Abstract—The objective of this study was to realize the backstroke with the swimming humanoid robot. By realizing the backstroke, the backstroke performance of the robot was assessed regarding the speed and the swimming behavior. The motion for the robot was generated based on the motion of an actual swimmer. However, since the robot did not have sufficient degrees-of-freedom to realize the motion, the actual motion was modified. The motion was investigated by simulation and later by the experiment. In the experiment, the robot successfully realized the backstroke at the stroke cycle 2.3 s with a swimming speed of 0.28 m/s.

Index Terms— Human Swimming, Humanoid Robot, Backstroke.

I. INTRODUCTION

Despite swimming having a long history and high popularity as a sport, the mechanics behind swimming still have not been fully clarified. As the human body was not designed for swimming naturally, it is difficult to understand the phenomenon that occurs in human swimming. From this point of view, many attempts were made to clarify the mechanics behind the swimming. By understanding the swimming mechanics, hopefully, the swimmer’s record could be improved, and the swimmer could swim more efficiently.

There are many experimental methods using human as a subject to learn the mechanics in human swimming. For example, equipping a pressure sensor glove to the swimmer to measure the propulsive forces [1], putting a spring wire on a swimmer to measure the drag [2], or using motion capture system to obtain and analyze the swimming motion [3, 4]. These methods require motion consistency and precision by the subject to have a better understanding of the mechanics. However, many trials were usually needed in this kind of experiment. It might affect the physical fatigue and the psychological stress of the subject. In addition, the joint angle for a human could not be changed arbitrarily.

An alternative method to eliminate the downside of using human as a subject is experiment by using physical models, such as a robot. In the prior researches, physical models that resembled a human arm were created to investigate the fluid forces acting on the arm in various motions and conditions of swimming [5-10]. In another work, a mannequin of a swimmer was used to measure the unsteady fluid force acting on the trunk [11]. One of the advantages of using a physical model instead of a human is that many variables such as joint angle and stroke cycle can be changed arbitrarily. So, the various conditions that were set in the simulation can be reproduced in the experiment to verify the simulation result. Also, the physical models do not have fatigue that a human has. Those advantages give us a better understanding of the swimming mechanics in any targeted motion. However, all example-mentioned physical models either only had a single limb or were immovable. The fluid forces acting on the whole human body during swimming could not be obtained accurately by using such models.

In past studies, the humanoid robots were often utilized for various activities [12, 13] such as investigating human motion on land, e.g., walking and running. Similarly, a humanoid robot also can be used to investigate human motion in the water. At the moment, a humanoid robot that could perform various swimming strokes called SWUMANOID had been developed [14]. The robot was built in the half-scale of a human. The body itself was created by a 3D printer with a human-detail shape. The robot also has 24 degrees-of-freedom (DOF) with 24 actuators installed to realize the complex motion of human swimming. To date, the front crawl [15, 16], the breaststroke [17], and the butterfly stroke [18] have been realized by the robot. However, the backstroke has not yet been realized.

Since the robot will be used as an experimental platform to investigate all the swimming strokes, the robot has to perform all the strokes. Therefore, the present study objectives were to realize the backstroke by the robot and investigate its swimming performance. The preliminary experiment has been conducted in the past [19]. However, the swimming performance of the robot in the previous experiment still can be improved. Therefore, in this study, two backstroke motions were realized by the robot. The first motion was obtained from the kinematics calculation, and the second motion was an improvement of the first motion. Then, the performance of the backstroke was defined by the swimming speed and swimming stability.
II. METHODS

A. Overview of SWUMANOID

A swimming humanoid robot called SWUMANOID was developed to reproduce an actual swimmer with precise motion. For that purpose, the robot had a human shape. The shape of the robot body itself was determined by a three-dimensionally scan of an actual swimmer. The robot had 24 actuated joints and a free joint at the neck to perform precisely such a complex swimming motion. Bluetooth was used to communicate wirelessly between the robot and the controller so that the robot could move freely in the water. The robot shape and its actuator locations are shown in Figure 1. The specification of the robot can be seen in Table 1.

