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Marc Elipot, Philippe Hellard, Frédéric Puel, Julien Morlier, Jean-René Cazalets

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Marc ELIPOT, Australian Institute of Sport, Canberra, Australia
Philippe HELLARD, Federation Francaise de Natation, Pantin, France
Frederic PUEL, Faculte des Sciences du Sport, University of Rouen, CETAPS, UPRES EA 3832, Mont Saint-Aignan, France
Julien MORLIER, University of Bordeaux, UMR CNRS 5287, Bordeaux, France
Jean-Rene CAZALETS, University of Bordeaux, UMR CNRS 5287, Bordeaux, France

Abstract — The main aim of this work was to apply to a group of young swimmers an 8 weeks training program focused on the underwater dolphin kick skills and identify the main kinematic and neuro-muscular adaptations resulting of it. The kinematic parameters were measured using a set of cameras placed under the water and in 3D: These parameters were the instantaneous velocity, the amplitude (trajectory corrected vertical distance covered by the end-effector during a single kick), the frequency, the distance per kick (horizontal distance covered by the centre of mass during a single kick), the flexion/extension angles for the main joints (decrease/increase of the joint angle on the sagittal plan), the angles of attack for the main limbs, and the motor coordination between the main joints. The muscles activities were measured using EMG units placed on the quadriceps, the hamstrings, the calf, the gluteal, the lumbar. The time of contraction, the quantity of contraction and the coordination between each muscle activations were then calculated. The main results of this study show an increase of the underwater kicking velocity for 7 of the 8 swimmers that took part to the program. It appeared that the ratio frequency/amplitude was adjusted with an increase of the frequency (reaching 2.5 kicks/second) and a decrease of the amplitude. The study also pointed out the upper body limbs angles of attack were all reduced for all of the swimmers. The results have also shown that each swimmer modified their joint angles using different strategies. Some joints' angles were sometimes increased or decreased depending on the swimmers and no global trend could be identified. However the coordination analysis tends to show that swimmers started developing a synergistic coordination between their joints. EMG data showed that the type of contraction of the muscles had changed. For the lower limbs muscles, the duration of contraction got shorter and the quantity of contraction more important. For the lumbar muscles, the time of contraction got longer and the quantity of contraction lower. The results consequently showed that for the gluteal, hamstring, quadriceps and calf muscles the profile of activation got closer to a phasic contraction, while for the lumbar muscle the profile of activation got closer to a tonic contraction. The sequence of contraction of the muscles was also modified.

Key words: *skills, Underwater kicking, Kinematics, EMG, Starts and turns*

1. Introduction

The temporal analysis of the different phases of a race has shown that dives and turns could respectively represent up to 26% and 40% of the total event time (Cossor and Mason, 2001). A close look at many short distance race analyses also points out that important differences can be created during the starts or the turns and that the underwater kicking phase is determinant for achieving a high level of performance for both starts and turns.

The motor activity of the swimmers when realising the underwater undulatory swimming task can be analysed using a model based on two different but interacting motor components. In this model, the first component is a locomotor component soliciting the swimmer's lower limbs (hip, thighs, legs and feet). This component aims producing the propulsive forces using undulatory kicking movement (Elipot et al., 2010). The second component is a postural component and regroups all the actions produced by the superior limbs. Its main goals are to optimise the transmission of the forces produced by the locomotor component and to minimise the hydrodynamic resistances (Connaboy et al., 2009).

Previous studies have identified 4 main factors conditioning the level of the hydrodynamic resistances during the underwater phases of the starts and the turns (Lyttle et al., 1998 ; Lyttle et al., 2000 ; Toussaint et al., 2002 ; Vennel et al., 2006 ; Marinho, 2009 ; Marinho, 2010 ; Costa, 2010): 1- the underwater swimming velocity of the swimmer; 2- the swimming depth; 3- the skin/ suit roughness; 4- the positions and orientations of every limbs of the swimmer. Recent works analysing the drag forces applied to a fully extended body moving at 2.5 $m.s^{-1}$ have shown that the hydrodynamic resistances are twice lower at a 3m depth than at a 1m depth (Lyttle et al., 1998, Vennel et al., 2006 ; Marinho et al., 2010). Marinho et al. (2009) also pointed out that, when fully under the water, the swimmer's postural activity optimisation significantly reduces the drag coefficients and the hydrodynamic resistances. Finally, Pease and Vennel (2010) have also shown that a decrease of the angle of attack of the trunk-arm segment results in a reduction of the hydrodynamic resistances experienced by the swimmer.

