A STUDY OF FLUID FORCES ACTING ON A FOOT DURING EGGBEATER KICKS OF WATER POLO PLAYERS

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The purpose of this study was to estimate fluid forces acting on a foot during eggbeater kicks of water polo players by the pressure-distribution-measuring method. Six male water polo players performed eggbeater kicks. Four pairs of pressure sensors were attached to the dominant foot to measure pressure distribution. Fluid-force vectors were calculated. The eggbeater kick cycles were divided into three phases (i.e. out-, in- and up-kick phase) based on the knee joint angle and the displacement of the ankle. Maximum values and mean values of the propulsive component of fluid forces were 165.4 ± 24.6 N and 38.2 ± 4.6 N (mean ± SD). Moreover, it was established that a swimmer mainly produces propulsive forces during out-kick and in-kick phases.

KEY WORDS: fluid dynamics, floating technique, pressure-distribution, 3D DLT method, dynamic pressure, propulsive force

INTRODUCTION: The eggbeater kick is a technique to produce upward propulsive forces. It consists of alternating circular rotations of the lower limbs (Homma and Homma, 2005; Sanders, 1999b). In water polo, force production by the eggbeater kick directly contributes to performance. For example, the eggbeater kick has an important role during physical contact in the game to stabilize the body in the water. Moreover, elevating the body by the eggbeater kick assists performance in shooting and blocking the shot. Therefore, it is very important to improve force production by the eggbeater kick for water polo players. However, few studies have investigated the mechanism of fluid force generation during the eggbeater kick.
In order to investigate propulsive forces produced by the eggbeater kick, the pressure-distribution-measuring method is useful. In recent years, the pressure-distribution-measuring method has been used to estimate the fluid force in competitive swimming in several studies (Takagi et al., 2014; Tsunokawa et al., 2012; 2015b). For this method, fluid force is estimated by measuring pressure distribution using pressure sensors attached to body segments because fluid force is reflected in the pressure distribution on the surface of the body segments. Tsunokawa et al. (2012; 2015b) investigated the fluid forces acting on a foot during breaststroke kicks by means of this method and reported that the fluid force analysis was an effective technique to evaluate the propulsive mechanism during swimming. Given that the eggbeater kick resembles the breaststroke kick in terms of its motion, to investigate the fluid force during the eggbeater kick by the pressure-distribution-measuring method is also effective to evaluate the propulsive mechanism of the eggbeater kick. Therefore, the purpose of this study was to estimate fluid forces acting on a foot during the eggbeater kick by the pressure-distribution-measuring method.

METHODS: Six male collegiate water polo players (age: 19.8 ± 1.7 years, body height: 1.75 ± 0.039 m, body weight: 77.8 ± 5.6 kg) performed eggbeater kicks. During the tests, swimmers were instructed to keep their suprasternal notch above the water without any arm strokes.
In the present study, the foot was divided into four segments in accordance with previous studies (Tsunokawa et al., 2012; 2015a; 2015b) (Figure 1). Four pairs of pressure sensors (PS05-KC, Kyowa Electronic Instruments Co. Ltd., Japan) were attached to each segment on the dorsal and plantar surfaces of dominant foot to measure pressure distributions (Figure 1). Moreover, nine anatomical landmarks of the body (great trochanter [left, right], knee joint [inside, outside], ankle joint [inside, outside], first toe, fifth toe, heel) were marked by LED lights and black tape (Figure 2). Swimmer's eggbeater kick motions performed in a pre-calibrated area were recorded by three video cameras.

Three-dimensional (3D) coordinates of each body landmark were obtained by the 3D direct linear transformation (DLT) method, and linear and angular kinematics were calculated. In the present study, one cycle of eggbeater kick motion was divided into three phases (i.e. out-, in- and up-kick phase) based on the knee joint angle and the displacement of the ankle (Figure 3). Dynamic pressures were calculated as pressure differences between dorsal and plantar sides. Fluid forces acting on each segment were calculated by multiplying the dynamic pressures by the projection area of each segment. Moreover, the fluid forces acting on the foot were obtained by summing the forces estimated at each segment, and X, Y and Z components of the fluid force vector were calculated (Tsunokawa et al., 2012; 2015a; 2015b). The Z (vertical) component of the forces was defined as the propulsive force during the eggbeater kick.

