エリート競泳選手を対象とした水中ドルフィンキックのパフォーマンス向上を目指したトレーニング介入：キック頻度と推進効率に着目して

仙石泰雄[1]，山川啓介[2]，角川隆明[1]，成田健造[3]
[1] 筑波大学
[2] 日本女子体育大学
[3] 鹿屋体育大学

キーワード：水中ドルフィンキック，パフォーマンス，トレーニング

【抄 録】

本研究は，1 シーズンのトレーニング前後における水中ドルフィンキック動作を分析し，水中ドルフィンキックの泳速度の向上に関与するキネマティク変数を明らかにすることを目的とした．本研究には，よくトレーニングされた大学競泳選手 32 名（男子 19 名，女子 13 名）が参加した．トレーニング期間前（Pre）と後（Post）の水中ドルフィンキックを２次元動作解析し，平均泳速度，キック頻度，キック幅，ストローハル数，アップキック所要時間およびダウンキック所要時間を分析した．水中ドルフィンキックの泳速度を向上するために，キック頻度の上昇と推進効率の改善を目指すトレーニングを継続的に実施した．その結果，トレーニング期間前後において男子と女子ともに泳速度が有意に向上した．また，トレーニング前後においてキック頻度が有意に上昇したものの，キック幅は変化しなかったことが明らかとなった．本研究結果より，水中ドルフィンキックの泳速度を向上させるには，キック幅を変化させることなくキック頻度を上昇させることが必要であることが明らかとなり，本研究で用いたトレーニング方法が有効である可能性が示唆された．

スポーツパフォーマンス研究, 12, 396-407, 2020 年, 受付日: 2020 年 3 月 23 日, 受理日: 2020 年 7 月 27 日
責任著者:仙石泰雄　筑波大学　つくば市天王台 1-1-1　sengoku.yasuo.ge@u.tsukuba.ac.jp

* * * *

Training to enhance underwater dolphin kick speed in elite swimmers: focusing on kick frequency and propelling efficiency

Yasuo Sengoku[1], Keisuke Kobayashi Yamakawa[2],
Takaaki Tsunokawa[1], Kenzo Narita[3]
[1] University of Tsukuba
[2] Japan Women’s College of Physical Education
[3] National Institute of Fitness and Sports in Kanoya

Key words: underwater dolphin kick, performance, training

[Abstract]

The purpose of the present study was to analyze well-trained university swimmers' underwater dolphin kick before and after one season's training, and to examine kinematic parameters related to any change in their underwater dolphin kick speed. The participants, 32 elite university swimmers (19 male, 13 female), received underwater dolphin kick training during the 2014 winter season. To analyze the participants' underwater dolphin kick performance and to evaluate the effectiveness of that season's training, motion analysis was conducted at the beginning (Pre) and the end (Post) of the training season. The average swimming speed, kick frequency, kick amplitude, Strouhal number, and up-kick and down-kick durations were measured. The average swimming speed increased significantly in both the male (Pre, 1.73 ±0.11 m/sec; Post, 1.81 ±0.11 m/sec; p<.01) and the female swimmers (Pre, 1.49 ±0.08 m/sec; Post, 1.58 ±0.08 m/sec; p <.01). Kick frequency also increased significantly in the male (Pre, 2.42 ± 0.29 m/sec; Post, 2.67 ±0.34 m/sec; p<.01) and the female swimmers (Pre, 2.06 ± 0.26 m/sec; Post, 2.38 ± 0.23 m/sec; p<0.01), however, none of the swimmers' kick amplitudes changed significantly. These data suggest that the improvement found in the participants' average swimming speed resulted from an increase in the swimmers' kick frequency, as their kick amplitudes did not change significantly.

1. Introduction

In addition to the four major swimming styles, butterfly, backstroke, breaststroke, and front crawl, the underwater dolphin kick is performed as a propelling swimming technique during competitive swimming races. The underwater dolphin kick has been described as the ‘fifth stroke’ (Collard et al., 2013), and has been investigated by several studies (Arellano et al., 2002, Atkison et al., 2014, Connaboy et al, 2009, Connaboy et al., 2014, Shimojo et al., 2014). Using the underwater dolphin kick, the high velocity acquired after starts and turns can be maintained longer compared to swimming at the surface (Arellano et al., 2002). Therefore, race time can be improved using this underwater technique.

