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Review article

Kinematic and electromyography characteristics of performing butterfly stroke with different swimming speeds in flow environment

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ABSTRACT

Objective: To investigate effect of flow speeds on the upper limb muscular activity of butterfly swimmers training in a flow environment. A comparison of kinematic characteristics and muscular activity of upper limbs were made when the swimmers training with different flow speeds in a swimming flume. The purpose was to provide a basis for scientifically formulating special swimming training advice for athletes' training in flow environment.
Methods: Ten youth female butterfly swimmers participated in the study with the speed of 70%, 80%, and 90% level of their max speeds. A stroke cycle was divided into four phases (entry, pull, push, and recovery). The kinematic parameters of upper limbs (stroke rate, stroke length, duration of each phase in a stroke cycle) and muscular activity (onset timing, integrated electromyography (iEMG), contribution ratio) of four muscles (Biceps brachii (BB), Triceps brachii (TB), Pectoralis major (PM), and Latissimus dorsi (LD)) were collected and analyzed in different stroke phases.
Results: There was no significant difference between stroke rate and stroke length with different flow speeds. There were significant differences among the duration of the four stroke phases. The entry phase had the longest duration, the pull phase had the shortest duration, the push phase was longer than the recovery phase, and the recovery phase was shorter than the entry phase. The BB and PM were activated significantly earlier at 90% of target speed than at 80% of target speed, while the TB was activated significantly later than other two speeds. The muscular contribution ratio of the PM was highest in the pull phase and lowest in the pushing phase. The muscular contribution ratio of the BB was significantly lower in the pushing phase than in other three stroke phases. The muscular contribution of the TB was significantly higher in the recovery phase than in other three stroke phases. The muscular contribution ratio of the LD was highest in the pushing phase, and it was significantly higher in pushing phase and recovery phase than in pull phase.
Conclusions: (1) When butterfly athletes training with 70%, 80% and 90% of their max speed in a flow environment, it didn't make significant differences between the kinematic or muscle activation characteristics of the upper limbs movement except the muscle onset timing. (2) Stroke phase was the main factor of the duration and the muscle contribution ratio during butterfly arm stroke for young athletes.

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1. Introduction

Swimming is a kind of self-propulsive locomotion carried in aquatic environment. Flow environment that simulates swimming was very important for elite athletes as there was no able to replace swimming with other exercise [1]. When the swimmers cannot sustain normal training in the swimming pool by some reasons, some alternative methods of swimming training have been proposed, such as tethered-swimming using a small pool with a bungee cord, a tub and a swimming flume or an endless swimming pool.

Flume and thread swimming were both important methods to measure the ability of the swimmers effectively apply force in the water. The comparison between pool and flume swimming suggested that swimmers training in the pool obtained the same results as those obtained in the flume and strong positive correlations were found besides small differences in the arm stroke's mean acceleration curve by tri-axial accelerometers [2]. Furthermore, flume swimming enabled assessment of the ability to effectively apply force in the water at higher water-flow velocities better [3]. Flume swimming allows the swimmer to adjust the speed and direction of the water flow, and to swim at different speeds and distances. It also simulates the effects of drag, buoyancy and motor behavior on the swimmer [4–8].

Because of the complexity of the movement in an aquatic environment, the measurement of surface electromyography characteristics of swimmers was not easy to carry out. Previous studies had examined the difference in muscle activation pattern and co-contraction of upper or lower limbers compared the different muscular activation between different levels of swimmers [9–14]. However, these studies focused mostly on front crawl swimming and merely mentioned other effect on muscle activation such as different swimming speed. The research on backstroke, breaststroke and butterfly and related feedback remain limited [15].

As the expert swimmers can maintain consistent and stable coordination when swimming between the pool and flume, a study about the effect of difference speeds using a flume on swimmers stroke would be valuable. More details about choosing an appropriate flow speed to match different training loads and how the flow environment affects the swimming technique and performance must be helpful for swimmers' training.

This study aimed to investigate the differences between butterfly strokes with different flow speed when the young athletes training in a flow environment. We hypothesized that: 1) The kinematic variables would increase with the swimming speed increasing; 2) The upper-limb muscles would show significant differences with different flow speeds.