Swimmers' underwater undulatory movements are often compared to aquatic species propulsive actions and to oscillating foils movements (Ungerechts et al., 1998 ; Triantafyllou et al., 2000 ; Arellano et al., 2002). Carangiform fishes create underwater propulsion mostly using their caudal fins and reducing the lateral movements of their trunks and heads. These specific movements allow producing an important backward thrust and a fast forward movement. This backward thrust is the result of a complex mechanism during which the momentum created by the body's movements is transferred to the surrounding water (McHenry et al., 1995).

The propulsive forces created by an oscillating foil moving in a fluid are the result of a periodic and continuous separation of water particles creating vortices (Guglielmini et al., 2004). The thrust production and the propulsion efficiency are then mainly depending on the properties of the street of vertices created by the oscillating movement. A succession of vortices defined as a reverse street of Karman vortices will produce propulsive forces. The properties of such a street of Karman vortices are essentially determined by 3 factors: 1- the angles of attack of the propulsive surface; 2- the Strouhal number; 3- the type of connexion between the heaving and pitching movements of the propulsive surface (Triantafylou et al., 1991 ; Anderson et al., 1998 ; Fish et Rohr, 1999; Read et al., 2003 ; Guglielmini et al., 2004 ; Hover et al., 2004 ; Schouveiler et al., 2005 ; Connaboy et al., 2009).

The underwater undulatory movement is a highly complex motor skill. To be executed at a high level of performance, such a motor task requires the activation of multiple limbs and muscles working together but not especially at the same time and in the same way. When facing a high complexity, it has been shown in many different activities that the brain shows in most cases a specific activation resulting in the production of coordination patterns named synergies (Bernstein, 1967; Latash, 2008; Elipot et al., 2010). In such coordination, the brain reduces the complexity and optimises the movement production and control by grouping the commands sent to the muscles and joints and processing together the sensorial feedback information.

Learning a motor skill having a high level of complexity represents a challenge. The mechanisms and mechanical transformations observed when applying a motor learning program focused on improving the underwater dolphin kicks have never been studied. Consequently, the main goal of this work was to identify the effect of a 8 weeks training program focused on the underwater dolphin kicks and understand the main kinematic and neuro-muscular adaptations resulting of it.

2. Methods

2.1. Participants and training program

Height swimmers aged from 13 to 15 years old and well trained (12 hours/week of swimming) participated to this study. The group followed a specific and integrated learning program aiming to improve the underwater undulatory skills. The sessions were scheduled 3 to 4 times per week, during 8 weeks. Every exercises and drills were integrated to the usual training session, sometimes directly into the main sets or sometimes as an independent set.

The learning program was directly inspired by Bandura's Social Learning theory (1986) and its integrated approach for motor skills proposed by Mc Cullagh et al. (1989). The program was made off 4 different types of learning situations: 1- Situations during which the expected optimal technical model was explained and demonstrated to the swimmers so that they could reproduce the correct actions; 2- Situations emphasising the sensori-motor and energetic training on dry-land and in the water; 3- Situations applying the biofeedback principles (self-regulations using immediate or semi-immediate video or kinematic feedbacks); 4- Situations during which the constraints of the task to realise were altered.

A pre-test and a post-test were conducted to monitor the evolution of the key kinematic and neuro-muscular adaptations. During these testing sessions, the swimmers were asked to perform 5 × 25m of underwater dolphin kicks at a maximum intensity. Only the section between the 10^{th} and 20^{th} meters was processed so that the analysed data were not affected by the impulse on the wall. Also, the fastest and slowest trials (time to cover the 10m of interest) were not processed. Only the 3 intermediate trials were analysed.

2.2. Kinematic data

Six camcorders (576 × 720) were used to collect the kinematic data. All the camcorders were placed in the water in waterproof housings. The cameras were positioned in such a way that the entire zone from the 10^{th} to the 20th meter marks was continuously shot by at least 2 camcorders (figure 1).

