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Estimating the hydrodynamic forces during eggbeater kicking by pressure distribution analysis

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Abstract

This study investigates the reliability and validity of the estimation of the hydrodynamic forces during eggbeater kicking (a water-treading technique) by pressure distribution analysis (PDA). Our PDA procedure is very similar to that used in a previous study concerning breaststroke kicking (Tsunokawa et al., 2015). In this method, the force estimation is limited to a particular part of the body. However, unlike previous analyses, the PDA method obtains dynamic fluid forces under unsteady flow conditions without requiring cumbersome motion analysis in water. Twelve participants completed the eggbeater kicking activity under four load conditions (0, 1, 2 and 3 weights), and the hydrodynamic forces acting on their right foot are detected by the pressure sensors. To confirm the reliability of our PDA using successive tests, five participants are additionally made to complete the activity under a no-load condition. Further, the PDA is validated in a linear regression analysis of the mean resultant force calculated using the PDA method versus the applied vertical load. The reliability evaluation yields a high degree of coincidence ($r = 0.99$) and a mean effort of 4.1%. In the validity test, the net vertical loads are

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significantly correlated with the estimated forces [coefficient of determination (r^2 = 0.91−1.00)]. Therefore, the PDA method is a reliable and valid estimator of eggbeater kicking.

Keywords: Mechanics, Mechanical engineering

1. Introduction

Eggbeater kicking, a water-treading technique, is commonly used in water polo, synchronised swimming and lifesaving. The eggbeater kick is a very specific movement in which both legs have to be turned in opposing circular motions. Owing to its relative rarity, the eggbeater kick has been rarely investigated in biomechanical (i.e. kinematic or kinetic) studies; further, studies referring to the hydrodynamic forces that are generated during eggbeater kicking are particularly sparse. This is owing to the difficulty in estimating the force, which is caused by the unsteadiness of water as it is a fluid [i.e. motion-generated vortices (Takagi et al., 2014) and added mass, which is the water's mass that is simultaneously accelerated with the lower limbs (Ungerechts and Arellano, 2011)]. Amongst the few existing studies, Oliveira et al. (2015) estimated the vertical force produced by an eggbeater kick used in water polo through motion analysis. They applied inverse dynamics to the independent lower body segments and combined the upper body segments. However, this method neglects the effect of the abovementioned unsteadiness of water. Moreover, Oliveira et al. (2015) did not verify the absolute value of the vertical force. In other studies, Nakashima et al. (2014) and Nakashima et al. (2015) have investigated the hydrodynamic forces that are mainly generated by the lower limbs' motion (including eggbeater kicking) when a water polo player performs a shooting motion. They computed the forces using an original numerical model SWUM (SWimming hUman Model) which allows the simulation of human motion in water (Nakashima et al., 2007). However, they did not compare their theoretical values with the measured values. Based on these studies, to estimate the hydrodynamic forces during the eggbeater kick, a validated force estimation method that considers the water's unsteadiness is required.

If the hydrodynamic forces can be measured precisely and directly, the information thus obtained would assist the swimmers and polo players to perfect their eggbeater kicks. However, a verified methodology to estimate the hydrodynamic forces generated during eggbeater kicking has so far been lacking. The pressure distribution analysis (PDA) method (Tsunokawa et al., 2015), which estimates hydrodynamic forces from the pressures obtained by small waterproof sensors, is potentially applicable to eggbeater kick measurements. In this method, force estimation is limited to a particular part of the body. However, unlike previous analyses, the PDA method obtains dynamic fluid forces under unsteady flow conditions without requiring cumbersome motion analysis in the water. This method has been validated in breaststroke kicking

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by a robotic leg (Tsunokawa et al., 2015), wherein the force estimated by the PDA method applied to the robotic leg was compared with the force measured by the load cell integrated in the robotic leg, and the reliability and validity were confirmed through these relationships. However, the PDA method has not been tested in terms of eggbeater kicking.

Therefore, the current study investigates the reliability and validity of estimating the hydrodynamic forces that are generated during eggbeater kicking by the PDA method. The limitations and applications of the method are also discussed.

2. Methods

2.1. Preconditions and hypothesis

To accomplish the purpose of this study, we fixed several preconditions and assumptions. Tsunokawa et al. (2015) acquired the hydrodynamic force on the foot of a robotic leg which has five degrees-of-freedom during a breaststroke kick under complete computer control and compared it to the force that was estimated using the PDA method. This approach is highly reliable. However, the motion of an eggbeater kick contains a very complex combination of hip, knee and ankle motions (Homma and Homma, 2005; Oliveira et al., 2015; Sanders, 1999), which is too complicated to reproduce using a robotic leg with respect to the degree of freedom of motion. Hence, we recruited real water polo players.