There are some differences between the robot and a human. The robot did not have a wrist joint because of the difficulty to install the actuator due to the small size of the wrist part. Although the range of angle for the wrist joint is smaller than those for the other joints in upper limbs, the effect of neglecting it is unclear. The effect of the wrist joint can be investigated by numerical simulation. However, such an investigation is out of the scope of the present study and will be an important future task. Similar discussions are applied to the trunk joint and the scapular joint since the robot could not perform the rotation (twisting motion) of the trunk and the scapular joint can only perform the flexion/extension motion. A fixer was installed to prevent the leg moving in the yaw-direction since such a motion was not realized in the backstroke. The robot ankle only had one actuator because in swimming, especially in the front crawl and backstroke, the kicking motion can be regarded as 1 DOF motion which corresponds to the flexion-extension motion. The comparison of DOF between the robot and a human is shown in Table 2.

For the sake of convenience, the robot was made half the size of an actual human. Consequently, the density of each part should be kept consistent with the human body. Some of the robot parts had a lighter density than a human due to the design. However, in total, the density of the robot was almost equal to that of an actual human. The parameters of each part are shown in Table 3.

B. Generation of swimming motion

The robot motion was created step by step, from analyzing the human motion to obtain the joint angle and then convert it to the robot actuators. The backstroke motion for the robot was created based on the actual swimmer (henceforth called human motion). The human motion itself has been obtained previously [20]. It was analyzed by using the simulation model “SWUM” [20, 21]. The motion was divided into 18-time steps and contained the joint angles for each of the body segments. The motion defined in SWUM was referred to the local coordinate systems of the model, which is different from the relative coordinate used for the robot. Thus, to realize the backstroke for the robot, forward kinematics was used to calculate the position target and the orientation of each of the body segments in SWUM. Then, from the result of the forward kinematics, the joint angle for each actuator can be obtained by the inverse kinematics. The details were described in the previous research [18]. Once the joint angles of each actuator were determined, they were put into the robot, and the motion was confirmed in a test on land.

---

**Table 1** Specifications of SWUMANOID

| Item           | Specification                  |
|----------------|--------------------------------|
| Size           |                                |
| Height         | 925 mm                         |
| Width          | 270 mm                         |
| Depth          | 119 mm                         |
| Weight         | 7.23 kg                        |
| Actuators      |                                |
| (Dynamixel:    |                                |
| Robotis Corp.) | RX28: 2.5 Nm                   |
|                | MX28: 3.1 Nm                   |
|                | MX64: 7.3 Nm                   |
| DOF            | Total: 24 DOFs                 |
| Arm            | 2 x 6 DOFs                     |
| Waist          | 2 DOFs                         |
| Leg            | 2 x 3 DOFs                     |
| Controller     | OpenCM 9.04e (Robotis Corp.)   |
| Microprocessor | Atmega 2561 (Atmel Corp.)      |
| Battery        | Li-Po 14.8 V 1550 mAh x 2      |
| Communication  | BT-100/110 (Robotis Corp.)     |

**Table 2** Comparison of degrees-of-freedom (DOF) between SWUMANOID and a human

| Joint          | DOF (SWUMANOID) | DOF (Human) |
|----------------|-----------------|-------------|
| Wrist          | 0               | 2           |
| Elbow          | 2               | 2           |
| Shoulder       | 3               | 3           |
| Scapular       | 1               | 3           |
| Waist          | 2               | 3           |
| Hip (Original) | 3               | 3           |
| Hip (Present)  | 2               | 3           |
| Knee           | 1               | 1           |
| Ankle          | 1               | 3           |
Table 3 Parameters of SWUMANOID parts