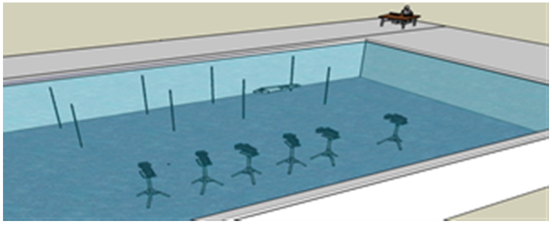

Fig. 1 Experimental setup.

The main joints of the swimmer's body were marked using black tape. These joints were: Finger tips, wrist, elbow, shoulder, head, knee, ankle, and toes (Winter, 1990). The pixel positions of these anatomical landmarks were manually digitised using a custom made user interface on Matlab. To minimise the digitising errors, both sides of the swimmer's body were considered as symmetrical. Consequently, only the markers on the left side of the swimmers were tracked. The videos were recorded at 25 frames/second and deinterlaced to finally obtain 50Hz clips.

A calibration frame was built using 8 independent poles and put in the water to cover the whole area of interest (figure 1). Each pole had 8 calibration points. The area of interest was calibrated using a method inspired by the 3D DLT algorithm (Abdel-Aziz and Karara, 1971 ; Elipot et al., 2010). The calibration accuracy was evaluated as defined by Kwon and Fiaud (2002) using the average and maximal reconstruction errors. The average reconstruction errors were respectively for the pre-test and post-test 0.8cm and 0.76cm (maximal errors: 1.3 and 1.27cm).

Once the metric coordinates of all the anatomical landmarks calculated, the position of the centre of mass was identified using the Dempster's anthropometric table (Dempster, 1959, Winter, 1990). The obtained data were then filtered using a Butterworth filter. The cut off frequencies and orders were selected individually analysing the residual curve of each signal (Winter, 1990). The cut off frequencies were included between 3 and 7Hz. The velocities of each anatomical landmark and the centre of mass were calculated. The angles of attack of the hand, the forearm, the arm, the trunk, the thigh, the leg and the foot were computed too. Each underwater undulatory cycle was defined from the highest point of the ankle to its next highest point. Kicking frequencies, amplitudes and distance per cycle were computed. Finally, the Strouhal number was calculated for each kick as defined by Triantafyllou et al. (1991).

2.3. Electromyographic data

The electromyographic data were collected using tripolar surface electrodes (diameter: 10 mm; interelectrode distance: 10 mm) connected to the wireless KineMyo system (Kine ehf Inc.). The activities of the following muscles were recorded: Lumbar (spinae erector at the T3 level), Gastrocnemius, Gluteus Maximus, Quadriceps (rectus femoris) and Hamstrings**.**

All the EMG signals were filtered using a low pass Butterworth filter, rectified, synchronised with the kinematic data and finally cut into individual files for each undulatory cycle. The envelopes were calculated using a 250ms long sliding window. The active phases of contraction of each muscle were identified as defined by Stirn et al. (2011) and the duration of contraction was determined from it. The quantity of contraction was calculated from the signal integral and the peak of contraction was identified.

2.3. Statistics

The comparisons between the pre and the post tests were realised using a one way ANOVA test for repeated measures (level of confidence $\alpha = 0.05$).

3. Results

Swimmers' improvements were assessed analysing the centre of mass average velocity per kick for each trial. The ANOVA comparisons show that for 7 out of the 8 swimmers, the centre of mass average velocity was significantly higher during the post-test. For the last swimmer, his velocity was significantly lower (table 1).

3.1. Descriptive kinematic parameters

The data relative to the evolution of the distance per dolphin kick show that 3 swimmers have a significantly higher distance per kick after the program, 4 have a significantly lower distance per kick, and 1 didn't show any significant evolution (table 2). Data relative to the amplitude/frequency ratio are displayed in table 3. The results show that the amplitude was significantly decreased and frequency significantly increased for half of the swimmers. The other half didn't show any significant evolution of the frequency/amplitude ratio.

3.2. Angular kinematic parameters

3.2.1 Postural component (upper body)

The analysis of the angles of attack of the hand (Hd), the forearm (F.A), the arm and the trunk (Tk) are presented in table 4. The results clearly show that almost all of the upper body angles of attack for all the swimmers are significantly lower after the program.