We interrelated several forces acting on the body during an eggbeater kick (see Fig. 1). Gravity (G) and buoyant forces (B) act vertically downward and upward on the player's body, respectively. By alternating the motions of their right and left legs, polo players maintain a certain body position above the water surface. To this end, the players must exert a vertically upward force that compensates the differential between the gravity and buoyancy forces (where gravity supersedes the buoyancy). Assuming that the hydrodynamic force generated by each leg is mainly produced by the foot part, the resultant force vector acting on a player ($\boldsymbol{ResF_{foot}}$) is the sum of the forces exerted by the right and left foot ($\boldsymbol{RF_{foot}}$ and $\boldsymbol{LF_{foot}}$). Under these preconditions, the resultant force and its absolute value ($|\boldsymbol{ResF_{foot}}|$) are respectively given by Eqs. (1) and (2) (see Fig. 1).

$$\boldsymbol{ResF_{foot}} = \boldsymbol{RF_{foot}} + \boldsymbol{LF_{foot}} \tag{1}$$

$$|\boldsymbol{ResF_{foot}}| + B = G \tag{2}$$

In the ideal situation, the correctness of $|\boldsymbol{ResF_{foot}}|$ should be directly assessed. However, the true hydrodynamic force generated during an eggbeater kick cannot be

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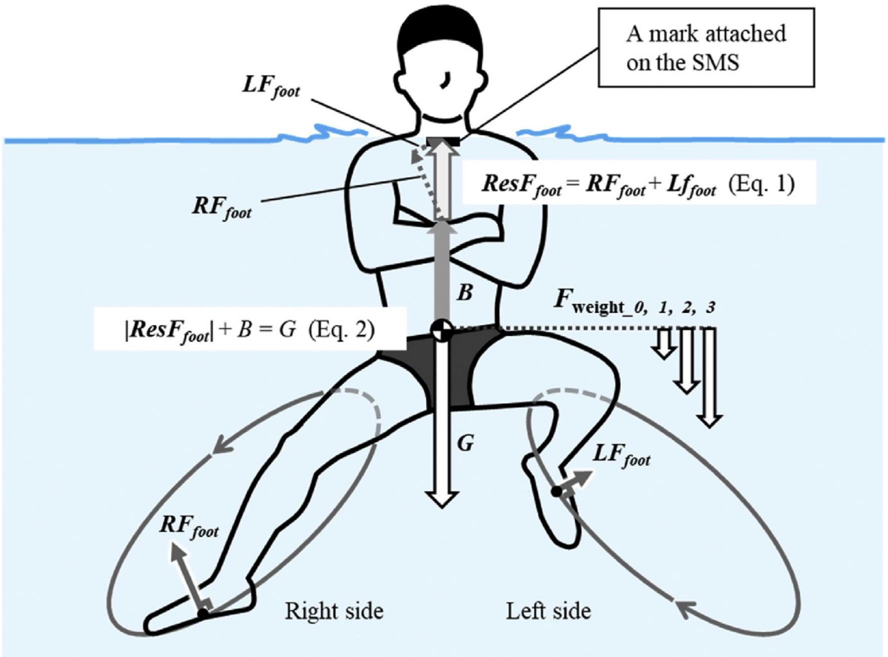

Fig. 1. Interrelations amongst the forces acting on the body during an eggbeater kick. Notes, G: gravity force; B: buoyant force; RF_{foot}: vector of hydrodynamic force produced by a right foot; LF_{foot}: vector of hydrodynamic force produced by a left foot; $ResF_{foot}$: vector of resultant hydrodynamic force; $|ResF_{foot}|$: mean absolute resultant hydrodynamic force; F_{weight_n}: net load of n of weights considering buoyancy; SMS: superior margin of the sternum.

known. Hence, we investigated the effect of vertical load increments on $|\boldsymbol{ResF_{foot}}|$. If a significant linear relationship is confirmed between the net-load and $|\boldsymbol{ResF_{foot}}|$, then $|\boldsymbol{ResF_{foot}}|$ is thought to correctly capture the actual hydrodynamic force during an eggbeater kick (Hypothesis 1). However, as only the hydrodynamic force of the right foot ($\boldsymbol{RF_{foot}}$) could be obtained by our measurement devices, but an equivalent hydrodynamic force is expected on the left foot, the expected slope of the regression line is approximately 0.5 (Hypothesis 2).

2.2. Participants

The study subjects were twelve Japanese first-division national-level male university water polo players. The age, physical characteristics and net vertical loads (*NVL*s) of the participants are listed in Table 1. The participants were experts in performing the eggbeater kick with more than seven years of competitive experience. Each participant received an oral explanation of the potential risks and benefits of the study and gave written informed consent to participate. The study was approved by the University of Tsukuba research ethics committee.