| Part            | Weight (g) | Volume (cm³) | Specific Gravity |
|-----------------|------------|--------------|-----------------|
| Head & Neck     | 703        | 679          | 1.04            |
| Breast          | 1039       | 1514         | 0.69            |
| Upper arm x 2   | 660        | 579          | 1.14            |
| Elbow x 2       | 256        | 215          | 1.19            |
| Forearm x 2     | 300        | 306          | 0.98            |
| Waist           | 1421       | 1460         | 0.97            |
| Hip             | 456        | 660          | 0.69            |
| Thigh x 2       | 1342       | 1460         | 0.92            |
| Shank x 2       | 954        | 748          | 1.28            |
| Foot x 2        | 106        | 200          | 0.53            |
| Upper body      | 4379       | 4753         | 0.92            |
| Lower body      | 2858       | 3068         | 0.93            |
| **TOTAL**       | **7237**   | **7821**     | **0.93**        |

A preliminary simulation was conducted for the robot motion that was obtained from the inverse-forward kinematic calculation of the human motion. From the simulation, it was found that its swimming performance was not satisfactory. The speed was slow since the hands were going out of the water in the power stroke. It occurred because the trunk rotation was not realized by the robot. It is stated in the other works that the for the trunk rotation is important in backstroke to keep the hands from going out of the water [22-24]. Therefore, based on the result of the preliminary simulation, the arm motion of the robot was modified to accommodate the absence of the trunk rotation joint. The modification was done by decreasing the maximum flexion angle of the elbow (ID 4 in Fig. 1) from 80° to 20° so that the hand could stay underwater during the power stroke. Thus, this modified motion, shown in Fig. 2, was called as Backstroke B.

The second motion shown in Fig. 3, called Backstroke B, was an improvement from Backstroke A on the arm joints. The modifications are explained as follows:

1. Changed the hand’s pronation/supination angle before and during the entry
2. Increased the maximum flexion angle of the elbow
3. Increased the acceleration during the first half of the recovery phase
4. Increased the acceleration of the arms during the push phase

Regarding 1), the hands’ angle was changed to minimize the hands’ angle of attack relative to the water so that the hands enter the water more smoothly. The angles are shown in Figs 2 and 3 as black lines (ID 1) during step No. 0 ~ 3. This modification is also schematically shown in Fig. 5. With regard to 4), during the push phase, the traveled angle of the arm in Backstroke B was made farther than Backstroke A. Comparing to Backstroke A where the arm was adducting from -50° to -5°, the arm for Backstroke B was started adducting from -57°. The value of -57° was chosen since it was the maximum acceleration for the actuator. The angles are shown in Figs. 2 and 3 as red lines (ID 2) during step No. 14 ~ 15. This modification was made to improve the swimming speed of the robot.

C. Experimental method

The experimental setup is schematically shown in Fig. 6. The robot swimming experiment was conducted in a pool with a length of 5 m, a width of 1.5 m and a depth of 0.7 m. Since the robot size was the half of a human, the depth of 0.7 m for the robot corresponds to that of 1.4 m for a human, which is a common depth in swimming pools. Besides, the arm of the robot was stroking just under the water surface in the backstroke. The fluid dynamic interaction will be insignificant between the robot and the floor. Two waterproof cameras (Nikon COOLPIX AW110, 1080p, 30 fps) were used to observe the robot motion from above-water and underwater, respectively. One cameraman recorded the video from above-water, holding the camera by hand, and walking together with the robot in the robot’s swimming direction at speed the same as possible to the robot. Another cameraman operated the underwater camera to shoot the robot from the front. The position of the robot was estimated by using a measuring tape located beside the pool to calculate the swimming speed [15]. The robot was controlled wirelessly using a PC. The stroke cycle of the motions was set to 2.3 seconds, which was the fastest stroke cycle that could be performed by the robot actuators. The motion was repeated for six cycles. Also, the robot swam only once in the experiment.

