Molecular & Cellular Biomechanics
DOI:10.32604/mcb.2020.011050
Article

Dynamic Resistance Parameters of Arm Stroke during Swimming

Bin Wang[1], Dayong Li[2] and Yuxin Qin[3,*]

[1]Yunnan University of Finance and Economics, Kunming, 650221, China
[2]School of Basic Science, Shuren University, Hangzhou, 310015, China
[3]Zhengzhou University of Aeronautics, Zhengzhou, 450046, China
*Corresponding Author: Yuxin Qin. Email: xqc6341@163.com
Received: 16 April 2020; Accepted: 29 May 2020

Abstract: Swimming, as a sport beneficial to body and mind, also has a place in international sports. For swimmers and coaches, it is always the most important to improve the propulsion and reduce the resistance during swimming. This paper briefly introduced the resistance of human body in swimming, described the dynamic resistance of human body in arm stroke, and then introduced the principle of micro disturbance method which was used for measuring the dynamic resistance in swimming. Finally, ten swimmers from school team and ten beginners were tested for the dynamic resistance in freestyle, backstroke and breaststroke when they swam with arm stroke only. After adding micro resistance, the swimming speed of the subjects decreased when they swam with all their strength; the speed of freestyle swimming was the largest, followed by backstroke and breaststroke before and after loading, and the swimming speed of school team members was larger than that of beginners; the dynamic resistance and dynamic resistance coefficient of breaststroke were the largest, backstroke was the second, freestyle was the smallest, and the dynamic resistance and dynamic resistance coefficient of school team members were always smaller than those of beginners no matter the swimmer took which swimming style.

Keywords: Swimming; swimming stroke; dynamic resistance; micro disturbance

1 Introduction

As the density of water is far greater than that of air, the human body will feel obvious resistance when swimming. In order to maintain swimming speed, it is necessary to obtain the propulsion force through arm stroke and leg kick [1]. Due to the limitation of human body structure, it is impossible for people to swim under the water surface for a long time in the swimming process. When taking the normal swimming posture, there must be a part of the body above the water surface; as the air density is far smaller than the water density, the air resistance can be ignored; finally the propulsion has periodicity [2]. In essence, the propulsive force obtained by the human body through the stroke is the component of the resistance generated by the movement of the limbs in the water in the direction of forward motion. In short, the propulsive force obtained by the human body during swimming is also the resistance of water, but the resistance is the same as the direction of forward motion. The approximate periodic change of the limb during the stroke will directly lead to the approximate periodic change of the resistance generated by the stroke and indirectly lead to the approximate periodic change of the propulsive force [3]. The change of propulsive force will directly affect the swimming speed, and the resistance from the water is related to the swimming speed, which will eventually lead to the dynamic change of the resistance during swimming. For swimmers, the key to improve swimming performance is to improve the propulsive force o and reduce the resistance from water. Huang et al. [4] monitored and evaluated swimming movements with sensors, studied the influence of sensor location on detection results, and found through experiments that the sensor could detect good data and the waveform recognition effect was good when it was set at the hand. Elaine et al. [5] studied the specific contribution of the total resistance and wave resistance at the beginning of swimming in the underwater stage and carried out tests under three depths and four speeds (totally 12 conditions). The results showed that the total resistance at the beginning of swimming in the underwater sliding stage decreased with the increase of the depth and the speed had little correlation. Houwelingen et al. [6] studied the influence of finger spread on the hydrodynamic resistance of swimming using the method of numerical simulation combined with indoor experiment and found that the resistance coefficient of spread finger in the numerical simulation and experimental results increased by 2% and 5% respectively compared with that of closed finger. This paper briefly introduced the resistance of human body in swimming, described the dynamic resistance of human body in arm stroke, and introduced the principle of micro disturbance method which was used for measuring the dynamic resistance in swimming. Finally, ten school team swimmers and ten beginners were tested for the dynamic resistance in freestyle, backstroke and breaststroke with arm stroke only.