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Table 1. Ages, physical characteristics and *NVL*s of the study participants. Notes, *NVL*: net vertical load taking account of the buoyancy in the water when each participant keeps a certain position (superior margin of the sternum above the water surface).

Participant (n = 12)	Age (years)	Height (m)	Weight (kg)	*NVL* (N)
A	20	1.71	77.50	61.80
B	22	1.69	77.20	66.82
C	19	1.75	72.90	62.15
D	22	1.78	80.00	53.19
E	19	1.80	88.20	76.17
F	21	1.77	70.80	65.60
G	22	1.80	88.80	72.77
H	21	1.74	71.00	66.43
I	20	1.77	75.30	74.68
J	20	1.69	64.20	67.37
K	21	1.75	62.70	65.83
L	22	1.71	77.70	54.54
Mean	20.75	1.75	75.53	65.61
SD	1.09	0.04	7.70	6.79

2.3. Experimental settings and protocol

The experiment was performed in a 50-m indoor pool (maximum water depth 3.8 m). First, to determine the *NVL*s of each participant in the water, a mark was attached at the superior margin of the sternum, and the participants maintained the position at which the mark corresponded to the water surface (see Fig. 2). As each participant held their maximal inspiratory level, the *NVL*s were measured using a digital force gauge (FGPX-100, Nidec-Shimpo Corporation, Japan) with a sampling frequency of 100 Hz.

Subsequently, the participants were asked to maintain the same condition as that in the *NVL* measurement while performing the eggbeater kick for 10 s. To estimate the hydrodynamic force during the eggbeater kick, eight pressure sensors [PS-05KC (rated capacity: 50 kPa; rated output: 0.25 mV/V or higher), Kyowa Electronic Instruments Co. Ltd., Japan] were attached using double-sided tape to the dorsal and plantar sides of each participant's right foot (Fig. 3). The actual errors of the measurement by the pressure sensors in water, i.e. the difference between the measured and theoretical hydrostatic pressure, was less than 2.5%. Measurements were recorded under four load conditions (see Fig. 4). First, each participant crossed his arms across his chest and maintained a steady level while eggbeater kicking (no-

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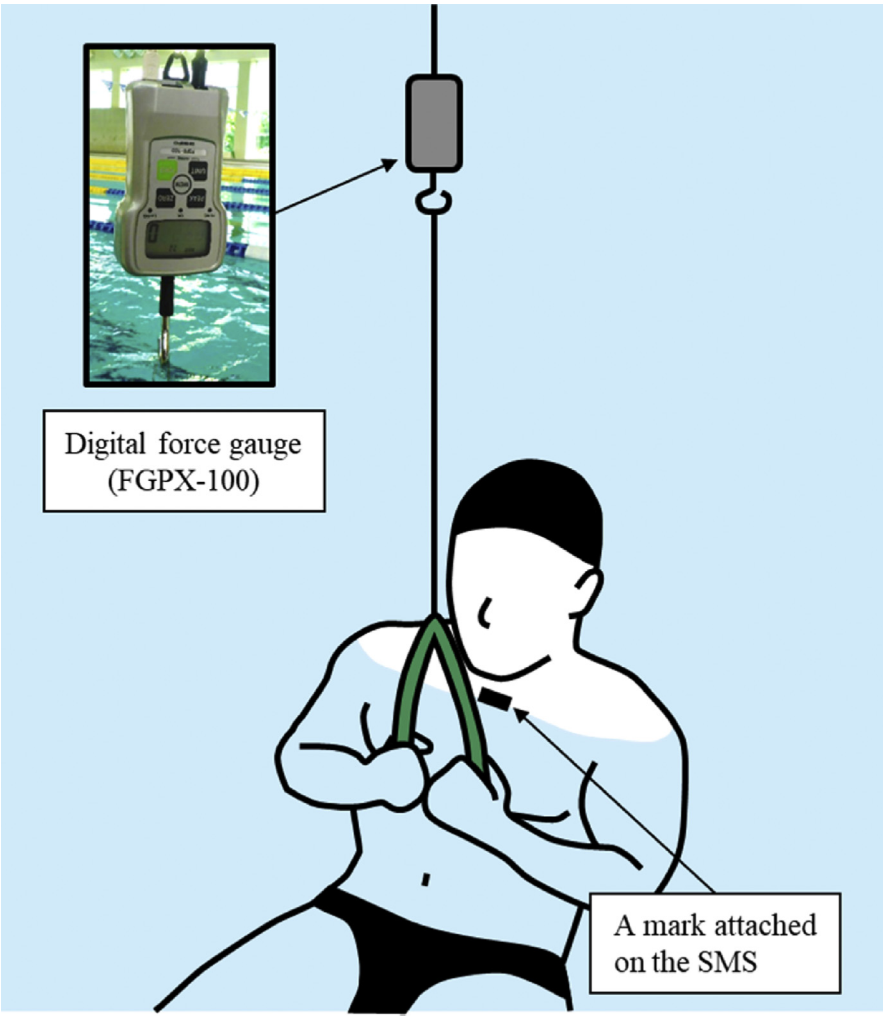