D. Simulation method

By using SWUM, both of the motions were investigated concerning the swimming performance and the swimming stability of the robot. The simulation was conducted to obtain data such as forces, displacement of the center of gravity (COG), the yaw angle, and etc., that could not be obtained in the experiment. For the simulation, the robot geometry was expressed in the simulation with the truncated elliptic cones. The model is shown in Fig. 7.

III. RESULTS AND DISCUSSION

A. Swimming performance of Backstroke A

The snapshots of Backstroke A in the experiment are shown in Fig. 8. Compared to human motion, Backstroke A showed different behavior in swimming. Even though for Backstroke A in which the maximum flexion angle was only 20° (human flexion angle was around 80° to
90°), it was found that the robot hands were still emerged during its propulsive action (at the time steps 6/18 and 15/18 where splashes of the water were spotted from the robot hands). It was discussed in the other work that the

Fig. 2  The joint angle and the robot posture of Backstroke A. The joint angle of the arm and the leg were represented by the right arm and the leg, respectively. Backstroke A was divided into 18 time steps. The ID numbers for the joints were shown in Fig. 1.
Arm stroke provided 70% of the total propulsive forces in the crawl stroke [25]. It means the flutter kick only provides 30% of the total propulsive forces. Since the backstroke also uses the arm stroke and flutter kick, it was supposed that the primary propulsive force in the backstroke also comes from the arm stroke. Thus, it is important to keep the arm underwater during the power stroke for faster swimming.

The propulsive hand had emerged from the water because of the bad timing of body roll performed by the robot. In the experiment, it seemed that the recovery hand moved too slow so that the robot rotated too much at the end of the pull phase. Hence, the propulsive hand emerged from the water. It seemed that the recovery motion could change the timing when the robot starts to rotate to the other side. Therefore, to keep the propulsive arm underwater, the recovery arm for the robot should be modified. Indeed, this was the reason for the modification 3) in Section II. B.

It was also found that the robot was bouncing during swimming. The bouncing was caused by the hand that pushed the water at the entry. In human motion, instead of pushing, the hand goes into the water like ‘slicing’ the water. If the robot can perform this motion like a human, then the bouncing effect could be reduced. The robot could not realize that kind of motion in Backstroke A because of the inability of the robot to rotate its own body.
as it could not realize the trunk motion described in Section II. A. Thus, the joint angle of arm in Backstroke A was not sufficient to make the hand slicing the water at the entry. This was the reason for modification 1) in Section II. B.

On the other hand, it also could be seen that the robot was yawing in the middle of the power stroke. The body was moved to the right side as the left arm finished half of its propulsion at time step 0 to 3, and vice versa for time step 9 to 12. The reason for the yawing was the bouncing which comes from the absence of the trunk joint to do the body roll. It was noticed that the robot body was going up when it changed direction. During time step 0 to 3, when the robot body was going up, the arm was doing the pull phase, which generated a force. This force moves the robot in a yaw direction because the robot body has slightly emerged from the water. Thus, it reduces the water ability to dampen the force. Therefore, to minimize the yawing, the bouncing should be reduced or solved first.

To summarize Backstroke A, several problems were observed in the experiment, such as the bouncing effect that also made the robot yawing periodically, and the hands were not underwater during the power stroke. These problems were caused by the joint angle of the arm that did not accommodate the lack of the trunk joint. In addition, the swimming speed in the experiment was 0.22±0.025 m/s. If the above-mentioned problems can be solved or reduced, then the swimming speed of the robot could be improved. Therefore, to solve the problem, Backstroke A needed to be improved in the arm motion. By addressing the issues, the swimming performance of the robot in the backstroke was expected to be increased.

### B. Swimming performance of Backstroke B

The snapshots of Backstroke B in the experiment are shown in Figure 9. The swimming performance was significantly improved in Backstroke B. The swimming speed was 0.28±0.025 m/s. The swimming speed of Backstroke B was 27% faster than Backstroke A.

