynamic pressure by the projection area of the "thumb" for P1 and P6, by the projection area of the "middle" for P2 and P5, and by the projection area of the "little" for P3 and P4. The projection area of each region was derived by drawing an outline of the hand on 1-mm square graph paper.

The following items were computed from the pressure value measured by the pressure sensors.

F_{hand} (N): The resultant hydrodynamic force acting on the entire hand

F_{vert} (N): The vertical direction component of F_{hand}

$P_{1\sim6}$ (Pa): The pressure value measured by the sensor on each area

RESULTS: ***Flat scull*** - The change with time of F_{hand} for the flat scull is shown in Figure 3. The value of F_{hand} produced a double peak curve in which a peak was created in the stroke phase of the out scull and of the in scull. The maximum value of F_{hand} for the respective loads was 41.3 N for no load, 43.0 N for the 1 kg load, 41.2 N for the 2 kg load, and 40.5 N for the 3 kg load; all were observed during the out scull. Additionally, when the load was increased to 2 kg or greater, the maximum value and average value for the in scull increased.

The change with time of $P_{1\sim6}$ for the flat scull with 3 kg load is shown in Figure 4. The changes in the pressure value show that when the value of F_{hand} was small, the difference in pressure between the palm and the dorsum of the hand was small, and when the value of F_{hand} was large, the difference in pressure was large. This was not caused by increased pressure on the palm, but by decreased pressure on the dorsum of the hand.

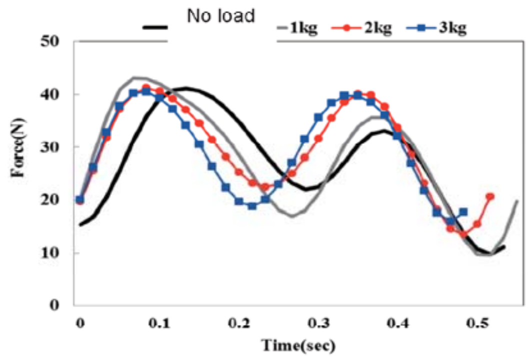

Figure 3: F_{hand} for the flat scull

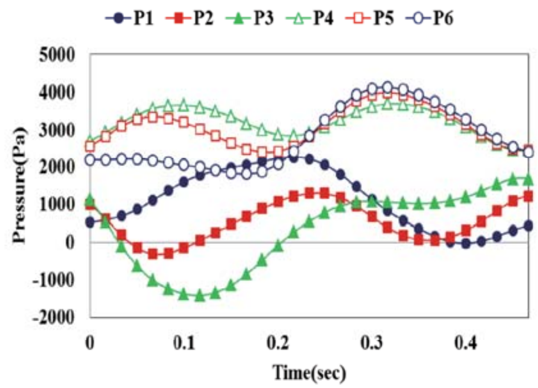

Figure 4: $P_{1\sim6}$ when the load is 3 kg

Support scull - The change with time of F_{hand} for the support scull is shown in Figure 5. The maximum value of F_{hand} for the respective loads was 67.7 N for no load, 72.3 N for the 1 kg load, 76.7 N for the 2 kg load, and 75.7 N for the 3 kg load; all were observed during the in scull. The average value for the in scull increased as the load increased.

The change with time of $P_{1\sim6}$ for the support scull with 3 kg load is shown in Figure 6. The changes in the pressure value show that when the value of F_{hand} was small, the difference in pressure between the palm and the dorsum of the hand was small, and when the value of F_{hand} was large, the difference in pressure was large. This was not caused by increased pressure on the palm, but by decreased pressure on the dorsum of the hand.