2. Methods

2.1. Subjects

A group of ten young female butterfly swimmers (age 15.9 ± 1.9 years, height 164.8 ± 4.5 cm, weight 51.8 ± 6.7 kg, FINA score 510–611) took part in this study. All of them were on a professional swimming team for 3–5 years and had no less than 20 h training every week without any injury in the past half year (Table 1). The subjects and their guardians consented to participate in this study after being informed of the purpose of the experiment. The study was reviewed and approved by the local ethics committee.

2.2. Testing procedures

The test was carried out in an indoor flume (TZ Leipzig, Germany) in Shanghai Swimming Training Center. The water temperature was about 26.5 °C and the room temperature was about 30 °C. All the subjects had a good rest before the test, and the swimmers performed a 15-min personalized warm-up in the flume with a self-selected flow speed before the test to undergo familiarization trials in the swimming flume. The speed of flow in the flume was set as 70%, 80% and 90% of their 200 m butterfly swimming maximal speed increasingly in the formal study. Participants were told to finish 3 trials in each flow speed for 30–40s to avoid fatigue [16] with 5 min rest for each trial. They had a more than 15 min rest between different speeds. To minimize the effect of the breathing pattern and maintain a general temporal stability in stroke phases performed when breathing, the swimmers adopted one breath every stroke in butterfly according to the prior study [4].

2.3. Data collection

The surface electromyography (sEMG) was measured using a wireless recorder with 8-channels sEMG waterproof sensors (Myon aktos, Switzerland). The sEMG data were recorded at a sampling frequency of 2000 Hz with 16-bit analogue to digital conversion. sEMG signals were recorded from 4 muscles (long head of Biceps brachii [BB], short head of Triceps brachii [TB], Latissimus dorsi [LD], Pectoralis major [PM]) based on previous studies of the shoulder movement [12,13,17,18]. Bipolar Ag– AgCl circular surface electrodes (3 M health care Inc.). The EMG signals were recorded from the left side of the body using bipolar (inter-electrode distance of 0.02 m) disposable Ag–AgCl circular electrodes. The locations of the electrodes were placed parallel to the direction of muscle fibers

Table 1
Essential information of participation.

Height (cm)	BW (kg)	Age (yr)	Years of athletes training	level
164.8 ± 4.5	51.8 ± 6.7	15.9 ± 1.9	3–5	Master

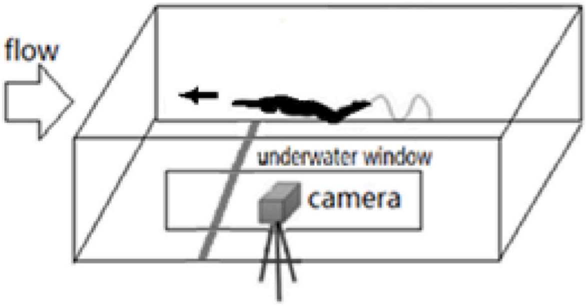

Fig. 1. Example of experimental design.

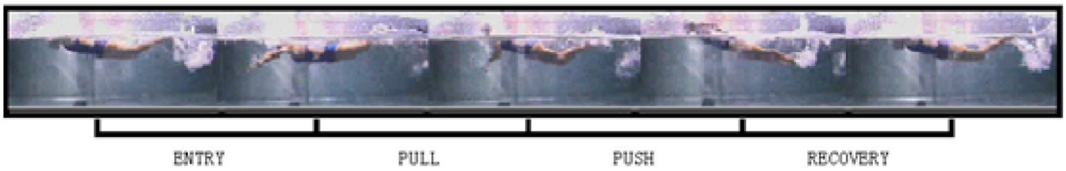

Fig. 2. Four phases of the butterfly stroke divided by the hand according to the video: Entry phase, Pull phase, Push phase and Recovery phase.

in the midpoint of the contracted muscle belly [19–22], according to International Society of Electrophysiology and kinesiology placement recommendations. Before electrode fixation, the skin surface was shaved and cleaned with alcohol. The electrodes were covered with water resistant transparent dressing tape (Tegaderm roll, 3 M health care Inc.) using the methodology of Kobayashi [23].

One camera filmed the sagittal swimmer's motion and recorded through underwater windows at a 50 Hz sampling rate (Fig. 1). The video was synchronized with the sEMG signals when starting the sEMG sensors [24].