To clarify factors that create a high underwater dolphin kick velocity, many cross sectional kinematical studies have been conducted (reviewed by Connaboy et al., 2009). These studies conclude that kick frequency, but not kick amplitude, is related to the high underwater dolphin kick velocity. In other words, faster underwater dolphin kick swimmers demonstrated higher kicking frequency compared to slower participants, and no statistical difference in kick amplitude was observed between the fast and slow swimmers. Furthermore, Zamparo et al. (2012) reported that higher propelling efficiency was significantly related to underwater dolphin kick velocity after a turn. These results suggest that swimmers should increase the kick frequency and/or improve propelling efficiency to achieve higher underwater dolphin kick performance.

Previous studies investigated dolphin kick velocity in the same individual by changing the kick frequency in sync with a metronome sound (Shimojo et al., 2014; Yamakawa et al., 2017). Both studies reported that the swimmer's dolphin kick velocity did not increase even when the swimmer attempted higher kick frequency than that of the maximum effort trial. This was because the kick amplitude and propelling efficiency decreased when the swimmers increased the kick frequency above the maximum effort. Furthermore, Connaboy et al. (2014) conducted a four week training intervention to clarify the training effect on maximal underwater dolphin kick speed. They could not achieve an improvement in underwater dolphin kick velocity after a four-week training period, and were unable to investigate factors relating to an underwater dolphin kick velocity increase in the same individual. Therefore, the kinematic parameters related to the enhancement in underwater dolphin kick velocity remain unclear.

As described above, there is scientific evidence reporting that higher kick frequency is related to faster underwater kick velocity and that propelling efficiency during underwater dolphin kick is important. However, there is a paucity in information about the actual training methodology that can enhance underwater dolphin kick performance.

The primary objectives of this study were to analyze underwater dolphin kick motion before and after one training season in well-trained university swimmers, and to clarify the kinematical parameters related to the enhancement of underwater dolphin kick velocity. A second objective was to develop training instruction that can improve underwater dolphin kick performance. We hypothesized that underwater dolphin kick velocity can be increased by increased kick frequency training and improvement in propelling efficiency during a one season training period.

2. Methods

2.1. Participants

Well-trained university swimmers, 19 males and 13 females, participated in this study (Males: mean age, 20.5 ± 1.3 years; mean height, 1.76 ± 0.07 m; mean weight, 70.2 ± 5.7 kg; Females: mean age, 20.3 ± 1.3 years; mean height, 1.62 ± 0.05 m; mean weight, 56.0 ± 4.7 kg), and all of the swimmers had competed at national level competition. Their specialized swimming style was Freestyle (n=11), Butterfly (n=6), Backstroke (n=5), Breaststroke (n=6), and Individual Medley (n=4). The swimmers trained for the same university swimming team. Participants trained 9-10 swim sessions per week with an average swimming distance of 36 km per week and participated in four strength training sessions per week. The experimental procedures of this study were approved by the local ethics committee and informed consent was obtained from the participants.

2.2. Underwater dolphin kick analysis

To analyze the participants' change in underwater dolphin kick performance, underwater motion analysis was conducted at the starting point of the winter training season (October 2014; Pre) and at the end (February 2015; Post) of the intensive training period. The main competitions for the investigated swimming team was March and beginning of April.

Analyses were conducted in an indoor swimming pool (50 m, 1.35-1.80 m depth). Before the experiment, the swimmers performed a middle-intensity 1000 m warm-up swim. Participants performed a 15 m maximal underwater dolphin kick twice, in accordance with the method by Shimojo et al., (2014). The underwater dolphin kick was performed approximately 1.0 m under the water surface to exclude the effect of wave drag (Lyttle et al., 2000).

2.3. Kinematic variables

The epiphysis of the fifth metatarsal (toe) and the greater trochanter of the femur (hip) were marked with LEDs (Kirameki, Nobby Tech Inc.) on the right side of the swimmer. The experimental setting is described in Figure 1. One video camera (High speed 1394 Camera Bcam, DKH Inc.) was positioned lateral to the swimmer for 2-dimensional motion analysis at an underwater window to film the swimmer's dolphin kick motion at a 100 Hz sampling rate.

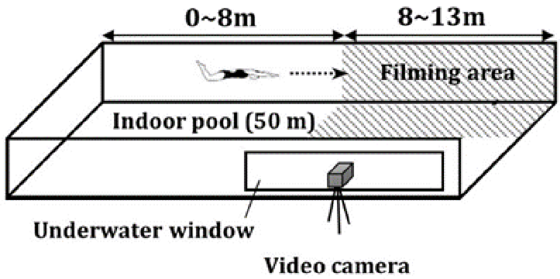

Figure 1 Schematic of the experimental setting. Underwater dolphin kick motion was filmed between 8 m and 14 m distance after pushing off the wall.