Fig. 2. Measurement system for determining the net vertical load when the participant maintains a certain position (superior margin of the sternum) above the water surface.

weight condition, i.e. F_{weight_0}). The pressure data measured by the pressure sensors were recorded on a laptop with a sampling frequency of 200 Hz via a sensor interface (PDC-330B-F, Kyowa Electronic Instruments Co. Ltd., Japan), and then filtered using a low-pass Butterworth filter with a 10 Hz cut-off frequency in accordance with a previous study (Tsunokawa et al., 2015). After a sufficient period rest, the participants repeated this activity under an additional vertical load (F_{weight_1}), namely, a weight (mass: 2 kg; cubic volume: 150 cm^3; net-load: 18.1 N) attached to a belt around his waist (see Fig. 4). Next, the number of weights was increased to two and three, and the participants attempted the same task under additional vertical loads F_{weight_2} and F_{weight_3}. For each participant, we obtained four sets of pressure data under four net-load conditions (with 0, 1, 2 and 3 weights). The pressure data that remained stable for 5 s were clipped and used for further analysis. Moreover, to

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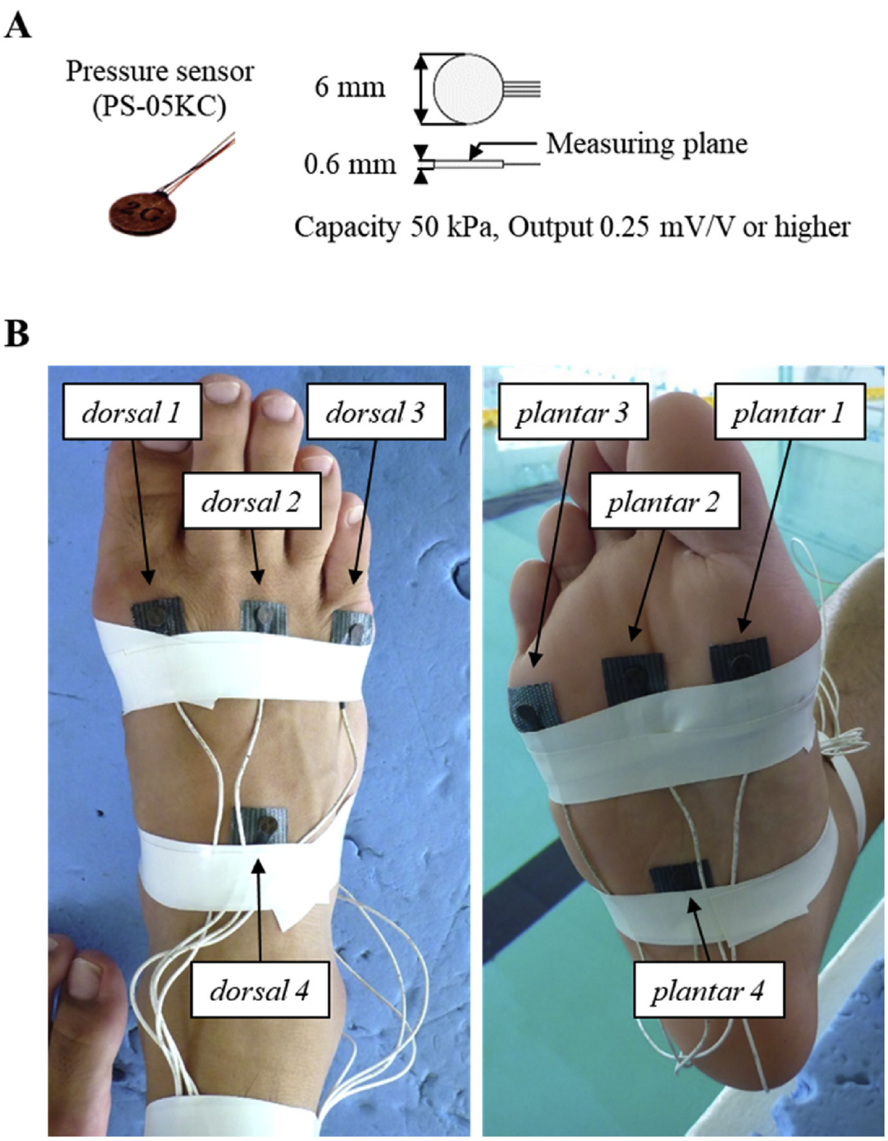

Fig. 3. (A) Pressure sensor and (B) positions affixed with pressure sensors.

evaluate the reliability of this methodology, we conducted a repeated the test with five participants under the no-weight condition after the main experiment.

