Abstract—The objective of this study was to realize the butterfly stroke by the swimming humanoid robot “SWUMANOID”, and to investigate the swimming performance of the robot. The robot was modified from its original condition in order to reduce the weight of the lower body. The swimming motion of the robot was generated based on that of an actual swimmer. By preliminary simulations, it was found that the swimming speed became significantly low when the stroke cycle was 2.0 s. In the experiment, successful propulsion was confirmed for the stroke cycles of 3.45 s. The swimming speed was 0.181 m/s.

Index Terms— Human Swimming, Humanoid robot, Butterfly Stroke.

I. INTRODUCTION

Swimming has long been a popular sport for both recreation and competition. Research on human swimming is also popular in the fields of sports biomechanics and sports medicine. However, its mechanics still have not been fully clarified yet. Among various research on human swimming, one approach is to conduct measurements directly. Various research attempted to measure propulsive forces and drag forces acting on an actual swimmer’s body during swimming [1][2][3]. However, it is difficult to sustain sufficient repeatability of the swimming motion of an actual swimmer. The second approach is to conduct numerical simulations [4][5][6][7][8][9]. Fluid forces are calculated through computational fluid dynamics, or using a fluid force model. Motion can be defined arbitrarily and even optimized in this case [10][11][12]. However, simulation always needs validation and improvement by comparing with experimental results, since it is not an actual phenomenon after all. The third approach is to measure the fluid forces on a physical model [13][14][15][16][17][18]. In this case, it is important whether the physical model reproduces an actual swimmer with high fidelity. As an ultimate physical model with such high fidelity, the swimming humanoid robot “SWUMANOID”, which had detailed human shape and many degrees-of-freedom (DOF) at the joints, was recently developed [19][20]. The free swimming of this robot for the crawl stroke [21] as well as breaststroke [22] has been already realized to date. However, the butterfly stroke and backstroke have remained unrealized.

The objectives of this study were to realize the butterfly stroke by the swimming humanoid robot SWUMANOID, and to investigate the swimming performance of the robot. The present study contributes to the enlargement of the possibility of the swimming humanoid robot. Indeed, developing a swimming humanoid robot is important because it will become an experimental platform for the research of human swimming, and because it can be applied to robots for special tasks accompanying a water environment, such as rescue robots in the sea and working robots around a pool in a nuclear plant.

II. METHODS

A. Overview of SWUMANOID

SWUMANOID is a humanoid robot whose size is half of an actual swimmer. It had originally 24 actuated joints. The location of the actuators and its corresponding motions are shown in Fig. 1. In order to realize the recovery stroke for the crawl and butterfly strokes, which is performed above the water surface, a pair of scapular joints was installed. The comparison of number of DOF between SWUMANOID and a human is shown in Table 1. The robot did not have any DOF at each wrist, because the range of motion at the wrist joint during swimming is generally smaller than the other joints, and because it was difficult to install motors at the wrist due to limitation of space. The robot had only one motor at each ankle joint, since the motion of a foot during swimming was regarded as one DOF motion. The shape of the body case of the robot was determined by three-dimensionally scanning the body of an actual elite swimmer. For waterproofing and easier maintenance, O-rings were used to seal the cases.*

* 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8552 Japan, E-mail: motomu@sc.e.titech.ac.jp
B. Modification for butterfly stroke

In the butterfly stroke, the yaw motion on the hip (ID: 17 in Fig. 1) was not necessary. Therefore, in order to reduce the weight of the lower body, two actuators for the yaw motion were removed. Instead, two fixers were installed on where the actuators were originally located. After the installation of the fixers, the total weight of the robot decreased from 7.4 kg to 7.23 kg. The specific gravity on the thigh decreased from 1.07 to 0.92. Floats were inserted in the hip empty area (a gap between the two thighs and waist) inside the hip cover. In addition, the communication module was changed from Zigbee to Bluetooth for better communication signal quality. As a result of this change, the possibility of communication error in which the robot did not receive start/stop command was decreased. The resultant specifications of SWUMANOID are summarized in Table 2. Segment parameters are shown in Table 3.

C. Generation of swimming motion

The method of swimming motion generation is schematically shown in Fig. 2. First, a video of the actual human swimming motion is analyzed. The motion is divided into step motions and put into the simulation program of SWUM. The program outputs swimming speed, joint torques, animation, and fluid forces acting on the swimmer while performing the joint motion. Once the swimming motion is validated, kinematics to solve the joint angles for the robot actuators can be calculated. The solution for the actuator angles are checked finally in 3D CAD simulation and with a land test before the swimming experiment.