The coordinates of all landmarks were digitized and converted to global coordinates using the 2-D direct linear transformation method. The calibration for 2-D motion analysis was conducted by filming a known length object. The length of calibration objects were 1.40 m and these were set vertically at 1 m intervals between 8 m to 14 m from the start point. The calibration was carried out at every trial, throughout the experiment. The standard errors between the actual value and the calculated value of the calibration points were 0.008 ± 0.002 m. One-kick cycle was defined as beginning at the highest vertical peak for the toe position and ending at the next highest peak. One-kick cycle was divided into down-kick phase and up-kick phase according to the vertical movement of the toe. According to Connaboy et al. (2010), all three data obtained from consecutive three kick cycles were used for analysis. The trial with the highest average swimming velocity was used for analysis.

Kick frequency (Hz) and kick amplitude (m) were calculated from the toe coordinates. Kick frequency was determined from the duration of one-kick cycle, whereas kick amplitude was the vertical displacement of the toe coordinates between the highest and lowest position of one-kick cycle (Shimojo et al., 2014). The average swimming velocity ($m \cdot sec^{-1}$) was the average horizontal hip velocity during one-kick cycle. Duration of the up and down-kick phase (sec) was investigated.

To evaluate the propelling efficiency of the underwater dolphin kick, the Strouhal number (*St*) was investigated (Connaboy et al., 2009). The *St* was calculated as:

$St = f \cdot A_{toe} \cdot U^{-1}$

where f is kick frequency, A_{toe} is kick amplitude, and U is average swimming velocity. St is a dimensionless number that describes the kick amplitude normalized to the progression given by the swimming velocity and kick frequency ratio. Past literature reported that maximum efficiency in undulatory movement is achieved with an St range of 0.25 to 0.4 in fish and cetaceans (Anderson et al., 1998; Triantafyllou et al., 1993). However, the St value of underwater dolphin kick in humans is found to be outside the range of 0.4 (Nicolas et al., 2007). In competitive swimmers, Arellano et al. (2002) reported that the St between international level swimmers and national level swimmers was significantly different, 0.79 vs 0.95, respectively.

2.4. Instruction for enhancing underwater dolphin kick performance

All participants were instructed to enhance their underwater dolphin kick performance by the following two methods. The two methods were adopted according to previous studies reporting that the higher kick frequency is related to faster underwater kick velocity (Connaboy et al., 2009) and that propelling efficiency during underwater dolphin kick is important (Zamparo et al., 2012).

First, Shimojo et al. (2014) reported that an effective undulatory mode can be achieved by decreasing kick frequency 15% compared to the frequency at maximum effort. Furthermore, as Nakashima (2009) reported, both swimming velocity and propulsive efficiency can be improved by undulating the trunk. Therefore, the swimmers attempted to conduct an effective dolphin kick technique by repeating submaximal underwater dolphin kicks in the prone position (Figure 2-A), and dolphin kicks at the water surface in the supine position (Figure 2-B). The swimmers swam 50 m at each posture alternatively, repeated it twice. During this 200 m swim, swimmers were instructed to move their chest forward and backward using the waist for the dolphin kick motion.

Second, high kick frequency is reported to relate significantly to high underwater dolphin kick velocity (Connaboy et al., 2009). Swimmers performed a maximum effort underwater dolphin kick with an elastic cord attached to their waist (Figure 2-C; Sengoku et al., 2014). After pushing off from the wall, swimmers were instructed to maximize their kick frequency against the elastic cord for five kick cycles. The swimmers repeated this exercise four times with adequate rest in between.

The underwater dolphin kick training protocols described were included in the ordinary training program by the swimming coach two to four times every week through the experimental period.