Table 1 (Left). Center of mass average velocities ($m.s^{-1}$) for the pre and post-tests; Table 2 (Right). Distance per kicks (m) for the pre and post-tests

	S1	S2	S3	S4	S5	S6	S7	S8
Pre-test	0.81	1.4	0.88	1.25	1.38	0.84	0.98	0.77
Post-test	1.23	1.45	1.07	1.17	1.46	1.14	1.15	1.09
Evolution	+0.42*	+0.05*	+0.19*	-0.07*	+0.08*	+0.1*	+0.17*	+0.32*

* Significant difference for α = 0.05

	S1	S2	S3	S4	S5	S6	S7	S8
Pre-test	0.35	0.66	0.49	0.51	0.55	0.52	0.42	0.49
Post-test	0.55	0.62	0.53	0.5	0.05	0.49	0.47	0.42
Evolution	+0.2*	-0.04*	+0.04*	+0.01	-0.05	-0.03	+0.05*	-0.07*

Table 3. Individual amplitudes (m) and frequencies ($kick.sec^{-1}$) for the pre and post-tests

	S1		S2		S3		S4		S5		S6		S7		S8	
	Amp	Freq	Amp	Freq	Amp	Freq	Amp	Freq	Amp	Freq	Amp	Freq	Amp	Freq	Amp	Freq
Pre-test	0.48	2.38	0.51	2.27	0.52	1.86	0.56	2.55	0.46	2.63	0.55	1.69	0.42	2.51	0.50	1.63
Post-test	0.49	2.35	0.51	2.40	0.48	2.17	0.56	2.46	0.39	3.09	0.48	2.43	0.42	2.58	0.34	2.81
Evolution	+0.01	-0.03	=	+0.13	-0.04*	+0.31*	=	-0.09	-0.07*	+0.46*	-0.07*	+0.74*	=	+0.07	-0.16*	+1.18*

* Significant difference for α = 0.05 With: Amp: Amplitude Freq: Frequency

The analysis of the upper body joints' angles (wrist, elbow and shoulder) is presented in table 5. The results for the wrist angle show that, 3 swimmers have significantly lower angle values after the program, 3 other swimmers have significantly higher values, and the value stays the same for the last two swimmers. The results for the elbow angle show that 3 swimmers score a significantly higher elbow angle after the training program, 4 swimmers a significantly lower angle and the value remains the same for the last one. Finally, it appears that 2 swimmers present the same shoulder angle before and after the training program, 2 swimmers have significantly increased the shoulder angles and the last 4 swimmers have significantly decreased their shoulder angles.

3.2.2 Locomotor component (lower body)

The Strouhal number individual comparisons shows that 6 out of 8 swimmers have significantly lower values after the training program (table 6). The 2 other swimmers don't present any significant evolution.

The analysis of the angles of attack of the foot, the leg, and the tight are also presented in table 4. The results for the foot angle of attack show that 4 swimmers present significantly lower values after the training program, and 4 present significantly higher values. The results for the leg angle of attack show that 4 out of 8 swimmers score significantly higher values after the training program, 2 other ones score significantly lower values, while the remaining 2 don't present any significant differences. Finally, the results for the thigh angle of attack point out that 5 swimmers present significantly lower values after the training program, while 1 has significantly higher values and the 2 remaining don't present any significant evolution. Finally, the results of the lower limbs joints angles are displayed on the table 5. It appears that 3 swimmers scored a significantly higher maximum hip angle during the post-test, while 3 others scored similar maximum hip angles and 2 others significantly lower maximum hip angles. In the same way, 4 swimmers present a significantly lower maximum knee angle after the training program, while only 1 has a significantly higher value. Three swimmers don't show any significant difference. Finally, 5 swimmers show a significantly lower maximum ankle angle, 1 shows a significantly higher maximum ankle angle and 2 didn't show any difference.

3.3. EMG parameters

The EMG data firstly show that the durations of contraction of the gluteus maximus, the hamstring, the rectus femoris and the gastrocnemius were significantly shorter after the training program for almost all the swimmers. In some rare cases, no significant different were recorded. In parallel, the quantities of contraction for the same muscles appear to be significantly higher after the training program in almost every case (table 7). The results for the duration of contraction of the erector spinae were not significantly different. However, the quantity for contraction for this muscle was significantly lower for all the swimmers (table 7).