It was observed that the robot arms in Backstroke B could stay underwater during its power stroke. It means that the robot could maintain its body to roll to the propulsive side. It was suggested that the first half of the recovery motion in Backstroke A was too slow for the robot’s stature. By making the arm moves faster at the first half of the recovery motion for Backstroke B, it was confirmed that the robot successfully maintained the body to keep rolled to the propulsive side. With such timing of the recovery arm (refer to Fig. 5), the ability to maintain the roll angle of the robot during swimming was improved.

The swimming stability was also improved in Backstroke B. To prove it, the vertical displacement of COG and the yaw angle were calculated by simulation. From the results, the displacement of COG for
Backstroke B was found to be 30 mm while for Backstroke A was 40 mm. In terms of the yaw angle, the maximum angle for Backstroke B and Backstroke A is 0.7° and 0.8°, respectively. Therefore, in the simulation, it was confirmed that the bouncing and the yawing for Backstroke B were reduced. The bouncing was reduced due to the hand position at the entry. Instead of pushing down the water like Backstroke A, the hand in Backstroke B was positioned to slice the water like the human motion. Since the hands did not push down the water, the bouncing was reduced. On the other hand, the yawing was reduced as the bouncing reduced.

Finally, by increasing the acceleration of the arm in the push phase (the modification 4) in Section II. B), the swimming performance of the robot was improved. In Backstroke A, the traveled angle for the adducting arm in a single step (step No. 14 ~ 15) was 45° (from 50° to 5°) while in Backstroke B, it was 52° (from 57° to 5°). It means that the adducting arm in Backstroke B was moving faster than Backstroke A. The faster the arm moves, the larger the force generated. From the simulation result, it was confirmed that the propulsive forces generated at the push phase of Backstroke A and Backstroke B were 13 N and 24 N, respectively. In summary, by making the arm traveled 16% farther, the propulsive force generated during the push phase in Backstroke B was 85% higher than Backstroke A.

Overall, the modifications 1) ~ 4) in Section II. B for Backstroke B successfully improved the performance of the robot. The hands submerged in the water during the power stroke. The bouncing and the yawing were reduced as well. As a result, the robot was able to swim straight and steadily. It should be noted that the improvement was realized from all of the modifications.

On the other hand, we were intrigued by the fact that the robot could roll its body even though the trunk rotation was not performed. It was stated in the other work that buoyancy is the primary source of body roll in front crawl [26]. The body roll was caused by a couple of forces generated by the submerged and the emerged sides. In this case, the submerged side has buoyancy force while the emerged side has gravity force. However, it is also a backstroke technique to roll the body to avoid shoulder injury and help the arm motion [22-24, 27]. These facts raise a question in producing the body roll in the backstroke whether the human created it with the
help of the waist joint, or it is just coming naturally from buoyancy and gravity force, or both.

C. Robot limitation

There is a limitation for the robot regarding the scaling. Generally, the Reynolds number and the Froude number are used for scaling from the full-size to the model. However, it was difficult for the present robot to adjust these numbers into the same ones as a human. Since the size of the robot basically half of a human, the swimming speed basically should be also half if the stroke cycles of the robot and a human are the same. In this case, the Reynolds number for the robot becomes four times smaller than that for a human. Also, the Froude number for the robot becomes 1.4 ($\sqrt{2}$) times smaller than that for a human. It is an important future task to clarify the effects of these differences.

Regarding the Reynolds number, in the present study, it was $3.2 \times 10^3 \sim 5.9 \times 10^4$ for the robot while it is $1.5 \times 10^4 \sim 4.3 \times 10^5$ for human swimming. It is generally known that in the range of $3.2 \times 10^3 \sim 4.3 \times 10^5$, the characteristic of fluid force does not change significantly according to the change in the Reynolds number [28]. Therefore, it might not become a major problem to apply the fluid force characteristics obtained in the robot experiment to human swimming.