2.4. Data treatment

Kinematical analyses comprised different phases of a complete stroke cycle according the former report [9,16,25] using DARTFISH 10.0 (Switzerland). The stroke rate (SR) and stroke length (SL) were calculated from 5 stroke cycles in the videos. The stroke rate (SR) was calculated as the reciprocal of average duration of 5 arm stroke cycles. As the swimmers were told to keep their body at a stable position in the flume with different flow speeds, so a stroke length was calculated as product of the duration(T) of a whole arm stroke and the water flow speed (U): $SL[m] = U[m/s] \times T[s]$. A butterfly arm stroke was divided into four phases [25].

(i) Entry phase (P1): comprised between the entry of the hand into the water;
(ii) Pull phase (P2): from the beginning of the backward movement of the hand to its entry into the vertical plane to the shoulder;
(iii) Push phase: between the positioning of the hand vertically below the shoulder and its exit from the water;
(iv) Recovery phase: between the exit of the hand from the water and its subsequent entry into the water (Fig. 2).

The duration of each phase was expressed in seconds and normalized by the total time duration of the stroke cycle (cycle %).

The sEMG data was acquired and exported using the EMG and Motion Tools 4.0.2.2 software (Cometa S. r.l, Italy). The sEMG processing was performed in MATLAB 2008a (Mathworks Inc., USA). Raw sEMG signals were full-wave rectified and filtered by a band-pass filter between 10 Hz and 500 Hz. The integrated sEMG was calculated by individual stroke phase. The Root Mean Square (RMS) curves were calculated on a 50 ms window of data according to prior studies. A percentage of average peak value of RMS was calculated to estimate the magnitude of muscular discharge for each muscle in the consideration of the fact that there is no consensus on the best normalization technique for dynamic tasks [14,26]. From the RMS curves, the onset of the muscle activation was confirm as the stroke length was above 10% of the peak value. Since different swimmers may show different stroke rate in each trial, the active phase (cycle %) was defined as the relative active phase, which is normalized by the stroke cycle time [10].

2.5. Statistics analysis

Mean and standard ($M \pm S$) deviation computations for descriptive analysis were obtained for most of the variables. Normal distribution of data was tested using Shapiro–Wilk test, and homogeneity was performed with Levene's test. Two-way Repeated Measures ANOVA (speed: 70%, 80%, and 90% of maximal speed × phase) was performed for the phase duration and muscular contribution ratio in each phase with different flow speeds, and Bonferroni was used for the post-hoc test. One-way Repeated Measures ANOVA (speed: 70%, 80%, and 90% of maximal speed) was performed for the onset timing of the muscle activation and kinematic parameters in a cycle with different flow speeds. All analysis was performed using SPSS 19.0 for Windows (SPSS Inc., Chicago, IL, USA). An alpha level of 5% was used for all statistical tests.

3. Results

3.1. Results of kinematic variables

Table 2 showed there was no significant interaction between flow speeds and the percentage of duration of each phase in a stroke cycle ($P = 0.235$). The flow speed had no significant effect on a stroke cycle ($P = 0.134$) (see Table 2). Regardless of the speed, there was a significant difference between the duration of different phases ($P < 0.001$). Entry phase cost a longest period in a stroke, and the pull phase was the shortest compared with the other phases (Fig. 3).

The results of the kinematic parameters were shown in Table 3. Statistical result showed there was no significant difference in stroke rate or stroke length with different flow speeds ($P > 0.05$). With the speed increasing, the stroke rate and stroke length increased both. Moreover, the stroke rate increasing a little faster than the stroke length.

3.2. Results of surface-electromyography variations

Table 4 and Fig. 4 illustrated the contribution ratio of each muscle in different phases in a stroke cycle. The pectoralis major had no difference between the entry and recovery phase. The contribution ratio of pectoralis major was the highest ($P < 0.05$) in pull phase, whereas at the push phase it was the lowest ($P < 0.05$). In push phase, the contribution ratio of latissimus dorsi was the highest ($P < 0.05$) among the muscles analyzed. However, it was the lowest in pull phase and the recovery phase. The contribution ratio of biceps brachii showed relative higher in both entry and recovery phases. Nevertheless in push phase, the contribution ratio of biceps brachii was significant lower, while the triceps brachii showed an opposite activity state completely. The contribution ratio of triceps brachii in push phase was much higher. Both the biceps brachii and the triceps brachii showed similar contribution ratio in other phases.