The actual swimming motion for the butterfly stroke was created based on a video of an actual swimmer. This swimming motion was analyzed by using SWUM in the previous study [23], in which it was confirmed that the...
nondimensional swimming speed in the simulation was consistent with the measured one within 0.5% error. Note that the stroke cycle was 1.3 s. The swimming motion was slightly modified from the original one due to the lack of degrees-of-freedom on the trunk joints and ankle joints. The determined joint angles are shown in Fig. 3. Joint numbers in the figure correspond to the motor ID numbers in Fig. 1. Note that the joint angles of the left arm were created symmetrically with those of the right arm.

D. Experimental method

The experiment was conducted in an outdoor pool at the University of Tsukuba. The schematic of the experimental setup is shown in Fig. 4. A measuring tape was attached along the side of the pool in order to measure the swimming speed. The swimming motions of the robot were filmed by two cameras, which were located above the water and underwater, respectively. The robot was controlled wirelessly through a laptop by a Bluetooth module beside the pool.

E. Simulation method

In order to investigate the swimming performance of the robot in advance, preliminary simulations reproducing the experimental situations were conducted by using SWUM. For the simulation, the shape of the robot as well as the specific gravities of the body segments were reproduced. The constructed simulation model of SWUMANOID is shown in Fig. 5. The joint motions shown in Fig. 3 were put into the model. The number of time steps for one stroke cycle was 72. Note that the stroke cycle was defined as the time to perform one swimming stroke. Ten cycles were calculated for each trial in order to obtain the swimming speed after the effect of the initial condition disappeared.

III. RESULTS AND DISCUSSION

A. Results of preliminary simulations

In order to examine the stroke cycle to be conducted in the experiment, preliminary simulations for various stroke cycles were carried out. The results of nondimensional swimming speeds were shown in Fig. 6.
The nondimensional swimming speed was defined as the swimming speed divided by the stature of the robot and multiplied by the stroke cycle, and can be considered as a propulsive distance normalized by the stature during one stroke cycle. First, the blue line represents the results for the simulation model of the original actual swimmer. It was found that the nondimensional swimming speed steeply decreased as the stroke cycle increased. Indeed, for the cases of stroke cycles more than 1.6 s, a stable swimming movement could not be obtained. Animation images at the moment of $t^* = 9.68$ (the beginning of the recovery stroke of the arms) for the four cases of stroke cycles, 0.7, 1.3, 1.5 and 1.6 s are shown in Fig. 7. The symbol $t^*$ represents the nondimensional time normalized by the stroke cycle. It was found that the lower body went down as the stroke cycle increased, and finally the whole body turned upside-down for the case of 1.6 s. Note that the stable swimming movement was obtained for the stroke cycle of 1.3 s, which was the measured value for the actual swimmer.

The red line in Fig. 6 represents the results for the simulation model of the robot before the modification to reduce the weight of the lower body described in Section II.B. It was found that the nondimensional swimming speed decreased steeply according to the increase in the stroke cycle, which was the same as the case of the original actual swimmer. The stable swimming movement could not be obtained in the cases of the stroke cycles that were more than 1.1 s.

The green line in Fig. 6 represents the results for the simulation model of the robot after the modification. The nondimensional swimming speed once decreased according to the increase in the stroke cycle from 0.7 s to 2.0 s. However, from the stroke cycle of 2.0 s, the nondimensional swimming speed steeply increased, and had a wide plateau when the stroke cycle was larger than 2.5 s. The reason for the steep valley at the stroke cycle of 2.0 s was that the recovery stroke of the arms failed when the stroke cycle was 2.0 s, although the robot did not turn upside-down thanks to the modification. The recovery strokes for the stroke cycles of 1.3, 2.0 and 3.5 s at the tenth cycle are shown in Fig. 8. The plane checkered in pale and dark blues represent the water surface. The length of one set of pale and dark blue areas in the propulsive direction represents the propelling distance in one stroke cycle. By this representation, it can be seen that the propelling distance in Fig. 8(b) is much shorter than those in Fig. 8(a) and (c). The red lines emitting from the robot’s body represent the points of application, directions and magnitudes of the fluid forces acting on the robot. As shown in Fig. 8(a), when the stroke cycle was 1.3 s, the recovery stroke basically succeeded although most parts of the upper arms were in the water. However, when the stroke cycle was 2.0 s as shown in Fig. 8(b), the recovery stroke failed, that is, almost the entire arm was in the water. As a result, large negative thrust occurred in this case, resulting in the low swimming speed. When the stroke cycle was 3.5 s as shown in Fig. 8(c), the recovery stroke again succeeded, although some parts of the upper arms were in the water. This phenomenon is considered to be induced by the relationship between the timing of the recovery stroke and the absolute movement of the robot, such as heaving and pitching. The entire robot body moved in the heave and pitch directions according to the underwater stroke by the arms as well as kicks by the legs. As a result of these motions, the depth at the shoulder became deeper when the stroke cycle was 2.0 s. Nondimensional displacement at the shoulder in the vertical direction for the tenth cycle is shown in Fig. 9. Zero in the vertical axis is the height of the water surface. The shaded region ($t^* = 9.75$~9.81) represents the recovery stroke. It was found that the height of the shoulder for the stroke cycle of 2.0 s (the red line) was deeper than that of 1.3 s (the blue line) during the recovery stroke. It was also found that the height for the stroke cycle of 3.5 s (the green line) became much shallower than that of 2.0 s due to increase in buoyancy at the lower body. To conclude, it was found that the stroke cycle of 2.0 s should be avoided.
in the swimming experiment for the robot after the modification.