The results for the timing of contraction relative to the beginning of the upbeat for the gluteus maximus and the hamstrings are quite conclusive. It clearly appears that the maxima of contraction between the gluteus maximus and hamstrings are significantly closer for all the swimmers except 1 that didn't show any significant difference. The results also show that the maxima of contraction of these muscles occur significantly closer to the beginning of the upbeat. In the same way, the results for the timing of the maxima of contraction for the gastrocnemius and the rectus femoris clearly show that the maxima of contraction of the gastrocnemius and the rectus femoris are significantly closer to each other after the training program for all the swimmers, except 1 that didn't show any significant difference. It also appears that the maxima of contraction of both muscles occur significantly closer to the downbeat initiation after the training program.

4. Discussion

The principal goal of this study was to identify the main kinematic and muscular modifications observed after a motor learning program focused on the underwater undulatory kicking skills. It appears that the very large majority of the swimmers participating to this study present a higher underwater kicking velocity after the training program. It is reasonable to think that such a performance improvement occurred thanks to important technical transformations. The first variable that may contribute to the observed velocity increase is the distance per kick. However, the analysis of the distance per kick evolution doesn't show any characteristic trend for all the swimmers. Some swimmers present a higher distance per kick while some others show lower or similar values. The velocity increase cannot then consistently be related to a specific increase or decrease of the distance per kick. The second variable having a potential impact on the velocity increase is the amplitude/frequency ratio of the kicks. The results of this study show that the swimmers having a specifically low frequency and high amplitude during the pre-test adapt their ratio by increasing the frequency and decreasing the amplitude. The other swimmers, having an initial frequency already quite high, didn't show any difference. It consequently appears that all the swimmers individually responded to the training program to show an optimal kicking frequency approximately included between 2.2 and 2.8 kicks/sec. These results are in agreement with the findings presented by Shimojo et al. (2014). Shimojo et al. (2014) indeed concluded that an increase of the kicking frequency wasn't always resulting in an increase of the underwater kicking speed, but that a reduction of the kicking frequency was significantly related to a decrease of the underwater undulatory swimming velocity. These findings strongly suggest the existence of an individual optimal kicking frequency, determined by the swimmer's skills and physical characteristics. The increase of the kicking frequency would allow then the swimmers optimising the net wise force and the swimming speed (Cohen et al., 2012). However, kicking at a frequency higher than what their skills and physical characteristics allow would result in a significant loss of efficiency and/or velocity for the swimmers (Yamakawa et al., 2017).

The systematic modification of the angles of attack for the postural component suggests that the control of the swimmers' upper body was adjusted in such a way that the hydrodynamic resistances were reduced. It is consequently possible that the improvement of the postural component through a better control of these angles of attack had direct consequences on the level of performance (Marinho et al., 2009). Furthermore, an increase of the upper body stiffness, as observed in this study, also results in a better transmission of the propulsive forces produced by the locomotor component (Connaboy et al. 2009).

Given that the limbs angles of attack are the results of the actions of all the proximal joints, it might be possible to formulate the hypothesis that the important modifications observed on the superior limbs angles of attack are related to important and characteristic modifications of the joints motor behaviours. However, the results show that they are no characteristic trends to define the evolution of the single actions of the shoulder, elbow or wrist. It indeed appears that each swimmer selected a different strategy to adopt a better control of the postural component. These observations are consistent with the results of multiple studies in other activities showing that an efficient postural control is rather achieved through the development of global multi-joints synergies rather than the individual control of a single joint (Latash, 2008; Alexandrov, 1998).

Furthermore, the analysis of the muscular contractions of the spinae erector shows a clear modification in its contraction pattern. This muscle went from a phasic type of contraction to a pattern rather similar to a tonic contraction: same duration of contraction, but lower quantity of contraction and lower peaks of contraction. This evidence supports the previous results pointing out that, after the training program, the swimmers rather adopt a body configuration with a fix and stiff postural component, resulting in a potential reduction of the drag and an increased transfer of momentum from the kicking movements to the water (Connaboy et al. 2009).