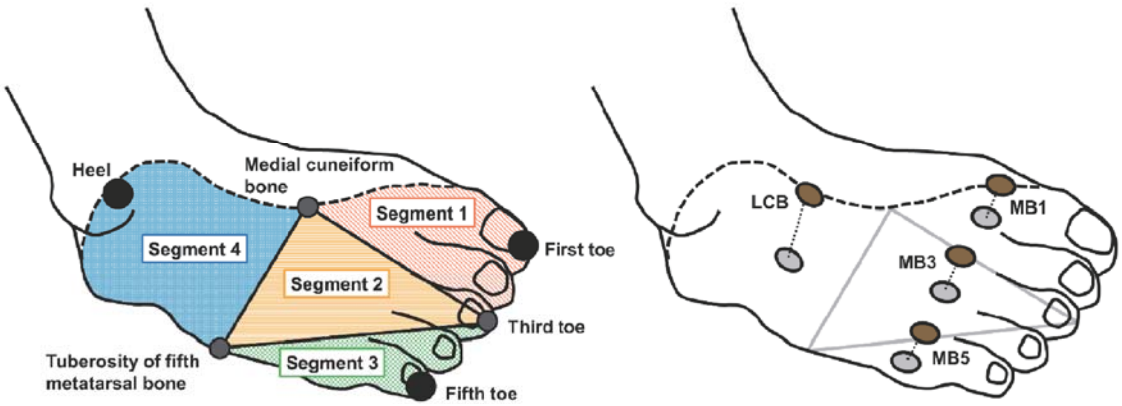

Figure 1: Construction of the foot, showing the four segments, and the points where pressure sensors were attached (the head of first metatarsal bone [MB1], the head of third metatarsal bone [MB3], the head of fifth metatarsal bone [MB5], and the base of lateral cuneiform bone [LCB]).

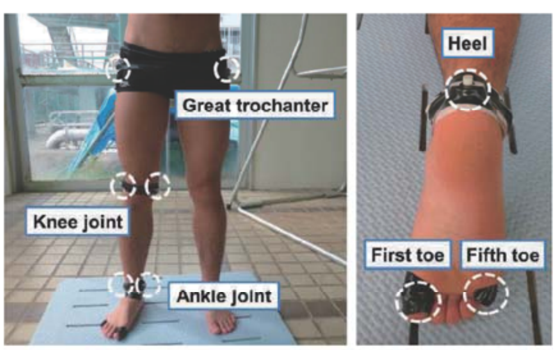

Figure 2: Nine anatomical landmarks of the body.

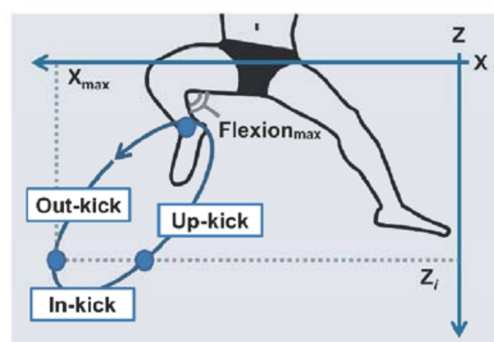

Figure 3: Three phases of the eggbeater kick.

RESULTS AND DISCUSSION: Maximum and mean values of the propulsive forces during the eggbeater kick are shown in Table 1. Maximum values and mean values of the propulsive forces were 165.4 ± 24.6 N and 38.2 ± 4.6 N (mean ± SD), respectively. Those values were higher than the values of the breaststroke kick (maximum values were 159.5 ± 66.1 N, and mean values were 30.3 ± 15.3 N) from the previous study (Tsunokawa et al., 2012). Moreover, it was established that the swimmer produces propulsive forces mainly during the out-kick phase and in-kick phase. This results confirmed the explanation of the previous studies hydrodynamically (Homma and Homma, 2005; Oliveira et al., 2010; Sanders, 1999a; 1999b). A change in the propulsive force during the eggbeater kick is shown in Figure 4. The propulsive force increased at the end of the out-kick phase, and this phase corresponds to the down-kick motion (Figure 5) of the subjects. This suggests that the down kick motion is important to produce propulsive force during the eggbeater kick. On the other hand, propulsive forces decreased over time during the in-kick phase. However, the mean value of the force during this phase was still higher than other phases. This result may be due to sculling-like motion (Figure 5) of the foot during the in-kick phase. Sculling motion is a hand stroke technique to produce lift forces consisting of outward and inward motion. This motion is also important to produce propulsive force during the eggbeater kick.