2 Dynamic Resistance of Arm Stroke in Swimming

In the international swimming competitions, the main swimming strokes include backstroke, butterfly, breaststroke and freestyle [7], among which backstroke and freestyle are relatively simple in movement technology, and they mainly rely on arm stroke to get driving force in the process of moving forward [8]. Although the legs can also get driving force from water, it is mainly used for ensuring the balance of stroke. Taking freestyle as an example, if only the arm stroke is used and the leg is only used to maintain balance, the schematic diagram of arm stroke in freestyle is shown in Fig. 1. The positive direction of X represents the horizontal direction of forward motion during swimming, point O represents the shoulder joint, OA represents the arm, point A represents the palm, V represents the speed of the palm, and θ is the angle between the arm and horizontal direction of swimming, between 0° and 180°. When the arm starts to pull, the water will produce resistance along the opposite direction of the arm movement, the size of which depends on the speed of the pull, and with the increase of the angle between the arm and

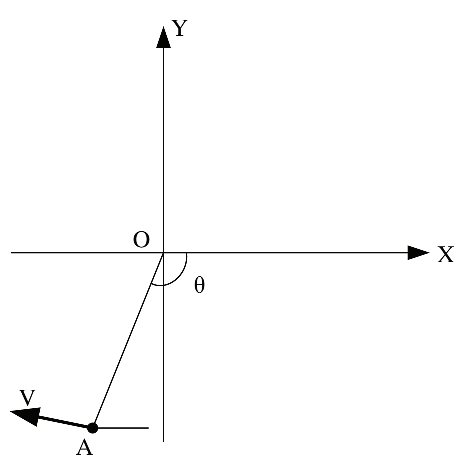

Figure 1: Sketch of arm stroke

horizontal direction of forward, the component force of the water generated resistance along the swimming direction increases first and then decreases. When θ is 180°, the component force along the direction of the swimming direction is 0, and then the arm extends out of the water surface and no longer obtains the power, but moreover, the other arm enters water to obtain the power, and its change rule is the same as the former. The two arms moves alternately to continuously provide the power for horizontal forward which periodically changes [9].

In the process of swimming, the human body only receives the action force from the water in the horizontal direction. When the human body is sliding in the water, the hydrodynamic force that the human body receives is static resistance, and its size is related to the sliding speed and the cross-sectional area of the human body in the speed direction. Generally speaking, the static resistance increases with the increase of the sliding speed [10]. In the actual swimming process, the swimmer will obtain the continuous driving force through the periodic arm stroke and legs stroke, and the posture of the human body will change periodically in the process of the periodic stroke, and finally the resistance from the water will also change periodically. Such a changed resistance is the dynamic resistance, and the main resistance in the swimming process is the dynamic resistance. For swimmers, the dynamic resistance can measure the technical performance in the swimming process, so as to provide an effective reference for improving swimming technology [11].

3 Measurement of Dynamic Resistance of Arm Stroke in the Process of Swimming

In order to measure the dynamic resistance of the human arm during continuous stroke, the micro disturbance method [12] was used in this study. The schematic diagram of the measurement of the dynamic resistance of the swimmer by the micro disturbance method is shown in Fig. 2. The micro disturbance method is relatively convenient to measure the dynamic resistance, a big change to the swimming pool is not needed, and the measurement method is basically not affected by the swimming posture. The main instruments used in this method include steel wire frame, tension sensor and cotton thread. When measuring, the slide block and tension sensor are connected with the waist of the subject using cotton thread [13]. The resistance of the slide block when sliding in the steel wire can be adjusted artificially, and it will not be set too high generally. Usually, the standard is that the cotton thread can be pulled gently and will not slide for a long distance under the action of inertia. The role of the slide block is to provide a small additional resistance to subjects. Tension sensor is used for measuring the tension on the cotton thread, i.e., the additional resistance provided by the slide block. The reason why the cotton thread is connected to the waist of the subject is that the waist changes little in the process of movement and the impact on the swimming style is the least.

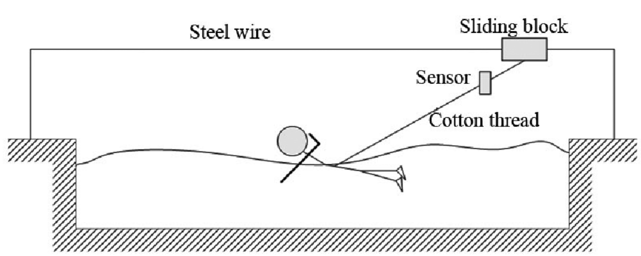

Figure 2: Schematic diagram of dynamic resistance measured by micro disturbance method

The principle of the micro disturbance method measuring the dynamic resistance is: the body shape and swimming posture of the subject before and after adding the micro resistance have no obvious influence on the swimming with all the strength, which can be regarded as the dynamic resistance of the subject before and after adding the micro resistance or the effective power to overcome the resistance is basically unchanged.