2.4. Estimation of hydrodynamic force via pressure distribution analysis

The PDA method was almost unchanged from the PDA described in a previous study (Tsunokawa et al., 2015). In this study, the foot was divided into four segments based on six anatomical foot landmarks, as shown in Fig. 5. The dorsal and plantar sides of each segment were fitted with four pairs of pressure sensors (one pair per segment). Sample raw pressure data on the dorsal and plantar sides of each segment

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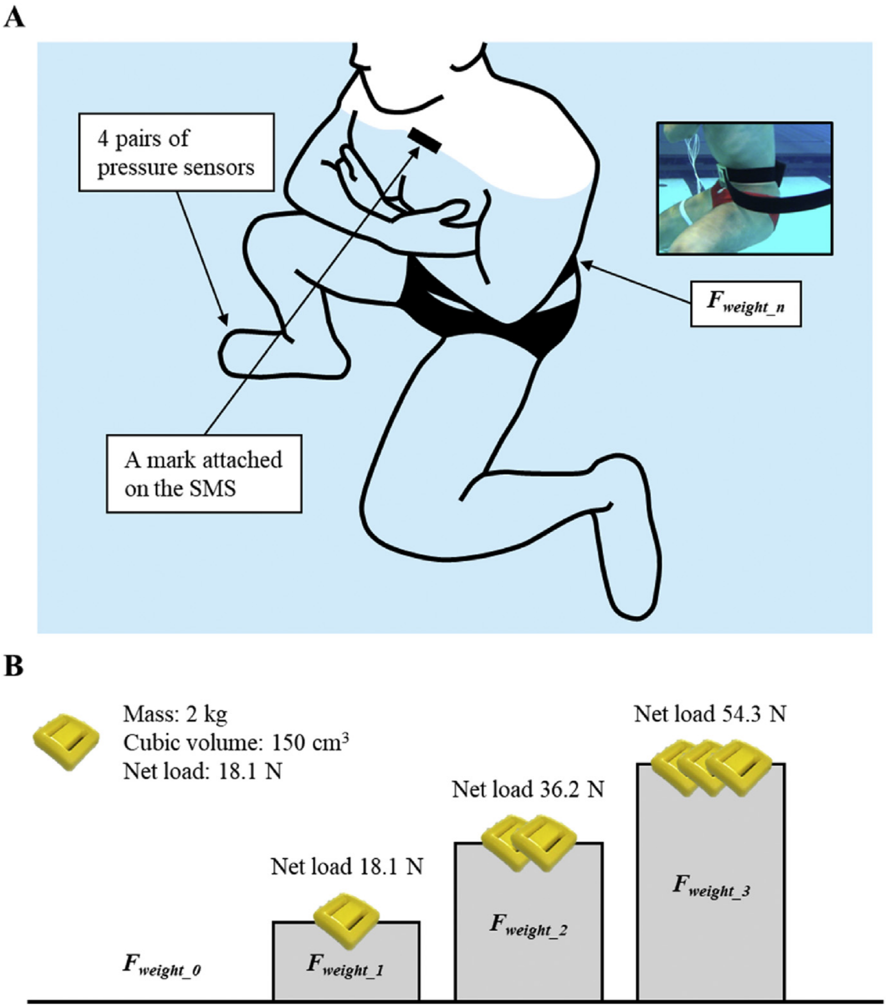

Fig. 4. (A) Experimental settings and (B) protocol.