The propulsion efficiency, related to the actions of

Table 4. Individual max angles of attack (°) for the pre and post-tests

	S1				S2				S3				S4				S5				S6				
	Hd	F.A	Arm	Tk	Hd	F.A	Arm	Tk	Hd	F.A	Arm	Tk	Hd	F.A	Arm	Tk	Hd	F.A	Arm	Tk	Hd	F.A	Arm	Tk	Hd
Pre-test	64	9	29	16	59	11	17	15	61	16	30	14	55	12	16	19	52	14	10	19	62	14	21	28	60
Post-test	57	2	22	21	56	9	12	12	57	12	20	15	57	10	13	17	56	8	14	14	57	6	17	20	56
Evolution	-7*	-7*	-7*	+5*	-3*	-2	-5*	-3*	-4*	-4*	-10*	+1	+2	-2	-3*	-2*	+4*	-6*	+4*	-5*	-5*	-8*	-4*	-8*	-4*

	Foot	Leg	Tight	Foot	Leg	Tight	Foot	Leg	Tight	Foot	Leg	Tight	Foot	Leg	Tight	Foot	Leg	Tight	Foo
Pre-test	37	4	24	24	15	10	35	60	20	24	41	16	30	37	16	41	56	22	26
Post-test	30	30	20	29	30	14	29	58	15	32	45	12	26	41	15	34	45	19	25
Evolution	-7*	+26*	-4*	+5*	+15*	+4*	-6*	-2	-5*	+8*	+4*	-4*	-4*	+4*	-1	-7*	-11*	-3*	+1

* Significant difference for α = 0.05 With: Hd: Hand F.A: Forearm Tk: Trunk

Table 5. Individual max joint angles (°) for the pre and post-tests

	S1			S2			S3			S4			S5			S6			
	Wrist	Elbow	Shoulder	Wrist	Elbow	Shoulder	Wrist	Elbow	Shoulder	Wrist	Elbow	Shoulder	Wrist	Elbow	Shoulder	Wrist	Elbow	Shoulder	Wrist El
Pre-test	58	35	10	54	12	6	47	43	16	52	21	9	49	9	16	57	29	16	53
Post-test	53	22	10	52	19	6	54	24	8	55	17	13	54	17	8	53	20	8	54
Evolution	-5*	-13*	=	-2	+7*	=	+7*	-19*	-8*	+3*	-4*	+4*	+5*	+8*	-8*	-4*	-9*	-8*	+1

	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip	Knee	Ankle	Hip
Pre-test	8	65	14	14	58	3	14	62	25	20	52	11	29	43	4	26	73	19	16
Post-test	19	56	11	20	50	8	24	64	15	21	48	5	25	47	6	25	55	10	8
Evolution	+11*	-9*	-3	+6*	-8*	-5*	+10*	-2	-10*	+1	-4*	-6*	-4*	+4*	+2	-1	-18*	-9*	-8*

* Significant difference for α = 0.05 NB: All joint angles are presented in absolute values

Table 6 (Left). Strouhal numbers for the pre and post-tests; Table 7 (Right). Evolution of the quantity and duration (s) of contraction during the pre and post-tests

	S1	S2	S3	S4	S5	S6	S7	S8
Pre-test	1.41	0.81	1.09	0.91	0.88	1.09	1.06	1.04
Post-test	0.94	0.82	0.98	0.94	0.82	1.02	0.93	0.86
Evolution	-0.47*	+0.01	-0.11*	+0.03	-0.06*	-0.07*	-0.13*	-0.18*

* Significant difference for α = 0.05

	S1		S2		S3		S4		S5		S6		S7	
	Dur	Qty	Dur	Qty	Dur	Qty	Dur	Qty	Dur	Qty	Dur	Qty	Dur	Qty
Gluteus	-0.14*	+1.48*	-0.08*	+1.28*	-0.04*	+0.04	-		-0.03	+1.42*	-0.22*	+1.69*	-0.06	+1.12
Hamstring	-0.05*	+1.30*	-0.14*	+2.29*	-0.05*	+2.01*	-		-0.04*	+4.52*	-0.12*	+0.45*	-0.06*	+2.08
Quadriceps	-0.09*	-0.50	-0.1*	+3.58*	-0.02	+0.98	-		-0.05*	+2.84*	-0.05*	+1.35*	-	
Gastrocnemius	-0.11*	+2.41*	-0.06*	+3.21*	-0.03	-0.39*	-		-0.04*	+1.75*	-0.10*	+5.71*	-	
Lumbar	-0.01	-1.48*	0	-1.28*	+0.01	-1.04*	-		-0.02	-1.42*	+0.01	-1.44*	+0.02	-1.12