Then the dynamic resistance can be calculated by measuring the swimming speed before and after adding the micro resistance. The calculation principle [14] is as follows:

$$\begin{cases} f_1 = \dfrac{C_d \rho A v_1^2}{2} \\ f_2 = \dfrac{C_d \rho A v_2^2}{2} + f_b \end{cases}, \tag{1}$$

where f_1 and f_2 are the dynamic resistance before and after the addition of micro resistance respectively, C_d is the resistance coefficient, ρ is the density of water, A is the effective water retaining area of human body when swimming in water, v_1 and v_2 are the speed of swimming with all strength before and after adding micro resistance respectively, and f_b is an additional micro resistance [15]. As mentioned above, since the resistance to the human body added by the slide block is relatively small, it can be considered that the effective power to overcome the dynamic resistance before and after the addition of the micro resistance has no change. The expression is as follows:

$$P_1 = F_1 \cdot v_1 = F_2 \cdot v_2 = P_2, \tag{2}$$

where F_1 and F_2 are the effective driving force before and after the addition of micro resistance respectively and P_1 and P_2 are the effective power before and after the addition of micro resistance. Compared with the long-distance swimming, the short-distance swimming consumes less body energy, so the swimming with all the strength can be approximately regarded as a stable and uniform movement in short-distance swimming (the acceleration process at the start and the deceleration process at the end are not included, so the collected data needs to be screened when measuring and calculating), then the driving force can be regarded as equal to the dynamic resistance, i.e.,

$$\begin{cases} f_1 = F_1 \\ f_2 = F_2 \end{cases}, \tag{3}$$

$$C_d = \frac{2 f_b v_2}{\rho A (v_1^3 - v_2^3)}, \tag{4}$$

is obtained by combining Eqs. (1)–(3). Eq. (4) is substituted to Eq. (1), then the dynamic resistance without the addition of micro resistance is obtained:

$$f_1 = \frac{f_b v_1^2 v_2}{v_1^3 - v_2^3}. \tag{5}$$

It can be seen from the final calculation results that the dynamic resistance can be calculated by measuring the size of the additional micro resistance and the swimming speed of the subjects before and after the addition of micro resistance. According to Fig. 2, the additional micro resistance should be calculated theoretically as the component force of the tension on the cotton thread in the horizontal direction, but the angle between the cotton thread and horizontal direction is difficult to remain unchanged in the actual measurement, which hinders the measurement and calculation of the dynamic resistance. In the actual measurement, although the angle between the cotton thread and horizontal direction is difficult to be fixed, the angle is relatively small. Combined with the micro disturbance method, it needs to ensure that the pull force on the cotton thread is small enough to not affect the swimming action. Therefore, the component force of the cotton thread in the horizontal direction can be approximately equal to the tension of cotton thread [16], which can be measured by the tension sensor.

4 Experimental Analysis

4.1 Experimental Environment

In this study, the test was carried out in the swimming pool of a gymnasium. The specification of the swimming pool was 50 m × 21 m, and the depth of water was 2 m. The basic information of the participants in the test is shown in Tab. 1. The total number of athletes participating the test was 20, all of them were males, with an average height of 1.81 ± 0.02 m, an average age of 21 ± 1.1 years, and an average weight of 80.3 ± 2.2 kg. The basic physical signs of them were similar. Moreover, they have not been injured in the past three months. Ten of them were athletes from school team who have mastered freestyle, breaststroke, butterfly and backstroke strokes and had standard techniques. The other ten were beginners. In this experiment, the beginners could float in the swimming pool and keep treading for a long time, i.e., they could swim in the normal sense, and basically understand freestyle, breaststroke, butterfly and backstroke. But they were not proficient enough and had non-standard actions, and their movements would change in the process of continuous swimming.

