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Review article

Underwater Surface Electromyography for the Evaluation of Muscle Activity during Front Crawl Swimming: A Systematic Review

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Abstract
This systematic review is aimed to provide an up-to-date summary and review on the use of surface electromyography (sEMG) in evaluating front crawl (FC) swim performance. Several online databases were searched by different combinations of selected keywords, in total 1956 articles were retrieved, and each article was assessed by a 10-item quality checklist. 16 articles were eligible to be included in this study, and most of the articles were evaluating the muscle activity about the swimming phases and focused on assessing the upper limbs muscles, only few studies have assessed the performance in starts and turns phases. Insufficient information about these two phases despite the critical contribution on final swimming time. Also, with the contribution roles of legs and trunk muscles in swimming performance, more research should be conducted to explore the overall muscle activation pattern and their roles on swimming performance. Moreover, more detailed description in participants' characteristics and more investigations of bilateral muscle activity and the asymmetrical effects on relevant biomechanical performance are recommended. Lastly, with increasing attention about the effects of muscles co-activation on swimming performance, more in-depth investigations on this topic are also highly recommended, for evaluating its influence on swimmers.

Key words: Muscle activity, front crawl, electromyography, bilateral asymmetry, sEMG, muscle co-activation.

Introduction

With no doubt that swimming athletes would swim as fast as they can, to perform with the shortest time by repetitive and propulsive arms and legs motions to overcome the drag force from water and also to produce forward movement (Barbosa et al., 2013). Accordingly, different stakeholders in swimming, including coaches, trainers, sports scientists, or swimmers are trying their best to explore different strategies to achieve better performance due to the increasing competitiveness in swimming competitions (Allen et al., 2015). Thus, swimmers can have improvement in performance, not only the time, but also improvement in different swimming techniques. Regarding to the competitive nature in swimming races, only minor time differences between the medallists, therefore, the progression and performance of each swimmer is necessary to be assessed and monitored in a more detailed and comprehensive way.

With the advancement of technology, this brings lots of benefits to the sports fields, that application of various devices to monitor, to record and to evaluate the athletic performance more conveniently in various types of sports (Chambers et al., 2015; Hartwig et al., 2006; Pino et al., 2007; Randers et al., 2010; Vlantes and Readdy, 2017). Regarding to the positive contribution and effects, various technology started adopted in both coaching and research purposes in swimming. With the support of technology, more objectives feedback can be given to athletes with scientific research support, instead of relying on own observations, or based on expertise and knowledge only (Lees, 2002; Mooney et al., 2016). One of the implemented technologies is electromyography (EMG), to measure muscle activity of participants and muscle fatigue in different sports (Clarys, 1985; De Luca, 1997; Türker and Sze, 2013). However, to measure the swimmers' muscle activity, it was limited by the environment because of the presence of water. With the improvement and evolution in the EMG technology, this aids the application of EMG in swimming, that from fine wire or needle wire EMG (invasive) to wired surface EMG (sEMG) and now with wireless sEMG (non-invasive) with high reliability (Olstad et al., 2014; Taborri et al., 2020). This made the measurement become more applicable and accessible for evaluating swimmers' muscle activity, and more commonly adopted in swimming for techniques evaluation (Olstad et al., 2014), by quantifying the muscle activity with sEMG data collection and also for better understanding different roles of targeted muscles in target movements (Türker and Sze, 2013), and aimed for performance enhancement or sports rehabilitation (Taborri et al., 2020; Vinod and Da, 2013).