Following the scaling rule, for Backstroke B, the swimming speed of the robot in human-size was supposed to be 0.56 m/s. However, from the simulation, the swimming speed of human with the same motion and stroke cycle as the robot was found to be 1.2 m/s. It means that the swimming speed of the robot was more than two times slower than the human. One possible reason for this discrepancy is the body shape. The body shape of the robot had many gaps, projections, squared edges, and electric wires. These might increase the drag acting on the body.

On the other hand, it is very difficult to realize all DOFs of a human perfectly by the robot. Some compromise is necessary to be made, and the insufficient DOFs of the robot have to be accommodated by some method. In the present study, the accommodation was made empirically (trial and error). However, it should be conducted more systematically in future study. As one systematic method, optimizing calculation will be promising. By an optimizing calculation, it will be possible to obtain the accommodating joint motion of the robot in which the resultant discrepancy from the human motion is minimized. It is also one of the important tasks in the future.

IV. CONCLUSION

The swimming humanoid robot successfully performed two motions, Backstroke A and Backstroke B at stroke cycle 2.3 s. For Backstroke A, the robot could swim at 0.22±0.025 m/s but was not stable in swimming direction. For Backstroke B, the swimming performance of the robot was improved. The robot was able to swim more steadily at 0.28±0.025 m/s (improved 27% than Backstroke A). With this study, all four of the most popular strokes were realized by the robot.

ACKNOWLEDGEMENT

The authors gratefully acknowledge the support from Indonesia Endowment Fund for Education (LPDP) for the present study. This work was supported by JSPS KAKENHI Grant Number JP17H02150.