Table 1: Basic information of personnel participating in the test

Swimming grade	Number of participants	Gender	Height	Age	Weight
Athletes from school team	10	Male	1.81 ± 0.02 m	21 ± 1.1 years	80.3 ± 2.2 kg
Beginner	10				

4.2 Experimental Equipment

The equipment used in this experiment included high-speed camera [17], adjustable resistance slider, tension sensor, data acquisition card, computer, and the iron frame and steel wire used for building the experimental equipment. The model number of high-speed camera was FASTCAM Nova S12, and the maximum full-frame shooting speed was 12800 frames/s. The adjustable resistance slider was equipped with screws, springs and steel balls on the basis of the ordinary slider, and the friction resistance between the slider and steel wire track was adjusted by rotating the screws. The model number of tension sensor was DYLY-101; the structure was column-type S shape, the measuring range was 100 kg, and the sensitivity was 2.0 ± 0.05 mV/V. The model type of data acquisition card was PCI8620, the number of channels was 16 channels at one end, and the precision was 12 bits.

4.3 Experiment Setup

The test site was the swimming pool of a gymnasium, and the general distribution of the setting points of the relevant measuring equipment is shown in Fig. 3. First of all, the main equipment that needed to be fixed in the whole test site were dynamic resistance measuring device and high-speed camera. The former was used to measure the dynamic resistance of athletes when swimming, and the latter was used to measure the speed of athletes when swimming. The bracket of the dynamic resistance measuring device was fixed on the shore of the starting edge of the swimming pool, and the steel wire was drawn from it and fixed on the opposite shore. Moreover, the steel wire was parallel to the water surface of the swimming pool, and the distance between the steel wire and water surface was 0.5 m. When the steel wire was set, a slider with a pull sensor was added to the steel wire. The high-speed camera was set at one side of the swimming pool, its photography direction was perpendicular to the steel wire, and the horizontal distance between the camera lens and the edge of the swimming pool was 5 m. In the swimming lane of the swimming pool, a buoy was fixed at the site which was 5 m away from the starting point as the mark of the measurement starting point, and the other buoy was fixed at the site which was 30 m away from the starting point as the mark of the measurement end point.

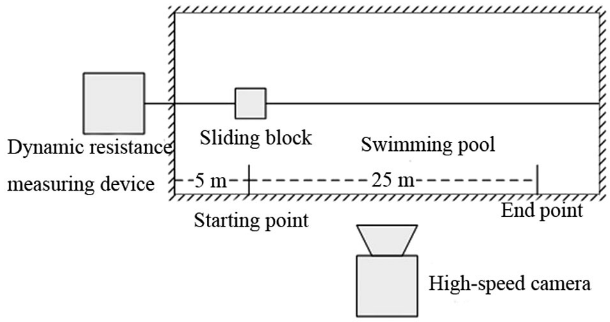

Figure 3: Schematic diagram of test site

4.4 Experiment Item

① No-load test: no-load test started for the twenty subjects after full preparation exercise. Firstly, freestyle test was conducted. As this study mainly analyzed the dynamic resistance of arm stroke, in order to reduce the impact of leg kick, a light foam board was fixed on the leg. The subjects swam with arms and all the strength. Timing started when the head passed the measuring starting point. The swimming process was photographed by the high-speed camera. Timing stopped when the head passed the measuring end point. The swimming speed was calculated by using the video taken by the high-speed camera. Each subject took turns for three times, and the average value was taken as the final result. The no-load test steps for backstroke and breaststroke were consistent with freestyle test, and the light foam board was fixed on the leg to reduce the influence of leg kick [18].

② Load test: after no-load experiment, twenty subjects rested for a period of time, and then the load test started. Firstly, one end of the cotton thread was fixed at the waist, and the other end was fixed at the tension sensor connected to the slider. A light foam board was fixed at the leg. Like the no-load test, the subjects swam with arms and all the strength. The swimming process was recorded by the high-speed camera, and the additional resistance measured by the tension sensor was also recorded. Each subject repeated each stroke three times, and the average value was taken. Then the dynamic resistance of each swimmer's arm in each stroke was calculated.

4.5 Experimental Results

In the test, after taking the swimming image with a high-speed camera, the average speed of swimming of every subject before and after load in different swimming postures was calculated according to labels of timing starting point and end point. The detailed data of the average speed of each subject before and after load in different swimming postures is shown in Tab. 2, and the comparison figure is shown in Fig. 4. It was seen intuitively from Tab. 2 and Fig. 4 that the speed of the subjects before load was higher than that after load when taking the same swimming stroke in swimming with all the strength; when taking the same stroke, no matter before load or after load, the speed of the school team subjects was always higher than that of the beginners in the swimming with all the strength. By comparing the speed of the same subject taking different strokes, it was found that the speed of the subject was the highest when swimming in freestyle, backstroke was the second, and breaststroke was the lowest.