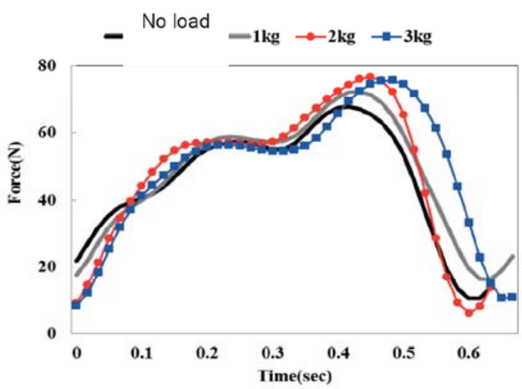

Figure 5: F_{hand} for the support scull

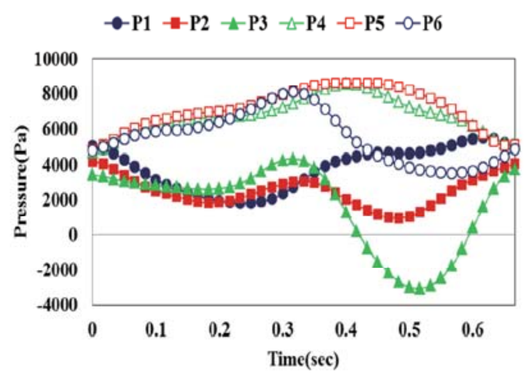

Figure 6: $P_{1\sim6}$ when the load is 3 kg

DISCUSSION:

Flat scull - The value of F_{hand} for the flat scull produced a double peak curve in which a peak was created in the stroke phase of the out scull and of the in scull. All maximum values were observed during the out scull. When the load was increased to 2 kg or greater, the value for the in scull increased and indicated values similar to those of the out scull. Based on these findings, it may be concluded that when the load is small, the out scull by itself can generate a large hydrodynamic force, such that the in scull acts merely as a recovery movement of the out scull; but when the load increases, the power generated by the out scull alone becomes insufficient to bear the load, and for this reason, the in scull begins to be used to generate power, so as to cope with the load. As a result, the following description in a representative manual for synchronized swimming may be said to be confirmed: "the pressure of the in scull and the out scull should be the same when sculling" (Homma 2006).

The changes in the pressure value of $P_{1\sim6}$ showed that when the value of F_{hand} was small, the difference in pressure between the palm and the dorsum of the hand was small, and when the value of F_{hand} was large, the difference in pressure was large. This was not caused by increased pressure on the palm, but by decreased pressure on the dorsum of the hand. Especially during the out scull, the sensor (P_3) near the little finger indicated a large negative value and during the in scull, the sensor (P_1) near the thumb indicated a low value. A similar trend was also observed under other loads. From these findings, it may be concluded that the pressure on the dorsum of the hand near the finger which is the first to move when the hand moves must be decreased to create large hydrodynamic force.

Support scull - The maximum value of F_{hand} for the support scull was entirely observed during the in scull. When the load was increased to 2 kg or greater, the maximum value also increased. A large teardrop-shaped sculling pattern, in which the hand moved toward the bottom of the pool and then drew a semicircle as it shifted from the out scull to the in scull, was observed (Homma et al. 2006); and the reason for this would appear to be that the movement of the hand which pushes water downward and then scoops it up generates large hydrodynamic force, composed largely of drag force.

The changes in the pressure value of $P_{1\sim6}$ showed that when the value of F_{hand} was small, the difference in pressure between the palm and the dorsum of the hand was small, and when the value of F_{hand} was large, the difference in pressure was large. This was not caused by increased pressure on the palm, but by decreased pressure on the dorsum of the hand. Especially during the out scull, the sensor (P_1) near the thumb indicated a low value; and during the in scull, the sensor (P_3) near the little finger indicated a large negative value. A similar trend was also observed under other loads. From these findings, it may be concluded that, as was the case for the flat scull, the pressure on the dorsum of the hand near the finger which is the first to move when the hand moves must be decreased to create large hydrodynamic force.

CONCLUSION: The following summary results were obtained in this study.

- At small loads in the flat scull, larger hydrodynamic force was observed during out-scull. As load increased, the hydrodynamic force increased during in-scull, and the values were observed to equalize between in-scull and out-scull.
- At all loads in the support scull, the larger value was observed during in-scull. It was apparent that in both sculls, the hydrodynamic force increased as the load increased, and the pressure on the dorsum of the hand decreased when large hydrodynamic force was generated.
- It was apparent that in the case of both sculls, the hydrodynamic force increased as the load increased, and the pressure on the dorsum of the hand decreased when large hydrodynamic force was generated.

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