(P_{dorsal_i} and $P_{plantar\_i}$, $i = 1{-}4$) are shown in Fig. 6. The hydrodynamic pressure was calculated as the pressure difference between the dorsal and plantar sides (P_{differ_i}, $i = 1{-}4$) (Eq. (3)). These calculated pressure differences were assumed as the pressure differences across the segments. The pressure-difference calculation required the angles between the pairs of pressure sensors. These angles were obtained by measuring the angles (θ_i) at the sagittal plane between the dorsal and plantar sides of the foot model in the standing position (Fig. 5).

$$P_{differ\_i} = P_{plantar\_i} - \boldsymbol{Cos}\ \theta_i\ P_{dorsal\_i} \tag{3}$$

Multiplying the pressure difference by the area of each segment (S_i, $i = 1{-}4$), we obtained the fluid forces acting on each segment ($F_{segment\_i}$, $i = 1{-}4$) (Eq. (4)).

$$F_{segment\_i} = S_i \times P_{differ\_i} \tag{4}$$

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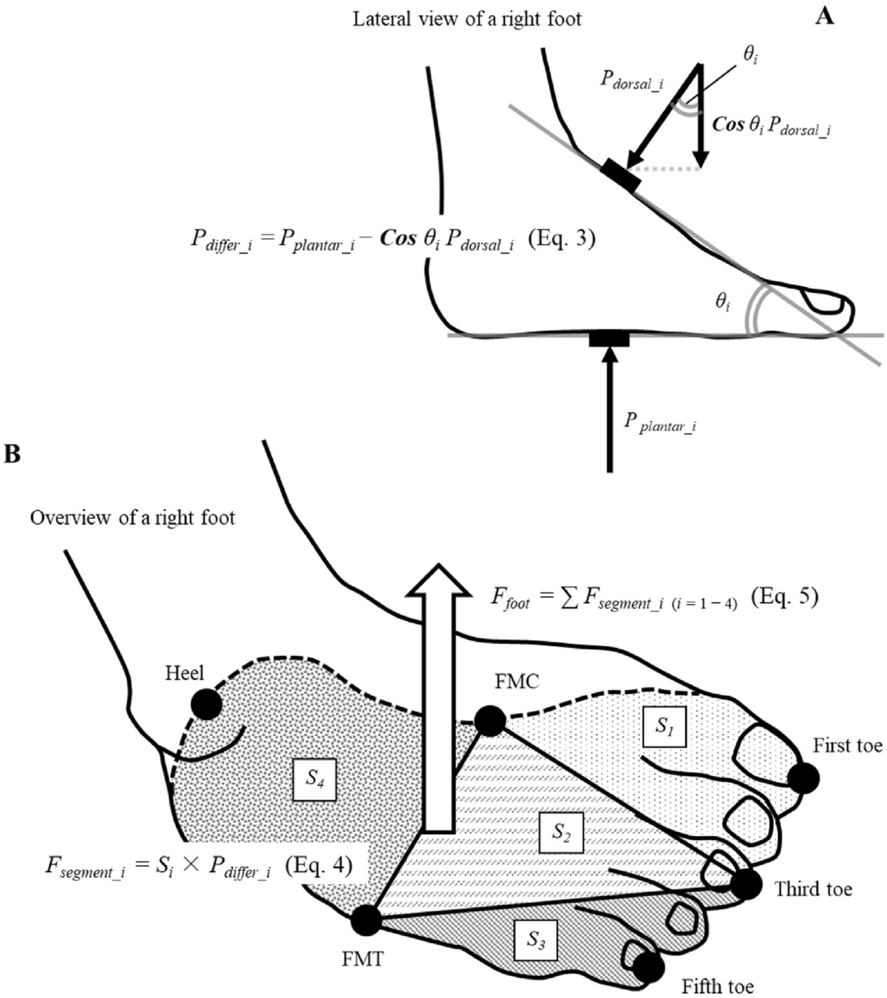

Fig. 5. Procedures of pressure distribution analysis. (A) Lateral view of a right foot. (B) Overview of a right foot. Notes, FMT: foot metatarsus-tuberosity of fifth metatarsal bone; FMC: foot medial cuneiform bone; P_{dorsal_i}: *i*th pressure value on the dorsal side of a foot; $P_{plantar\_i}$: *i*th pressure value on the plantar side of a foot; P_{differ_i}: *i*th pressure differential value between the plantar and dorsal side of a foot; S_i: *i*th segment's area; $F_{segment\_i}$: hydrodynamic force acting on *i*th segment; F_{foot}: Summation of $F_{segment\_i}$ from $i = 1$ to 4.

The fluid forces acting across the entire foot (F_{foot}) were obtained by summing the forces calculated on each segment (Eq. (5)). Fig. 7 shows sample raw data of the fluctuations in the calculated hydrodynamic force.

$$F_{foot} = \Sigma\ F_{segment\_i\ (i\ =\ 1-4)} \tag{5}$$

The expected representative force under each experimental condition is the time average of F_{foot}. However, as only the F_{foot} of the right foot was obtainable in this