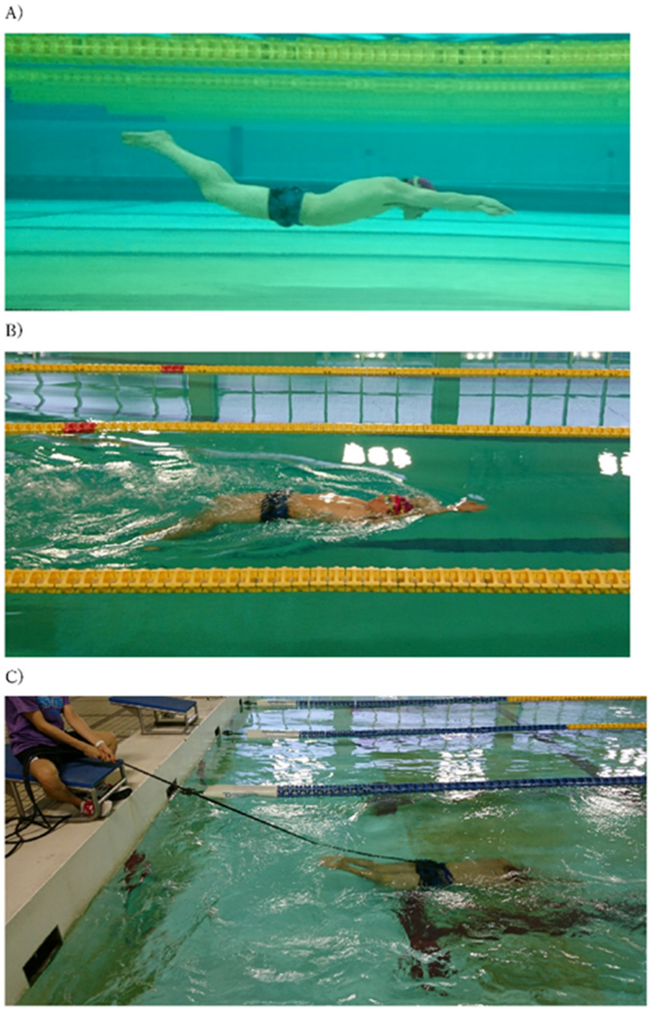

Figure 2 Demonstration of the training instructions prescribed to enhance the underwater dolphin kick performance. A) submaximal underwater dolphin kicks in the prone position, B) dolphin kicks at the water surface in the supine position, and C) maximum effort underwater dolphin kick with an elastic cord attached to the swimmer's waist.

2.5. Statistical analysis

All kinematic variables are presented as the mean and the standard deviation (Mean ± SD). Two-way repeated measures ANOVA with Tukey's post-hoc tests were used to assess the difference between the factor of time (Pre vs. Post) and sex (male vs. female). A p value < .05 was considered statistically significant. Statistical analyses were conducted using SPSS for Windows 25.0 (IBM Inc.).

3. Results

The results of the two-way ANOVA are shown in Table 1. After a one month training season, significant main effect of time was observed with the average swimming velocity (p < .01), indicating that the underwater dolphin kick velocity was significantly improved in both genders. Furthermore, a significant main effect of time was observed with the kick frequency, down-kick duration and up-kick duration ($p < .01$), suggesting that subjects increased kick frequency by decreasing the duration of both down- and up-kick. The St showed a significant main effect of time ($p < .01$), indicating that propelling efficiency decreased after training in both genders. Significant change was not observed with the kick amplitude. No difference in the change of underwater dolphin kick kinematics between gender was observed, as there was no significant interaction in all variables.

Table 1 The kinematical variables before and after the four month training period.

			Pre			Post			ANOVA Sex	Time	Interaction
Average Swimmig Velocity	(m·sec^{-1})	M	1.73	±	0.11	1.81	±	0.11	$p < .01$	$p < .01$	N.S.
		F	1.49	±	0.08	1.58	±	0.08			
Kick Frequency	(Hz)	M	2.42	±	0.29	2.67	±	0.34	$p < .01$	$p < .01$	N.S.
		F	2.06	±	0.26	2.38	±	0.23			
Kick Amplitude	(m)	M	0.48	±	0.06	0.50	±	0.05	N.S.	N.S.	N.S.
		F	0.47	±	0.05	0.46	±	0.04			
Strouhal Number		M	0.66	±	0.04	0.73	±	0.07	N.S.	$p < .01$	N.S.
		F	0.64	±	0.05	0.69	±	0.07			
Duration of Down Kick Phase	(sec)	M	0.20	±	0.02	0.16	±	0.03	$p < .01$	$p < .01$	N.S.
		F	0.23	±	0.02	0.19	±	0.01			
Duration of Up Kick Phase	(sec)	M	0.23	±	0.03	0.22	±	0.03	$p < .01$	$p < .01$	N.S.
		F	0.27	±	0.05	0.24	±	0.03			

Main effect: Sex = M v.s. F, Time = Pre v.s. Post

4. Discussion

The primary purpose of this study was to analyze the underwater dolphin kick motion in well trained university swimmers before and after a one training season, and to clarify the kinematical parameters related to the change in underwater dolphin kick velocity. Our findings demonstrate that enhancement in average swimming speed was achieved by increasing kick frequency while the kick amplitude was not significantly different.