According to the speed of the subjects before and after load in the swimming with all the strength and the additional resistance detected by the tension sensor, the dynamic resistance of the subjects taking the three swimming postures was calculated, as shown in Fig. 5. It was found from Fig. 5 that the dynamic resistance of school team members was smaller compared with beginners no matter they took which swimming stroke. The comparison of the dynamic resistance of the same subject taking different strokes suggested that the dynamic resistance was the largest when the subject swam in breaststroke, followed by backstroke and

Table 2: The average speed of subjects taking three swimming postures before and after load

Subject number	Freestyle without load m/s	Freestyle with load m/s	Backstroke without load m/s	Backstroke with load m/s	Breaststroke without load m/s	Breaststroke with load m/s
School team No. ①	1.854	1.758	1.555	1.495	1.236	1.195
School team No. ②	1.847	1.751	1.547	1.489	1.233	1.192
School team No. ③	1.851	1.755	1.551	1.492	1.235	1.194
Beginner No. ①	1.541	1.493	1.205	1.175	1.171	1.148
Beginner No. ②	1.505	1.455	1.255	1.226	1.172	1.148
Beginner No. ③	1.565	1.517	1.315	1.287	1.163	1.138

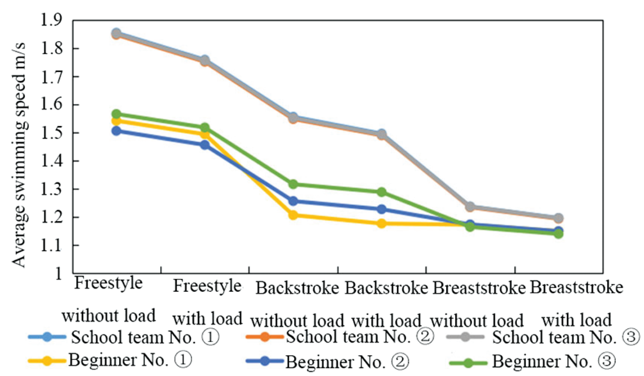

Figure 4: Comparison of the average speed of subjects taking in three swimming postures before and after load

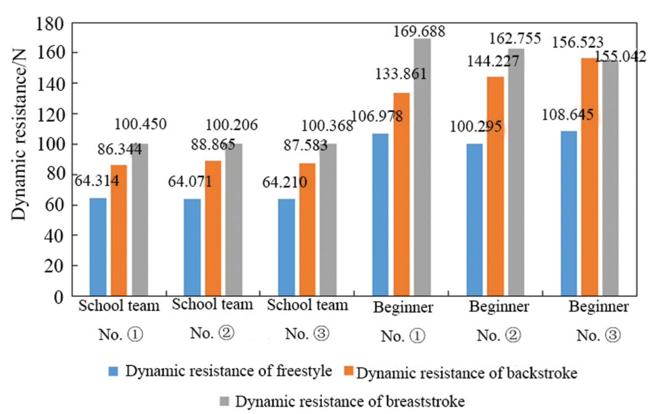

Figure 5: The average dynamic resistance of subjects taking three swimming postures in the swimming with all the strength

freestyle. Overall, the dynamic resistance of the team members were significantly smaller during swimming, which was because that the swimming posture of beginners were not as standard as the team members who have trained for a long time and the defect was obviously amplified in the water. The force the human body receives during swimming is from water. One part of the resistance to moving one's arms in the water will be the resistance, and the other part will be the driving force. The more standard the swimming posture is, the more the resistance will be transformed to the driving force and the smaller the resistance to advance is.