With Dur: Duration Qty: quantity

the locomotor component, is as defined by Hover et al. (2004) a function of: 1- the Strouhal number; 2- the maximal angle of attack of each segment involved; 3- the profile of the angle of attack signal. The results of this study show individual evolutions of the lower limbs' angles of attack for each swimmer. However, all the swimmers score values included between approximately 20 and 40° depending on the limbs (thigh, leg or foot). The swimmers also show a significant decrease of the Strouhal number (from values close to 1-1.1 to values close to 0.8-0.9). Hover et al. (2004) showed that for a cosine profile of angles of attack, as observed in this study, and for angles of attack included between 20 and 35° , the propulsion efficiency of a foil is substantially increased when the Strouhal number is reduced and gets closer to 0.3-0.5. We might consequently formulate the hypothesis that, given the results observed in this study, the swimmers' propulsive efficiency was increased after the training program. The high Strouhal number values observed in this study are similar to the values observed in other publications (Hochstein at al., 2014; Connaboy et al., 2009). Hochstein et al. (2014) points out that these high values, compared to swimming animals, are logical as the swimmers are mostly trying to reach the highest velocities and don't directly try to optimise their underwater undulatory swimming efficiency.

Same as for the postural component, the results for the locomotor component don't show any characteristic and systematic evolution of the joints' angles. The observations made for the lower limbs' angles of attack and propulsive efficiency can't be consequently explained by a modification of the actions of a single lower body joints. However, a trend can be noticed for the knee control. Swimmers having indeed a large knee flexion at the beginning of the program tend to lower it, which is consistent with results find in previous studies (Arellano et al., 2003, Higgs et al., 2017).

The combined analysis of the duration of contraction and quantity of contraction for the locomotor component muscles shows an opposite trend as what observed for the postural component. It indeed appears that the gastrocnemius, the gluteus maximus, the hamstring and the rectus femoris present a pattern closer to a phasic contraction after the training program than before: shorter duration of contraction but higher quantity of contraction. We can hypothesise that the swimmers' capacity in producing these short but strong muscle contractions has had an effect on the kicking frequency increase. Finally, the EMG results also clearly show a modification of the coordination involved between the different muscles of the locomotor component. It indeed appears that the hamstring and gluteus maximus, mainly involved during the upbeat movement, are re-synchronised after the training program, so that their maxima of contraction occur almost at the same time and at the beginning of the upbeat. In the same way, the rectus femoris and gastrocnemius, mostly responsible for the downbeat movement, are re-synchronised after the training program so that their maxima of contraction is also occurring almost at the same time but at the beginning of the downbeat. Consequently, the modification of the type of contraction seem to allow reaching higher kicking frequencies and the modification of the coordination may have an impact on the swimmers' capacity to produce more efficient movements. The type of muscular contractions observed during the underwater undulatory swimming (phasic versus tonic) has never been directly addressed. Yamakawa et al. (2017) recently showed that, when increasing the underwater kicking frequency, the resulting increase of the magnitude of muscular activation did not allow an increase of the swimming velocity. The increase in the muscle co-active phase would possibly lead to a decrease in the net torque power produced by the swimmer (Winter, 2009; Yamakawa et al., 2017). However, the results of these studies are based on conditions where the swimmers were forced to modify their kicking frequency without any specific and prior training. The purpose of the training program proposed in this current study was actually to allow the swimmer increasing their kicking frequency while maintaining a good level of skills and then a good efficiency.

Globally, these findings seem to point out that the modification observed at the level of the postural component aren't supported by a correction of the control of a specific joint or a specific muscle. Same as for the postural component, this study tend to show that the swimmers have first of all modify their coordination, improving the interactions between all the elements of the system (muscles and joints). These results are consistent with the results of some previous works (Elipot et al., 2012) or what is observed in other activities (Berstein, 1967; Latash, 2008).

Conclusion

This study investigated the effects of a training program on the kinematic and neuro-muscular characteristics of the underwater undulatory swimming. Our main findings suggested that: 1- The underwater swimming velocity was significantly increased; 2- The increase of the swimming velocity couldn't be directly associated to the modification of a single joint or muscle action, but was rather caused by an optimisation of the coordination between each elements (joints and muscles) of the swimmer's body; 3- The swimmers tend to find an optimal frequency/amplitude ratio, individually determined depending on their personal skills and physical characteristics.

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