The participants' underwater dolphin kick velocity at Pre was greater than that of previous reports including reports examining well-trained male swimmers (Atkison et al., 2014; Shimojo et al., 2014) and female swimmers (von Loebbecke et al., 2009). These results suggest that the swimmers' underwater dolphin kick performance in the present study was relatively higher at the Pre condition compared to the subjects in previous studies. After the one season training period, the average dolphin kick velocity showed a significant increase in both genders.

A significant change in kick frequency was observed in male and female swimmers, while the kick amplitude was not statistically different after the one season training period. Arellano et al. (2002) investigated the underwater dolphin kick performance difference between the international and national level swimmers and reported that the international level swimmers showed a higher average velocity with a higher kick frequency in men and women over that of the national level swimmers. Previous cross-sectional studies (reviewed by Connaboy et al., 2009) demonstrated that high kick frequency was related to faster underwater dolphin kick velocity, which suggests the importance of training to increase kick frequency. From above, a training method to maximize kick frequency in a short duration may lead to increased underwater dolphin kick frequency, resulting in enhancing underwater dolphin kick performance.

To increase kick frequency, swimmers shorten the duration of the up-kick and/or down kick-phase. Our results suggest that the subjects increased the kick frequency by decreasing the duration of both down- and up-kick. Previous studies investigating the underwater dolphin kick using particle image velocimetry reported that a strong backward and downward jet is generated during the down-kick, indicating that a higher propelling force is produced by the down-kick (Hochstein and Blickhan, 2011; Shimojo et al., 2019). Furthermore, Atkinson et al. (2014) reported that maximal horizontal velocity was observed during the down-kick phase, however, faster swimmers spent less time at the up-kick than slower swimmers, and the highest correlation was observed between average velocity during the up-kick and average horizontal swimming velocity. It was suggested that well-trained swimmers should decrease both down- and up-kick duration to improve underwater dolphin kick performance regardless of gender.

Velocity during the underwater dolphin kick is affected by the combination of kick frequency and kick amplitude. Therefore, it is important to note that average velocity will not change if the magnitude of the increase in kick frequency is equivalent with the decrease in kick amplitude. This is consistent with results of previous studies reporting that even if the kick frequency was increased immediately in sync with a metronome sound, the underwater dolphin kick velocity did not increase because the kick amplitude decreased (Shimojo et al., 2014; Yamakawa et al., 2017). The present study suggests that swimmers could increase the kick frequency while keeping the kick amplitude non-statistically different during longer training durations. Instructing the swimmers not only to increase the kick frequency, but also to be aware of propelling efficiency, may prevent decrement in the kick amplitude during maximum effort underwater dolphin kick.

The *St* showed an increase in male and female swimmers, suggesting that the propelling efficiency in these swimmers decreased with training. This result disagreed with our hypothesis. The Post *St* in the present study was lower than that reported by Arellano et al. (2002), indicating a high efficiency level in our swimmers. However, the increase in *St* was contrary to the training purpose that aimed to improve propelling efficiency by undulating the trunk during the submaximal velocity swim (Nakashima, 2009; Shimojo et al., 2014). Yamakawa et al. (2017) reported that the trunk muscular activation pattern is related to propelling efficiency. Therefore, the movement of the swimmers' trunk should be investigated in detail to evaluate their underwater dolphin kick technique. By this further investigation, the relationship between the change in kick frequency and the propelling efficiency may be clarified.

The training instructions prescribed to the participants in the present study was twofold: a submaximal frequency swim to obtain efficient trunk undulatory movement, and a maximal frequency stimulus using the elastic cord. The previous training intervention study (Connaboy et al., 2014) only focused on training at a preferred cycle frequency decided by the swimmer, and could not result in improving underwater dolphin kick velocity. The present study did not clarify which training instruction was effective, however, the combination of the two instruction methods may result in the enhancement of underwater dolphin kick velocity.

The data obtained in this study is an evaluation from a 15 m maximal effort swim and may differ from the performance during actual competition conditions, which is a limitation of the present study. Furthermore, in addition to the underwater dolphin kick training, each swimmer engaged in different types of swim training depending on their specific swimming style and race duration. Therefore, we could not clarify the exact training effect from the three underwater dolphin kick instruction introduced in this study. However, 17 of 19 male swimmers and all 13 female swimmers enhanced their maximal average swimming speed. This is the first study to clarify the kinematical variables associated with enhancement in underwater dolphin kick velocity in the same individual. Further research, including a more precise motion analysis of the underwater dolphin kick, is needed to investigate the training outcome from each training instruction.