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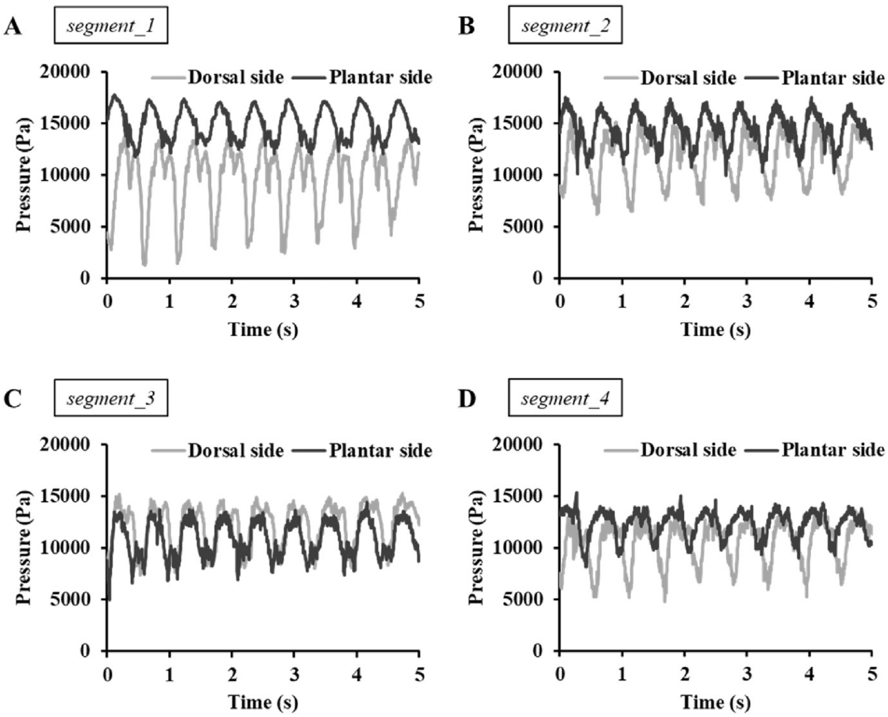

Fig. 6. Sampled raw pressure data on the dorsal and plantar sides (P_{dorsal_i} and $P_{plantar\_i}$) of the four foot segments. (A) P_{dorsal_1} and $P_{plantar\_1}$. (B) P_{dorsal_2} and $P_{plantar\_2}$. (C) P_{dorsal_3} and $P_{plantar\_3}$. (D) P_{dorsal_4} and $P_{plantar\_4}$.

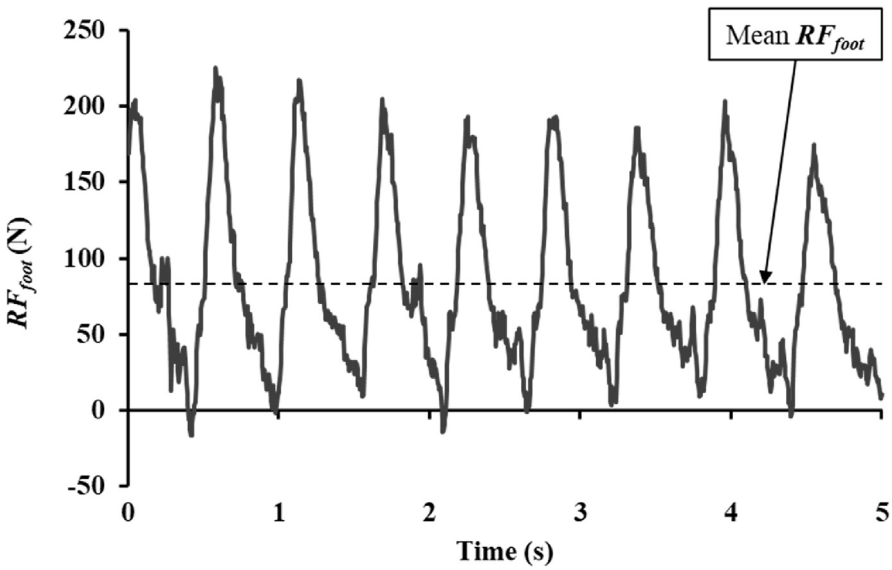

Fig. 7. Sampled raw data of the estimated resultant hydrodynamic forces generated by the right foot.

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study, we computed the time average of $\boldsymbol{RF_{foot}}$ (Mean $\boldsymbol{RF_{foot}}$) as the representative value (Fig. 7).

2.5. Statistical analysis

The test-retest reliability of the mean $\boldsymbol{RF_{foot}}$ was assessed on the five participants who undertook the main experiment as well as the retest. To validate the methodology, the net vertical loads and mean $\boldsymbol{RF_{foot}}$ values of the twelve participants were assigned as the independent and dependent variables, respectively, and subjected to a simple linear regression analysis. The statistical analyses were conducted in IBM SPSS Statistics 22 for Windows at the $p < 0.05$ significance level.