B. Experimental results

Based on the preliminary investigation by the simulation in the previous section, two trials of fast and slow motions were carried out in the experiment. The stroke cycle of the fast trial was 1.58 s. It was smaller than 2.0 s, which was found to be avoided in the preliminary simulation. The stroke cycle of the slow trial was 3.45 s, which was sufficiently larger than 2.0 s. The results of the swimming speed for the fast trial are shown in Fig. 10. As shown in the figure, the swimming speed in the experiment was much lower than that in the simulation. The average swimming speed of the latter five cycles in the experiment was 0.082 m/s, while that in the simulation was 0.318 m/s. The experimental swimming speed was 74% lower than that in the simulation. This large discrepancy was because the swimming motion in this stroke cycle was too fast for the currently installed motors. Indeed, by a visual confirmation for the recorded video images, it was apparently confirmed that significant phase lags on motor positions caused the swimming motion to differ from expected. This difference resulted in failure of the recovery stroke, which caused a negative thrust preventing the robot from accelerating forward. The photographs of the recovery stroke of the experiment are shown in Fig. 11. It was found that both arms sank in the water at the recovery stroke.

The results of swimming speed for the slow trial are shown in Fig. 12. In this case, the robot successfully accelerated forward and the swimming speed almost reached a certain steady value. The average swimming speed of the latter five cycles was 0.181 m/s. Although this was 12% lower than that in the simulation (0.206 m/s), the discrepancy between the experiment and simulation was significantly smaller than that in the fast trial. The snapshots of the robot for one stroke cycle are shown in Fig. 13. Contrary to Fig. 10, it was found that the recovery stroke (11/18~16/18) succeeded since most of the arms were above the water surface. The photographs of the recovery stroke (1.58 s) are shown in Fig. 11. The photographs of the recovery stroke (3.45 s) are shown in Fig. 12. The photographs of the recovery stroke are shown in Fig. 13.
human. It is difficult to realize such situation by the present robot. Indeed, this is a limitation of this study. However, it will be possible to discuss human swimming by using the present robot while considering the differences in the Reynolds and Froude numbers. This issue should be discussed in detail in the future study.

IV. CONCLUSIONS

The butterfly stroke was realized by a swimming humanoid robot and its swimming performance was investigated in the present study. The swimming motion of the butterfly stroke as joint angles of the robot was generated based on that of an actual swimmer. Preliminary simulations were carried out for the generated swimming motion in order to investigate the relationship between the stroke cycle and swimming speed. As a result of the simulation, it was found that the swimming speed became significantly low when the stroke cycle was 2.0 s. In the experiment, two trials were conducted for the stroke cycles of 1.58 s and 3.45 s, which were faster and slower than the case of 2.0s, respectively. For the fast case, the swimming speed in the experiment was 0.082 m/s, although that in the simulation was 0.318 m/s. For the slow case, successful propulsion was confirmed. The swimming speed in the experiment was 0.181 m/s, while that in the simulation was 0.206 m/s.

As the future task, improvement of the motors and motor driving system has to be performed since currently installed motors could not perform the recovery stroke for the fast trial.

REFERENCES

[1] Hollander, A.P., De Groot, G., van Ingen Schenau, G.J., Toussaint, H.M., De Best, H., Peeters, W., Meulemans, A., and Schreurs, A.W., Measurement of active drag during crawl arm stroke swimming. *Journal of Sports Sciences*, Vol. 4, No. 1, (1986), pp 21-30.

[2] Kolmogorov, S.V. and Duplishcheva, O.A., Active drag, useful mechanical power output and hydrodynamic force coefficient in different swimming strokes at maximal velocity, *Journal of Biomechanics*, Vol. 25, No. 3, (1992), pp 311-318.