Due to dynamic resistance $f \propto v^2$, it was regarded as $f = k \cdot v^2$, where f stands for the dynamic resistance, v stands for the swimming speed, and k is the coefficient between them. After k was regarded as the dynamic resistance coefficient, the calculation formula of the dynamic resistance coefficient is $C_k = f / v^2$. The processed results are shown in Fig. 6. It was seen from Fig. 6 that the resistance coefficient of breaststroke was the largest, backstroke was the second, and freestyle was the smallest. The comparison of the resistance coefficient between school team members and beginners taking the same stroke suggested that the resistance coefficient of school team members was about half of the beginners. When the human body is swimming in the water, there will be turbulence when water flows on the surface of the human body as it is not an ideal fluid. The Reynolds number of the turbulence changes with the change of the flow speed, and the resistance caused by the turbulence also changes. In addition, the human body is not a regular shape such as a cylinder, and the constant change of the human body movements during swimming aggravates the irregularity of the human body in the water. Therefore, when the human body adopts different swimming posture, the velocity of water body in local position is different, and the Reynolds number of turbulence is also different, which leads to different resistance and resistance coefficient. The body type and weight of the beginners and school team members were close, and the physical ability was also very close. The difference produced in the test was because that the school team members swam with standard actions and the beginners swam with non-standard actions, uncoordinated left arm and right arm and non-uniform swimming speed. The final test results showed that the non-standard technical action of arm stroke in swimming could lead to the increase of resistance coefficient, seriously hinder the swimming of human body, and increase the consumption of human body. Therefore, in swimming training, dynamic resistance coefficient can be used as one of the evaluation indicator of training effect, and the dynamic resistance coefficient can be used to judge whether the physical strength enhances or the technique improves after self training.

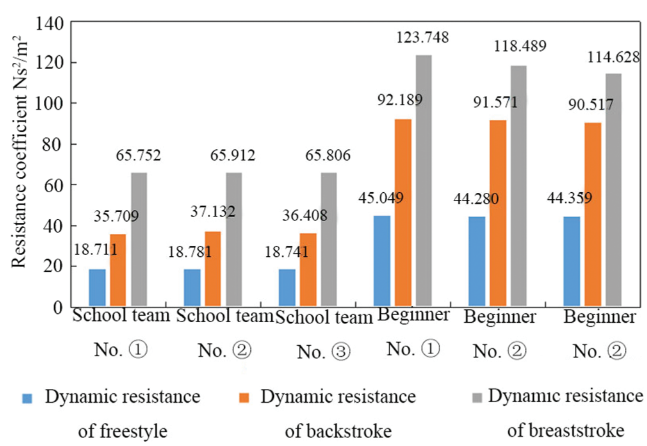

Figure 6: The average dynamic resistance coefficient of subjects taking three swimming postures in the swimming with all the strength

5 Conclusion

In this study, the resistance of human body in swimming was introduced, the dynamic resistance of human body during arm stroke was described, the principle of micro disturbance method for measuring the dynamic resistance in the swimming with all the strength was introduced, and the dynamic resistance tests of freestyle, backstroke and breaststroke in which only arm stroke was used were carried out on ten school team swimmers and ten beginners. The results are as follows: (1) the swimming speed decreased with the increase of micro resistance; the swimming speed of freestyle swimming was the largest, followed by backstroke and breaststroke; the swimming speed of school team members was larger than that of beginners; (2) the dynamic resistance of the school team members was smaller than beginners no matter which swimming posture was taken; the dynamic resistance of the same subject was the largest when doing breaststroke, followed by backstroke and freestyle; (3) according to the dynamic resistance and the dynamic resistance coefficient obtained from the no-load swimming speed, the dynamic resistance coefficient of breaststroke was the largest, the backstroke was the second, and the freestyle was the smallest; the dynamic resistance coefficient of school team members was smaller than that of beginners when taking the same swimming posture. The novelty of this study is that the micro disturbance method is used to measure the dynamic resistance of swimmers when they are swimming. The micro disturbance method can not only measure the dynamic resistance of human body in swimming, but also does not affect the swimming action of human body in the process of measurement, which further increases the accuracy of dynamic resistance measurement.