Table 1: Maximum values and mean values of the propulsive forces of each phase.

	Entire kick	Out-kick	In-kick	Up-kick
Maximum (N)	165.4 ± 24.6	164.2 ± 22.8	151.9 ± 28.9	47.7 ± 7.4
Mean (N)	38.2 ± 4.6	49.9 ± 12.9	91.6 ± 19.0	9.1 ± 2.7

Values are expressed as mean ± SD (n = 6)

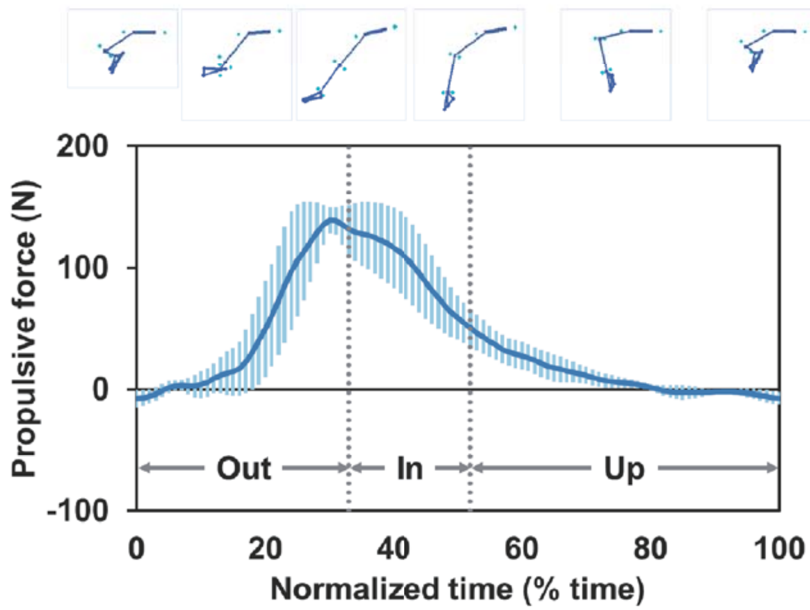

Figure 4: A change in the propulsive force during the eggbeater kick. Line is expressed as mean ± SD (n=6).

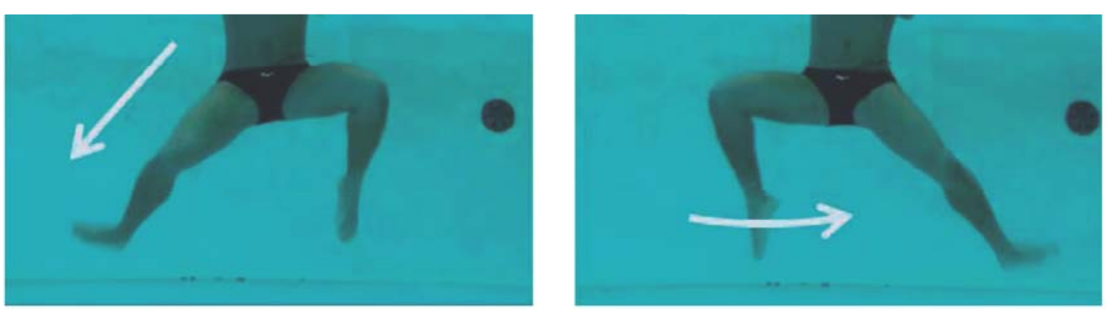

Figure 5: Down-kick motion (left picture) and sculling-like motion (right picture).

CONCLUSION: It was concluded that maximum values and mean values of the propulsive forces were 165.4 ± 24.6 N and 38.2 ± 4.6 N, and a swimmer mainly produces propulsive forces during the out-kick and in-kick phases. This was the first study in which the propulsive force during the eggbeater kick was quantified from pressure distribution. It is considered that this method will be helpful for future studies.

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