The onset of muscle activation showed difference significantly with different exercise intensities. The pectoralis major, latissimus dorsi and biceps brachii active more lately with the 80% max speed ($p = 0.016$, $p = 0.017$) compared with 70% or 90%. The latissimus dorsi and triceps brachii activated earlier with the swimming speed increasing. The triceps brachii showed an obvious variation. Swimming with 70% the triceps brachii active more lately than both the 80% ($p = 0.013$) and the 90% (Fig. 5).

Table 2
The duration of each phase in a stroke cycle with different flow speeds.

Phases	speeds			Interaction		Phases		speeds	
	70%	80%	90%	F	P	F	P	F	P
P1	37.10 ± 5.47	35.67 ± 6.24	32.13 ± 7.20	1.392	0.235	85.485	<0.001	2.250	0.134
P2	16.70 ± 2.79	16.89 ± 2.92	20.88 ± 9.73						
P3	25.90 ± 2.66	25.78 ± 3.26	23.63 ± 5.02						
P4	20.40 ± 1.85	21.11 ± 2.08	22.75 ± 2.86						

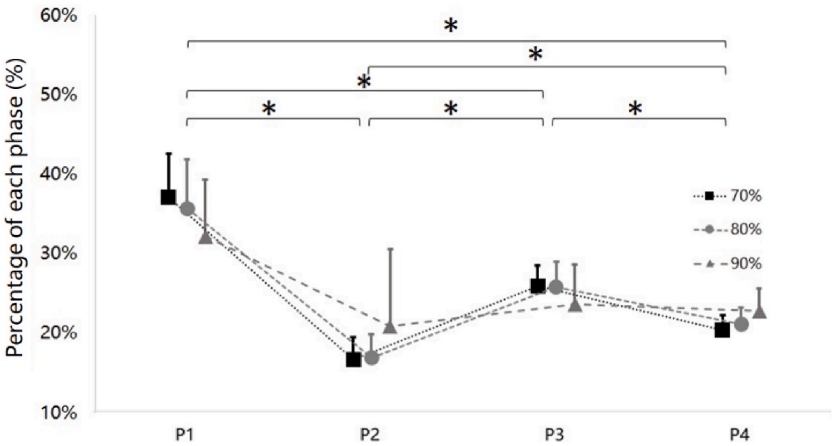

Fig. 3. The percentage of each phase in a stroke cycle with different flow speeds. P1: Entry phase, P2: Pull phase, P3: Push phase, P4: Recovery phase.*: indicated significant difference between phases.

Table 3
The kinematic parameters of different.

	speed(m/s)	$\triangle_{Speed}$%	SR(/min)	$\triangle_{SR}$%	SL(m)	$\triangle_{SL}$%
70%	1.10 ± 0.04	–	41.89 ± 3.58	–	1.59 ± 0.14	–
80%	1.18 ± 0.04	+7.27	43.82 ± 3.58	+4.62	1.65 ± 0.14	+4.23
90%	1.33 ± 0.04	+12.71	45.83 ± 4.71	+4.59	1.72 ± 0.19	+3.92

Table 4
The contribution ratio of muscles with different flow speeds.

		speeds			Interaction		Phases		speeds	
	Phases	70%	80%	90%	F	P	F	P	F	P
PM	P1	17.53 ± 5.66	18.49 ± 10.85	20.83 ± 12.01	0.227	0.966	33.399	<0.001	0.395	0.681
	P2	25.90 ± 8.59	26.22 ± 8.02	28.35 ± 8.65						
	P3	5.76 ± 1.10	6.28 ± 1.44	7.12 ± 1.48						
	P4	23.78 ± 9.40	19.33 ± 5.33	23.68 ± 7.19						
BB	P1	33.49 ± 10.45	31.10 ± 9.74	28.30 ± 11.44	0.677	0.669	20.708	<0.001	0.277	0.762
	P2	29.16 ± 9.80	29.32 ± 8.26	28.00 ± 11.09						
	P3	10.92 ± 3.92	11.26 ± 3.48	11.86 ± 2.36						
	P4	31.86 ± 13.45	37.08 ± 13.90	36.94 ± 14.18						
TB	P1	28.58 ± 13.02	27.71 ± 14.77	33.73 ± 16.86	0.374	0.891	19.066	<0.001	0.256	0.777
	P2	29.64 ± 10.12	30.02 ± 9.02	28.80 ± 9.69						
	P3	51.91 ± 7.10	51.26 ± 7.26	50.94 ± 7.98						
	P4	31.11 ± 14.29	30.94 ± 13.88	29.31 ± 13.28						
LD	P1	20.39 ± 7.30	22.70 ± 7.58	17.14 ± 7.14	0.523	0.788	44.497	<0.001	2.844	0.092
	P2	15.30 ± 5.92	14.44 ± 5.26	14.86 ± 6.27						
	P3	31.41 ± 6.38	31.19 ± 6.91	30.08 ± 6.07						
	P4	13.26 ± 4.81	12.65 ± 5.32	10.06 ± 2.97						