3. Results & discussion

3.1. Reliability and validity of pressure distribution analysis

The degree of coincidence in the test-retest reliability was considerably high ($r = 0.99$) and the mean effort was 4.1%, confirming the reliability of the PDA method during eggbeater kicking. The results of the participant-by-participant simple linear regression analysis are shown in Table 2. For all participants, the mean resultant force was significantly correlated with the applied load, with coefficients of determination (r^2) ranging from 0.91 from 1.00 (mean = 0.97). Thereby, a significant linear relationship was confirmed between the net-load and the hydrodynamic force

Table 2. Linear regression results of each participant. Notes, a: slope; b: intercept; r^2: determination coefficient; p: probability value.

Participant	a	b	r^2	p
A	0.47	20.85	0.96	0.02
B	0.53	43.81	0.91	0.04
C	0.57	39.86	0.96	0.02
D	0.56	60.12	0.98	0.01
E	0.51	43.13	0.98	0.01
F	0.35	38.57	1.00	0.00
G	0.65	26.57	0.99	0.01
H	0.49	43.58	0.95	0.03
I	0.51	9.70	1.00	0.00
J	0.48	34.97	0.97	0.01
K	0.45	28.14	0.99	0.00
L	0.38	31.05	1.00	0.00
Mean	0.50	35.03	0.97	0.01
SD	0.08	12.45	0.02	0.01

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estimated by the PDA method, confirming that the methodology correctly measured the hydrodynamic forces during eggbeater kicking. Moreover, as the mean slope of the regression line (a) was 0.5 (Table 2), the right foot produced approximately half of $|\boldsymbol{ResF}_{foot}|$. Collectively, these results confirm the reliability and validity of the PDA method during eggbeater kicking.

Moreover, the PDA method reveals the time series of the changing pressure distribution around the foot, which surmises the mechanism of generation of hydrodynamic forces. As shown in Figs. 6 and 7, in almost all segments except segment 3, the pressure differences increased with a decrease in the dorsal side pressure, which is consistent with the increase in resultant hydrodynamic forces. This phenomenon was observed for all participants. It has been reported that in front crawl and sculling motion, unsteady flows with vortices develop on the dorsal side of the hand and reduce the pressure on that side (Matsuuchi et al., 2009; Takagi et al., 2013; Takagi et al., 2014). The decreased pressure on the dorsal side increases the pressure difference between the palm and the dorsal sides, thereby generating non-steady flow-induced effects, which are related to the generation of hydrodynamic forces. In the present study, we confirmed that the pressure decreases on the dorsal side of the foot during the eggbeater kick. Similar to the case of the hand during swimming, the above finding suggests that the decrease in pressure on the dorsal side of the foot generates unsteady hydrodynamic forces. The hydrodynamic mechanisms that decrease the pressure on the dorsal side of the foot should be investigated in future studies.

3.2. Limitations and applications

Although the reliability and validity of the methodology was confirmed, some limitations must be recognised. First, the obtained hydrodynamic force data represent only the force generated by the foot. In reality, the hydrodynamic force exerted during an eggbeater kick will be contributed by the foot, lower leg and thigh; therefore, the estimated hydrodynamic force did not represent the force generated by the whole leg. Moreover, in the present study, only the data of the right foot were measured to acquire the data of many high-level players within a limited period. The methodology must be verified using the data of both feet in the future.

Second, to establish a simpler methodology that is less inconvenient to participants, the hydrodynamic force data was obtained from a minimum number of pressure data (i.e. the pressures on the eight representative points of the foot) in accordance with a previous study (Tsunokawa et al., 2015); however, the actual hydrodynamic force on a surface cannot be calculated using only several points of pressures. Thus, a foot experimental coefficient should be derived in the future, which considers the differences between local and average pressures.

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Third, although the estimated force hypothetically acts perpendicularly to the plane of the foot sole, the 3-dimensional coordinates of the sole plane are unknown in this method; hence, the true direction of the estimated force cannot be determined. Therefore, we must recognise that a larger estimated force does not always act vertically and not necessarily imply an excellent eggbeater kicking skill; rather, it means that the participant exerted a needless large force to maintain his body in the requested position.

Finally, no motion analysis was attempted in this study. By combining the PDA method with a motion analysis, we could obtain useful information for improving athletes' eggbeater kicking skills. In particular, the clarified relations between various kinematic data and hydrodynamic force data would upskill the performances of water-polo players, synchronised swimmers, lifeguards and participants in other water sports.

Declarations

Author contribution statement

Eisuke Kawai, Takaaki Tsunokawa: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Hideki Takagi: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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