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Full Length Article

The effect of paddles on pressure and force generation at the hand during front crawl

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A R T I C L E I N F O

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A B S T R A C T

Through pressure measurement, this study aimed to clarify the effects of hand paddle use on pressure and force generation around the hand during the front crawl. Eight male swimmers performed two trials of front crawl swimming with maximal effort, once using only their hands and once aided by hand paddles. During trials, pressure sensors and underwater motion capture cameras were used together to analyze hand kinematics and pressure forces acting on the hand. Six pressure sensors were attached to the right hand, and pressure forces acting on the right hand were estimated by multiplying the areas and the pressure differences between the palm side and dorsal side of the hand. Acting directions of pressure forces were analyzed using a normal vector perpendicular to the hand, calculated from coordinates of the right hand. As a result, using hand paddles decreases pressure differences between the palm and dorsal sides of hand related to the magnitude of pressure force. However, no difference was found in the mean value of resultant pressure forces compared with using hands alone, because the large surface area of the hand paddle compensated the decreased pressure differences due to decreased hand velocity. In addition, when hand paddles were used, the component of the pressure force acting in propulsive direction was significantly higher. Thus, the ratio of forces acting in the propulsive direction was higher than without hand paddles. These results suggest that the training loads with hand paddles are not high even if the swimming velocities increase because the power generated by upper limb motion didn't increase.

1. Introduction

Hand paddles are used while training for competitive swimming to increase force and power generated by upper limb motion. In previous studies on the effects of hand paddles, kinematics, such as stroke length, stroke rate, hand velocity, coordination of upper limb motions and efficiency of propulsion and energy consumption using physiological methods have been reported. A study using image analysis (Gourgoulis, Aggelousis, Vezos, & Mavromatis, 2006) reported that stroke length and swimming velocity increased with increase in paddle size, despite reduction of the velocity of hand and stroke rate. Furthermore, a study measuring propelling efficiency reported that, in comparison with bare hand swimming at the same velocity, swimmers increased their propelling

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efficiency by about 7.8% with hand paddles (Toussaint, Janssen, & Kluft, 1991). Additionally, several investigations have shown that oxygen uptake in swimming with hand paddles was lower than without them at given submaximal velocities, due to increased propelling efficiency (Ogita, Onodera, & Tabata, 1999; Ogita & Tabata, 1993).

The effects of hand paddles on the lift and drag forces during the front crawl were also estimated (Gourgoulis et al., 2008) based on kinematic data, using a quasi-static approach (Sanders, 1999). As a result, the surface area of the hand paddle caused an increased drag, lift, resultant forces, and propelling efficiency. However, the quasi-static approach applies drag and lift coefficients obtained under steady flow conditions to predict force acting on motion under unsteady flow conditions; this result in ignoring the effect of changes in acceleration and vortices around the body of swimmer. Since unsteady flow occurs around the hand during swimming (Kudo, Vennell, & Wilson, 2013; Matsuuchi et al., 2009; Takagi, Nakashima, Ozaki, & Matsuuchi, 2013; Takagi, Nakashima, Ozaki, & Matsuuchi, 2014; Toussaint, Van den Berg, & Beek, 2002), it was reported that force estimated by the quasi-static approach (Schleihauf, Gray, & DeRose, 1983) became a large error (Lauder & Dabnichki, 2005; Pai & Hay, 1988).

To fulfil these requirements, a growing number of studies have focused on pressure forces during swimming. In these studies, pressure forces acting on the body of swimmer were estimated from the pressure of body surface while considering unsteady motion (Kudo, Yanai, Wilson, Takagi, & Vennell, 2008; Takagi & Wilson, 1999; Tsunokawa, Nakashima, & Takagi, 2015). As swimmers move their hands through water, pressure forces acts in the normal direction, and frictional force in the tangential direction to the hand surface. Swimmers propel themselves by the sum of these forces in the propulsive direction. In a study using computational fluid dynamics (Marinho et al., 2009), the ratio of the pressure forces to total drag experiences during gliding position were 86.95–92.05%. Thus, frictional forces are considerably less than pressure forces. The use of pressure measurement can clarify the effects of hand paddle use on the propulsion during swimming. If these matters are clarified, the factors that increase propelling efficiency, velocity, and stroke length with the use of hand paddles become clear.

Therefore, by using pressure measurement, this study aimed to clarify the effects of hand paddle use on pressure and force generation around the hand during the front crawl. It was hypothesized that swimming velocity and propulsive forces would increase when use hand paddles. This hypothesis may seem to be in contrast with the reports by previous studies that hand velocity decreases with the use of hand paddles. If the pressures and force generations processes are clarified, the reasons why swimming velocity and propulsive forces increase despite a reduction of hand velocity should become clear. In addition, we hope to clarify how much the pressure forces and propulsive forces change when use hand paddles. If propulsive forces increase without an increase in the resultant pressure forces, this would mean that the muscle power generated by the upper limbs does not increase but propelling efficiency improves.

2. Method

2.1. Participants

The study sample consisted of eight national-level male swimmers (age: 20.4 ± 1.3; height: 1.75 ± 0.06 m; mass: 69.2 ± 7.9 kg; area of hand: 0.0161 ± 0.0011 m^2; FINA point: 672.3 ± 25.1), with best performances in the 100-m front crawl between 52.9 and 55.0 s. Test procedures were fully explained to participants before they provided written consent to participate in the study, which was approved by the Ethics Committee of institute (approval number: 3–16).

2.2. Experimental trials

Experiments were conducted in an indoor pool (length: 50.0 m; width: 21.0 m; depth: 2.0 m; water temperature: 27.5 °C). Each swimmer performed 16 m front crawl swimming with maximal effort starting with a push-off start at the wall. To clarify the effects of hand paddles, swimmers swam two trials in randomized order, once using only their hands (hand trials) and once aided by hand paddles on both hands (paddle trials). In both trials, swimmers performed only arm strokes while a buoy supported their legs. In paddle trials, plastic resin hand paddles were used (surface area: 0.0336 m^2; longitudinal: 0.21 m; width: 0.20 m; thickness: 3.0 mm).

2.3. Experimental design

In both trials, reflective markers were attached to each hip, and five markers were attached to landmark points on the right hand. Elastic medical tape made of cotton and strong magnets was used for attaching reflective markers. Positions of markers were determined according to previous studies (Gourgoulis et al., 2008; Monnet, Samson, Bernard, David, & Lacouture, 2014). In hand trials, five reflective markers on the right hand were attached on the tip of the third finger, the second (M2) and fifth (M5) metacarpophalangeal joints, the radial styloid and the ulnar styloid. In paddle trials, five reflective markers were attached at the five edge points of hand paddles (Fig. 1). A Qualisys motion capture system composed of 15 underwater cameras (Qualisys Opus Underwater, Qualisys, Sweden) was used. The markers reflected the light of the LEDs, so it could be captured by the CCD sensors of cameras. The 3D coordinates of markers were recorded with software for motion capture (Qualisys Track Manager, Qualisys, Sweden) at a frame rate of 200 Hz. In the present study, the horizontal direction was defined as the X axis, the swimming direction as the Y axis and the vertical direction as the Z axis; the measurement volume was 2.0 m in the X axis, 7.0 m in the Y axis, and 2.0 m in the Z axis. The measurement volume in the Y axis was set from 8.0 m to 15.0 m from the wall. For calibration of motion capture, a carbon fiber rod with reflective markers on both ends was moved underwater, and the distance between markers was analyzed. Using the ruler, the distance between the reflective markers attached to both ends was measured before calibration. Calibration confirmed that accuracy