[3] Takagi, H. and Sanders, R., Measurement of propulsion by the hand during competitive swimming. In: The Engineering of Sport 4 (Eds. S. Ujihashi and S.J. Haake): Blackwell Publishing, (2002), pp 631-637.

[4] Bixler, B. and Riewald, S., Analysis of a swimmer’s hand and arm in steady flow conditions using computational fluid dynamics, *Journal of Biomechanics*, Vol. 35, (2002), pp 713-717.

[5] Cohen, R.C., Cleary, P.W. and Mason, B., Simulations of dolphin kick swimming using smoothed particle...
[6] Rouboa, A., Silva, A., Leal, L., Rocha, J. and Alves, F., The effect of swimmer’s hand/forearm acceleration on propulsive forces generation using computational fluid dynamics, *Journal of Biomechanics*, Vol. 39, No. 7, (2006), pp.1239-1248.

[7] Sato, Y. and Hino, T., A computational fluid dynamics analysis of hydrodynamic force acting on a swimmer’s hand in a swimming competition, *Journal of Sports Science and Medicine*, Vol. 12, No. 4, (2013), pp.679-689.

[8] von Loebbecke, A., Mittal, R., Mark, R. and Hahn, J., A computational method for analysis of underwater dolphin kick hydrodynamics in human swimming, *Sports Biomechanics*, Vol. 8, No. 1, (2009), pp.60-77.

[9] Nakashima, M., Modeling and simulation of human swimming, *Journal of Aero Aqua Bio-mechanisms*, Vol. 1, No. 1, (2010), pp.11-17.

[10] Nakashima, M., Simulation analysis of the effect of trunk undulation on swimming performance in underwater dolphin kick of human, *Journal of Biomechanical Science and Engineering*, Vol.4, No.1, (2009), pp.94-104.

[11] Nakashima, M., Maeda, S., Miwa, T. and Ichikawa, H., Optimizing simulation of the arm stroke in crawl swimming considering muscle strength characteristics of athlete swimmers, *Journal of Biomechanical Science and Engineering*, Vol. 7, No. 2, (2012), pp.102-117.

[12] Nakashima, M. and Ono, A., Maximum joint torque dependency of the crawl swimming with optimized arm stroke, *Journal of Biomechanical Science and Engineering*, Vol. 9, No.1, (2014), pp.1-9.

[13] Lauder, M.A. and Dabnichki, P., Estimating propulsive forces-sink or swim?, *Journal of Biomechanics*, Vol. 38, No. 10, (2005), pp.1984-1990.

[14] Sidelnik, N.O., and Young, B.W., Optimising the freestyle swimming stroke: the effect of finger spread, *Sports Engineering*, Vol. 9, No. 3, (2006), pp.129-135.

[15] Berger, M.A.M., de-Groot, G. and Hollander, A.P., Hydrodynamic drag and lift forces on human hand/arm models, *Journal of Biomechanics*, Vol. 28, No. 2, (1995), pp.125-133.

[16] Kudo, S., Yanai, T., Wilson, B., Takagi, H. and Vennel, R., Prediction of fluid forces acting on a hand model in unsteady flow conditions, *Journal of Biomechanics*, Vol. 41, (2008), pp.1131-1136.

[17] Nakashima, M. and Takahashi, A., 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, (2012), pp.100-113.

[18] Nakashima, M. and Takahashi, A., 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, (2012), pp.114-128.

[19] Chung, C. and Nakashima, M., Development of a swimming humanoid robot for research of human swimming, *Journal of Aero Aqua Bio-mechanisms*, Vol. 3, No. 1, (2013), pp.109-117.

[20] Chung, C. and Nakashima, M., Swimming humanoid robot “SWUMANOID” as an experimental platform for research of human swimming, *Journal of Robotics and Mechatronics*, Vol.26, No.2, (2014), pp.265-266.

[21] Chung, C. and Nakashima, M., Free swimming of the swimming humanoid robot for the crawl stroke, *Journal of Aero Aqua Bio-mechanisms*, Vol. 3, No. 1, (2013), p. 118-126.

[22] Nakashima, M. and Kuwahara, K., Realization and swimming performance of the breaststroke by a swimming humanoid robot, *ROBOMECH Journal*, Vol. 3, No. 1, (2016), pp.1-10.

[23] Nakashima, M., Analysis of breast, back and butterfly strokes by the swimming human simulation model SWUM. In: Bio-mechanisms of Swimming and Flying - Fluid Dynamics, Biomimetic Robots, and Sports Science- (eds. Naomi Kato and Shiji Kamimura), Springer, (2007), pp 361-372.

[24] Nakashima, M. and Yusuke Ejiri, Y., 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 (2012), pp.11-24.