REFERENCES

[1] H. Takagi and R. H. Sanders, “Measurement of propulsion by the hand during competitive swimming,” The Engineering of Sport, vol. 4, pp. 631-637, 2002.
[2] K. Narita, M. Nakashima and H. Takagi, “Developing a methodology for estimating the drag in front-crawl swimming at various velocities,” Journal of Biomechanics, vol. 54, pp. 123-128, 2017.
[3] T. Monnet, M. Samson, A. Bernard, L. David and P. Lacourt, “Measurement of three-dimensional hand kinematics during swimming with a motion capture system: a feasibility study,” Sports Engineering, vol. 17, no. 3, pp. 171-181, 2014.
[4] F. Ferryanto and M. Nakashima, “Development of a markerless optical motion capture system for daily use of training in swimming,” Sports Engineering, vol. 20, no. 1, pp. 63-72, 2017.
[5] M. A. Lauder and P. Dabnikski, “Estimating propulsive forces sink or swim?,” Journal of Biomechanics, vol. 38, no. 10, pp. 1984-1990, 2005.
[6] S. Kudo, R. Vennell and B. Wilson, “The effect of unsteady flow due to acceleration on hydrodynamic forces acting on the hand in swimming,” Journal of Biomechanics, vol. 46, no. 10, pp. 1697-1704, 2013.
[7] M. Nakashima and A. Takahashi, “Clarification of unsteady fluid forces acting on limbs in swimming using an underwater robot arm: Development of an underwater robot arm and measurement of fluid forces,” Journal of Fluid Science and Technology, vol. 7, no. 1, pp. 100-113, 2012.
[8] M. Nakashima and A. Takahashi, “Clarification of unsteady fluid forces acting on limbs in swimming using an underwater robot arm: (2nd Report, Modeling of fluid force using experimental results),” Journal of Fluid Science and Technology, vol. 7, no. 1, pp. 114-128, 2012.
[9] M. Nakashima and Y. Karako, “Effect of bubbles around an underwater robot arm on thrust during the crawl stroke motion,” Procedia Engineering, vol. 72, pp. 715-719, 2014.
[10] H. Takagi, M. Nakashima, T. Ozaki and K. Matsuuchi, “Unsteady hydrodynamic forces acting on a robotic arm and its flow field: Application to the crawl stroke,” Journal of Biomechanics, vol. 47, no. 6, pp. 1401-1408, 2014.
[11] M. Nakashima and Y. Ejiri, “Measurement and modeling of unsteady fluid force acting on the trunk of a swimmer using a swimmer mannequin robot,” Journal of Fluid Science and Technology, vol. 7, no. 1, pp. 11-24, 2012.
[12] S. Behnke, “Humanoid robots - from fiction to reality?,” KI-Zeitschrift, vol. 22, no. 4, pp. 5-9, 2008.
[13] J. Denny, M. Elyas, S. A. D’costa and R. D. D’Souza, “Humanoid robots – past, present and the future,” European Journal of Advances in Engineering and Technology, vol. 3, no. 5, pp. 8-15, 2016.
[14] C. Chung and M. Nakashima, “Development of a swimming humanoid robot for research of human swimming,” Journal of Aero Aqua Bio-mechanism, vol. 3, no. 1, pp. 109-117, 2013.
[15] C. Chung and M. Nakashima, “Free swimming of the swimming humanoid robot for the crawl stroke,” Journal of Aero Aqua Bio-mechanism, vol. 3, no. 1, pp. 118-126, 2013.
[16] M. Nakashima and Y. Tsunoda, “Improvement of crawl for the swimming humanoid robot,” Procedia Engineering, vol. 112, pp. 517-521, 2015.
[17] M. Nakashima and K. Kuwahara, “Realization and swimming performance of the breaststroke by a swimming humanoid robot,” ROBOMECH Journal, vol. 3, no. 1, pp. 10, 2016.
[18] M. Nakashima and C. L. Tsai, “Realization and swimming performance of the butterfly stroke,” Journal of Aero Aqua Biomechanisms, vol. 6, no. 1, pp. 9-15, 2017.
[19] F. Razi and M. Nakashima, “Preliminary experiment of backstroke by the swimming humanoid robot,” The Proceedings of JSME annual Conference on Robotics and Mechatronics (ROBOMECH), vol. 2018, 2P2-F11, 2018.
[20] M. Nakashima, “Analysis of breast, back and butterfly strokes by the swimming human simulation model SWUM,” In Biomechanisms of Swimming and Flying, pp. 361-372, Springer, Tokyo, 2008.
[21] M. Nakashima, K. Satou and Y. Miura, “Development of swimming human simulation model considering rigid body dynamics and unsteady fluid force for whole body,” Journal of Fluid Science and Technology, vol. 2, no. 1, pp. 56-67, 2007.
[22] C. Colwin, Breakthrough swimming, Champaign, IL: Human Kinetics, Chapter 1, pp. 24-25, 2002.
[23] E. W. Maglischo, Swimming fastest, Champaign, IL: Human Kinetics, pp. 181-218, 2003.
[24] S. A. Heinlein and A. J. Cosgarea, “Biomechanical considerations in the competitive swimmer’s shoulder,” Sports health, vol. 2, no. 6, pp. 519-525, 2010.
[25] P. G. Morouço, D. A. Marinho, M. Izquierdo, H. Neiva and M. C. Marques, “Relative contribution of arms and legs in 30 s fully tethered front crawl swimming,” BioMed Research International, vol. 2015, 2015.
[26] T. Yanai, “Buoyancy is the primary source of generating body roll in front-crawl swimming,” Journal of Biomechanics, vol. 37, no. 5, pp. 605-612, 2004.
[27] S. G. Psycharakis and R. H. Sanders, “Body roll in swimming: A review,” Journal of Sports Science, vol. 28, no. 3, pp. 229-236, 2010.
[28] S.F. Hoerner, Fluid-dynamic drag, Bakersfield, CA: Hoerner Fluid Dynamics, Chapter 3, pp. 1-28, 1965.