Funding Statement: The author(s) received no specific funding for this study.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

References

1. Crowley, E., Harrison, A. J., Lyons, M. (2017). The impact of resistance training on swimming performance: a systematic review. *Sports Medicine, 47(11),* 2285–2307. DOI 10.1007/s40279-017-0730-2.
2. Yuan, H. T., Hu, W. R. (2017). A numerical study of tadpole swimming in the wake of a D-section cylinder. *Journal of Hydrodynamics, 29(6),* 142–151.
3. Tor, E., Pease, D. L., Ball, K. A. (2015). Comparing three underwater trajectories of the swimming start. *Journal of Science and Medicine in Sport, 18(6),* 725–729. DOI 10.1016/j.jsams.2014.10.005.
4. Huang, K. C., Chu, C. P., Chiu, T. K., Chen, J. C. (2017). Comparison of sensor analysis for swimming in different positions, *IEEE International Conference on Applied System Innovation, Sapporo, Japan.*
5. Elaine, T., Pease, D. L., Ball, K. A. (2015). How does drag affect the underwater phase of a swimming start? *Journal of Applied Biomechanics, 31(1),* 8–12. DOI 10.1123/JAB.2014-0081.
6. van Houwelingen, J., Willemsen, D. H. J., Kunnen, R. P. J., van Heijst, G. J. F., Grift, E. J. et al. (2017). The effect of finger spreading on drag of the hand in human swimming. *Journal of Biomechanics, 63,* 67–73. DOI 10.1016/j.jbiomech.2017.08.002.
7. García-Echauri, L. L., Jeffs, A. (2018). Swimming energetics of the post-larvae of the spiny lobster Jasus edwardsii in New Zealand. *Bulletin of Marine Science, 94(3),* 821–833.
8. Fan, J. Z., Zhang, W., Kong, P. C., Cao, H. G., Liu, G. F. (2017). Design and dynamic model of a frog-inspired swimming robot powered by pneumatic muscles. *Chinese Journal of Mechanical Engineering, 30(5),* 1–10. DOI 10.3901/CJME.2017.0101.001.
9. Tabatabaei, M., Bahadır Olcay, A., Gokçen, G., Heperkan, H. A. (2015). Drag force and jet propulsion investigation of a swimming squid. *European Physical Journal Conferences, 92,* 02092. DOI 10.1051/epjconf/20159202092.
10. Wiyono, E. S., Ihsan. (2015). The dynamic of landing blue swimming crab (*Portunus pelagicus*) catches in Pangkajene Kepulauan, South Sulawesi, Indonesia. *AACL Bioflux, 8(2),* 134–141.
11. Park, J. S., Kim, D., Shin, J. H., Weitz, D. A. (2015). Efficient nematode swimming in a shear thinning colloidal suspension. *Soft Matter, 12(6),* 1892–1897. DOI 10.1039/C5SM01824B.

12. Samson, M., Monnet, T., Bernard, A., Lacouture, P., David, L. (2018). Comparative study between fully tethered and free swimming at different paces of swimming in front crawl. *Sports Biomechanics, 18(6),* 571–586. DOI 10.1080/14763141.2018.1443492.
13. Liu, Y. K., Zhang, G. G., Qin, H., Geng, Y., Wang, J. et al. (2018). Prediction of the dynamic contact resistance of circuit breaker based on the kernel partial least squares. *IET Generation, Transmission & Distribution, 12(8),* 1815–1821. DOI 10.1049/iet-gtd.2017.1235.
14. Akanyeti, O., Putney, J., Yanagitsuru, Y. R., Lauder, G. V., Stewart, W. J. et al. (2017). Accelerating fishes increase propulsive efficiency by modulating vortex ring geometry. *Proceedings of the National Academy of Sciences of the United States of America, 114(52),* 201705968.
15. Tor, E., Pease, D. L., Ball, K. A. (2015). Comparing three underwater trajectories of the swimming start. *Journal of Science and Medicine in Sport, 18(6),* 725–729. DOI 10.1016/j.jsams.2014.10.005.
16. Kwak, B., Bae, J. (2017). Design of hair-like appendages and comparative analysis on their coordination toward steady and efficient swimming. *Bioinspiration & Biomimetics, 12(3),* 036014. DOI 10.1088/1748-3190/aa6c7a.
17. Suzuki, I., Sato, K., Fahlman, A., Naito, Y., Miyazaki, N. et al. (2014). Drag, but not buoyancy, affects swim speed in captive Steller sea lions. *Biology Open, 3(5),* 379–386. DOI 10.1242/bio.20146130.
18. Holley, M. T., Nagarajan, N., Danielson, C., Zorlutuna, P., Park, K. (2016). Development and characterization of muscle-based actuators for self-stabilizing swimming biorobots. *Lab on a Chip, 16(18),* 3473–3484. DOI 10.1039/C6LC00681G.