4. Discussion

4.1. The effect of different flow speeds on kinematic characteristic

This study aimed to investigate the effect when training with different flow speeds on kinematic parameters and sEMG of swimmers' upper-limbers. The kinematic results showed that the stroke rate or stroke length didn't show significantly difference between 70%, 80% and 90% of max speed when swimming in a flume. The results were inconsistent with the hypotheses of this study. Although the increasing didn't have statistic significant, we found the increasing of swimming speed lead to the tendency of the stroke rate and length increased both in our study, which was consistent with literature about butterfly swimming. These results were inconsistent with previous results about front crawl [27]. Franken [28] found the stroke rate increased with swimming speed increasing under 90%–105% extreme load with the stroke length decreased, which was thought as a neuromuscular adaptation to accommodate greater a swimming intensity [29]. The swimming speed was calculated by stroke rate times stroke length. A similar stroke rate with a tendency of speed increasing suggested the increasing of stroke efficiency. Butterfly swimmer obtained faster velocity by faster a stroke rate and a greater stroke length per stroke [30]. The difference between butterfly and front crawl swimming showed different strategy in speed up. In the other side, this change might an adaptation of flume swimming.

As swimming speed increased, the percentage of duration of entry and push phases decreased. Relatively, the duration of pull and recovery phases increased. However, the change with different speeds had no statistic significant. Previous studies have found that when high-level butterfly swimmers increased their swimming speed, the main change in their technique was an increase in duration of the entry phase [25]. Another study found that when the increased from 95% to 110%, the proportion of duration spent underwater phase decreased accompanied with the proportion of time spent in the entry phase increased, which was benefit for improving the paddling efficiency and increase the swimming speed [31]. This suggests that swimmers speed up by adjusting the relative percentage of the four stroke phases [32]. To swim faster, swimmers naturally move their arms faster. We did not find any significant change in the duration of entry phase and pull phase with different flow speeds. However, a tendency of decreasing on the duration of entry phase and increasing of the duration of pull phase was found. As the duration of recovery phase increased, the underwater phase decreased as reported [31]. The inconsistent maybe related to individual differences, swimming skill level, range and other factors. In addition, we took the upper-limb as the main object, ignored the influence of the different water flow environments on the lower-limb movement. The upper-lower limb coordination changed with different swimming speed [5,33,34]. Swimmers typically decrease non-propulsive time to decrease stroke time and increase stroke rate to swim faster. Whether the decreasing in the non-propulsive time produce further performance improvement in future need to refer to more studies at different flow speeds in butterfly swimming.

Different swimming environments, such as a swimming flume and a pool may affect the swimmers' technical movements and