References

- Anderson, J. M., Streitlien, K., Barret, D. S., and Triantafyllou, M. S. (1998) Oscillating foils of high propulsive efficiency. J. Fluid Mech. 360: 51-72.
- Arellano, R., Pardillo, S., and Gavilán, A. (2002) Underwater undulatory swimming: Kinematic characteristics, vortex generation and application during the start, turn and swimming strokes. In E. K. Gianikellis (eds.), Proceedings of the XXth international symposium on biomechanics in sports. Caceras, Universidad de

Extremadura.
・ Atkison, R. R., Dickey, J. P., Dragunas, A., and Nolte, V. (2014) Importance of sagittal kick symmetry for underwater dolphin kick performance. Hum. Mov. Sci. 33: 298-311.
・ Collard, L., Gourmelin, E., and Schwob, V. (2013) The fifth stroke: The effect of learning the dolphin - kick technique on swimming speed in 22 novice swimmers. J. Swimming Research, 21.
・ Connaboy, C., Coleman, S., and Sanders, R. H. (2009) Hydrodynamics of undulatory underwater swimming: A review. Sports Biomech. 8: 360-380.
・ Connaboy, C., Coleman, S., Moir, G., and Sanders R. (2010) Measures of reliability in the kinematics of maximal undulatory underwater swimming. Med. Sci. Sports Exerc. 42: 762-770.
・ Connaboy, C., Moir, G., Coleman, S., and Sanders, R. (2014) Effects of imposed cycle frequency training on the heave and pitch phase relationships in undulatory underwater swimming. 32nd Conference of the International Society of Biomechanics in Sports, 101-104.
・ Hochstein, S. and Blickhan, R. (2011) Vortex re-capturing and kinematics in human underwater undulatory swimming. Hum. Mov. Sci. 30: 998-1007.
・ Lyttle, A. D. Blanksby, B. A. Elliott, B. C., and Lloyd, D. G. (2000) Net forces during tethered simulation of underwater streamlined gliding and kicking techniques of the freestyle turn. J. Sports Sci. 18: 801–807.
・ Nakashima, M. (2009) Simulation analysis of the effect of trunk undulation on swimming performance in underwater dolphin kick of human. J. Biomech. Sci. Eng. 4: 94-104.
・ Nicolas, G., Bideau, B., Colobert, B, and Berton, E. (2007) How are Strouhal number, drag, and efficiency adjusted in high level underwater monofin-swimming? Hum. Mov. Sci. 26: 426-442.
・ Sengoku, Y., Tsunokawa, T., Kobayashi, K., and Tsubakimoto, S. (2014) Comparison of the training load during High Intensity Interval Resisted Training programed by different exercise duration. In B. Mason (eds.), Biomechanics and Medicine in Swimming XII. Australian Institute of Sports.　pp.328-332.
・ Shimojo, H., Sengoku, Y., Miyoshi, T., Tsubakimoto, S., and Takagi, H. (2014) Effect of imposing changes in kick frequency on kinematics during undulatory underwater swimming at maximal effort in male swimmers. Hum. Mov. Sci. 38: 94-105.
・ Shimojo, H., Gonjo, T., Sakakibara, J., Sengoku, Y., Sanders, R., Takagi, H. (2019) A quasi three-dimensional visualization of unsteady wake flow in human undulatory swimming. J. Biomech. 93: 60-69.

・ Triantafyllou, G., Triantafyllou, M. S., and Gopalkrishnan, R. (1993) Optimal thrust development in oscillating foils with application to fish propulsion. J. Fluids Struct. 7: 201-224.
・ von Loebbecke, A., Mittal, R., Fish, F., and Mark, R. A. (2009) Comparison of the kinematics of the dolphin kick in humans and cetaceans. Hum. Mov. Sci. 28: 99–112.
・ Yamakawa, K. K., Shimojo, H., Takagi, H., Tsubakomoto, S., and Sengoku, Y. (2017) Effect of increased kick frequency on propelling efficiency and muscular co-activation during underwater dolphin kick. Hum. Mov. Sci. 54: 276-286.
・ Zamparo, P., Pendergast, D., Termin, B., and Minetti, A. (2002) The contribution of underwater kicking efficiency in determining “turning performance” in front crawl swimming. J. Sports Med. Phys. Fitness. 52: 457-464.