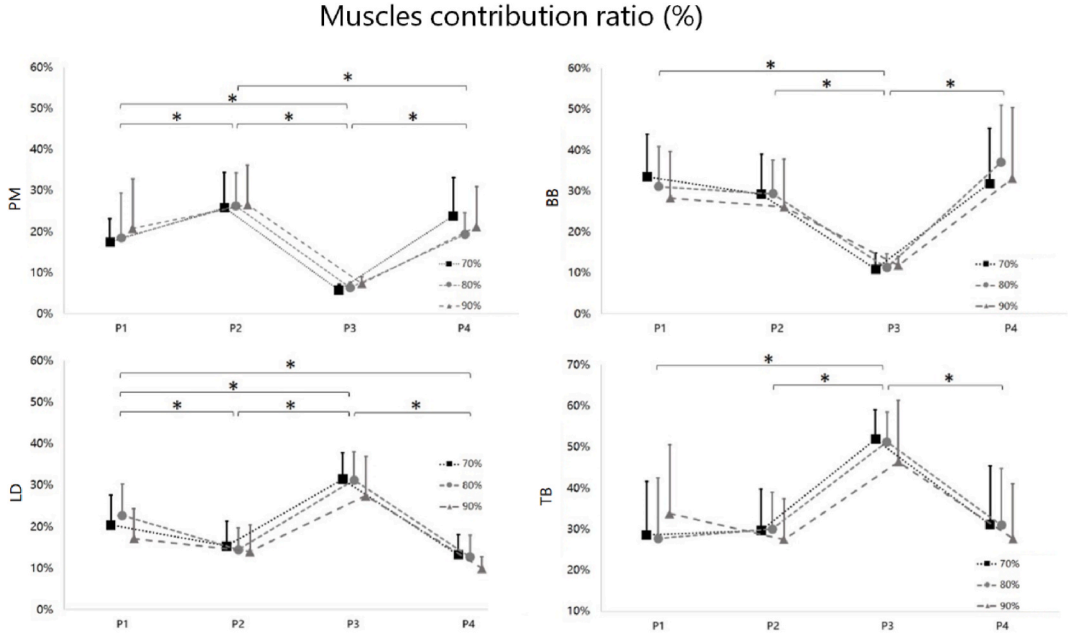

Fig. 4. The contribution ratio of the muscles with different flow speeds. PM: Pectoralis Major, LD: latissimus dorsi, BB: biceps brachii, TB: Triceps brachii. P1: Entry phase, P2: Pull phase, P3: Push phase, P4: Recovery phase.

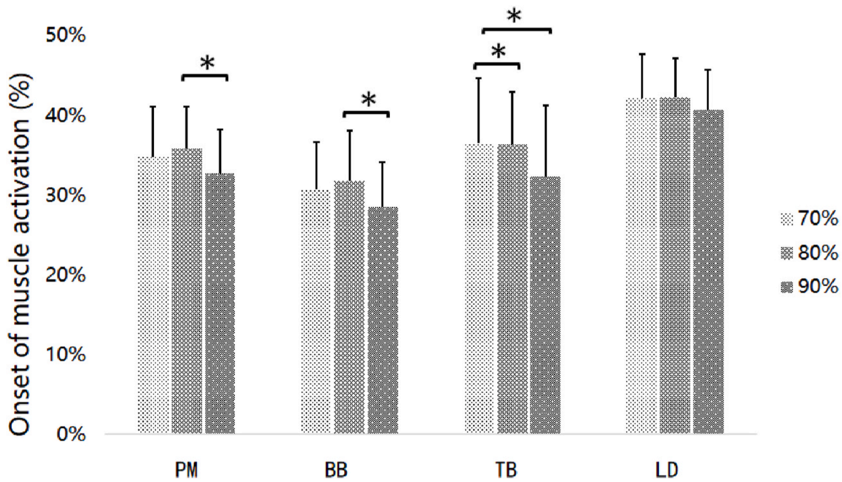

Fig. 5. The onset of muscle activation in a stroke cycle with different flow speeds. *: indicated significant difference between phases. PM: Pectoralis Major, LD: latissimus dorsi, BB: biceps brachii, TB: Triceps brachii.

kinematic characteristic. Literatures had shown that the four stroke phases (entry, pull, push and recovery) have different time proportions depending on the swimming speed [35]. Moreover, some studies have reported that swimmers have a lower stroke rate in the pool than in the flume at low speed for breaststroke and at high speed for freestyle [36]. However, the duration of each phase in our study did not vary significantly with different speeds. This maybe attributed to the different flow environment of flume and pool. With a clear reference points in the flume that allow swimmers to focus more on their technique and improve their movement efficiency. Therefore, further analysis need to make a deeper comparison on the differences in technical movements between these two different swimming environments.

4.2. The effect of different flow speeds on muscular activation

The statistics result showed the significant difference between different flow speeds of the muscle onset timing of pectoralis major, biceps brachii and triceps brachii. This means that the flow speeds affected the muscles activation in different ways. Although, the flow speeds did not affect the muscles contribution ratio, the muscles contribution ratio in the four phases showed significant different between each other. Rouard [22] et al. found that muscle activity was more similar in different movement phases during freestyle swimming and butterfly swimming, which was similar with the results for butterfly swimming movement phases in this paper.

The entry and push phases are the main phases that produce propulsion in butterfly swimming [37]. The entry phase was thought to be the preparation for the pull, and it was short and not of propulsive significance [18]. In butterfly swimming, the arm extends forward into the water during the entry phase, followed by a tendency of forearm flexion and upper arm adduction and then began pulling [38]. The pectoralis major, biceps brachii and triceps brachii muscles are the main force-producing muscles in entry. The latissimus dorsi muscle has a lower muscle activation during the entry phase, resulting in no significant difference in activation time between different flow speeds, but an increase in flows speed lead a trend of earlier response.

The arm stroke produced the propulsion in swimming, and the muscle activity of the arm was directly related to the efficiency of the arm stroke [37]. Olstad et al. believed that the mean activation pattern remained similar across the different effort levels while the muscles showed longer activation periods relative to the stroke cycle and increased integrated sEMG with increasing effort [39]. The results of this study exhibited some difference with the literature. The EMG results in our study showed that as the flow speed increased, the onset timing of the pectoralis major, biceps brachii and triceps brachii responded significantly earlier, although the onset timing of the latissimus dorsi did not showed significant change, it also had a tendency of earlier.

The pull and the push phase were two propulsive phases of a stroke, and the pectoralis major and latissimus dorsi generated power in pull and push phases, they were believed two main propulsive when swimming [13,18]. Biceps brachii was active in entry and pulling phase, and triceps brachii was active in pulling and pushing phase. Although this study did not observe significant differences in muscle contribution ratio with increasing flow speeds, with the increase of flow, pectoralis major muscle contribution rate in entry and push phases showed an increasing trend, while triceps brachii and latissimus dorsi muscles showed a decreasing trend. Previous study had already found the importance of pectoralis major to maintain swimming velocity during the front crawl swimming [40]. As training in a flow environment, when the flow increased, athletes' arms will be pushed backwards by the water during underwater stroke. When the arms move with the flow, it was difficulty for the muscle to generate much power. In that reason, drop of the muscle contribution ratio maybe understand. In addition, athletes would cost more time to find a "point" to reaction on the water, as the propulsive muscles needs to "catch" the proper point to active. When the muscles active missed the right point, the activation may be less or incomplete. That maybe some explanations for the irregularities changing of muscle activation with the flow speed increased. During the push phase, the decreasing of activation of triceps brachii and latissimus dorsi muscle can be understood then. There already showed some tendency of muscle activation with speed increasing, and the special strength training should be strengthened for muscles with increased activity during exercise.

Through the study results exhibited less significant difference between three flow speeds, indicating that training with each flow speed may be similar and a choice according to the contribution ratio of different muscles in different phases maybe a better choice.

The subjects in this study were adolescent athletes, their maximum speed corresponding to swim speed compared to adult excellent athletes may be low, this limited the rang of flow speed in this study, resulting less significant difference in muscle activation. Therefore, a study for elite athletes' muscle activation characteristics and kinematic parameters when swimming in a flume with different flow speed need further research and discussion.

5. Conclusion and suggestions

(1) When butterfly athletes training with 70%, 80% and 90% of their max speed in a flow environment, it didn't make significant differences between in the kinematic or muscle activation characteristics of the upper limbs movement except the muscle onset timing.
(2) Stroke phase was the main factor of the duration and the muscle contribution ratio during butterfly arm stroke for young athletes.

6. Limitation

The analysis on the kinematic parameters and muscular activity in the flume provided more information about flume training. In addition, the analysis of upper limber muscle activity showed the tendency of the muscle activity variation with different flow speeds, while it showed a little significant difference in the results, because of a conservative experiments design and a group of low level participates. Moreover, another analysis about elite athlete would be interesting. Although few studies on butterfly swimming exist in literature, it is difficult to say which speed is "better". The assumption that higher flume speed must be coupled with more effort must not be true in a nonstationary situation.

Author contribution statement

All authors listed have significantly contributed to the development and the writing of this article.

Data availability statement

Data included in article/supp. material/referenced in article.

Additional information

No additional information is available for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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