Swimming consists of 3 main parts including starts, turns and swimming phases and each part plays important role despite swimming parts might contribute more to the final swimming time, but starts and turns phases also correlated with swimming performance (Morais et al., 2021a; 2019) and minor improvement might be critical on overall competitions performance. Thus, instead of only reviewing the study on evaluating the muscle activity during swimming, but review on the activity in starts and turns will also be important as more exploration and discussion on different phases was suggested in recent research (Gonjo and Olstad, 2021; Marinho et al., 2020; Ruiz-Navarro et al., 2022). Also, this action would favour coaches or sports scientists to formulate a suitable training program for their swimmers by providing more comprehensive and scientific information to them by research. However, the most recent systematic review about sEMG measurement in swimming was published in 2015 (Martens et al., 2015b), but it did

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not include those research that investigating muscle activity during the start or turn phases, despite start and turn also played important roles to overall performance. To the best of the authors knowledge, a review that evaluating the muscle activity in all 3 phases in front crawl swim has not been conducted yet. Lack of resources and incomprehensive information might limit coaches and swimmers understanding (Thompson et al., 2022) on the muscle engagement in different phases and might affect their arrangement and planning in regular training regime.

Furthermore, we would like to bring our focus on reviewing front crawl swim, as front crawl is the fastest stroke and consists of higher number of events in competitions (Bartolomeu et al., 2018; Kennedy et al., 1990). Also, the time differences between the winners were very small as shown in recent Olympic games, which showed the competitiveness in front crawl competitions is relatively high, hence, front crawl was chosen to be the stroke that being reviewed in our study. With regards to the insufficient information on muscle activity measurement in different swimming phases in front crawl swim, including start, turns, and swimming phases, a more comprehensive systematic review should be conducted. Therefore, the objectives of this systematic review were:

1. to provide a more all-rounded and comprehensive review on literature that identifying and evaluating the muscle activity of front crawl swimmers in different swimming phases;
2. to find out research gaps in recent research and underscore its importance for providing future investigation direction and insight to relevant parties.

In this review study, we would like to address and examine the following research questions:

1. What muscles are involved in different swimming phases and are there any insufficiency in existing literature?
2. What kinds of participants were mostly be investigated in existing literature and What information on certain types of participants are insufficient?
3. What were the objectives of the study through measurement of muscle activity of competitive swimmers and what are the implications of the results of sEMG measurement?
4. What is the most commonly adopted method for sEMG data processing and how do they process the data collected?

Methods

Database search & keywords

A comprehensive search of existing available literature was done using different combination or abbreviations of keywords: “Swimming OR Front crawl OR Freestyle or FC” AND “surface electromyography OR sEMG”. Several electronic databases were searched, PubMed, SPORTDiscus, Science Direct, Medline, Embase, Cochrane Library and CINAHL, for studies were published from inception to 2021. Also, the reference lists of all articles were screened to extract more relevant studies to include in our systematic review. The review protocol was not registered as PROSPERO do not accept reviews that assessing sports performance.

Inclusion & exclusion criteria

The inclusion criteria were (1) studies conducted were using EMG to measure muscle activity of swimmers, (2) studies the muscle activity in front crawl, including starts, turns or swimming phases, (3) recruited participants were competitive level or above or at least have two regular swimming trainings per week. Exclusion criteria were (1) studies did not conduct on human, (2) studies on paralyzed, water-polo, synchronized swim, triathlon athletes, (3) studies were not evaluating the performance related in FC swim, (4) muscle activity was measured through simulated swimming on dry-land, and (5) postgraduate students’ (Master or Doctoral) theses and books.

Article selection process and quality assessment

After the extraction of articles, 2 independent reviewers were invited to proceed the screening process according to the inclusion and exclusion criteria and discussion would be conducted if there was disagreement between two reviewers, and the third reviewer would join the discussion as a coordinator to solve the disagreement. After all screening and selection processes, eligible studies were subject to have a quality assessment by a 10-item checklist that created by Kmet and his team in 2004 (Kmet et al., 2004) and revised by Martens et al. (2015b), regarding to his systematic review, that specifically for evaluating the quality of certain studies in this topic, with 10 items included. The quality assessment process was followed the procedures presented in Martens’ systematic review (Martens et al., 2015b). Reviewers would score each item with 0, 1, 2 or NA if the item was not applicable for that study. If the studies clearly presented and described that item, 2 scores would be given, while for those not fully reported or inferred from other parts, 1 score was given. If the authors did not present or report, 0 score would be given for that item. Only for item 9, score distribution was different; If participants of that study were over 20, this item would be scored 6; 4 marks were scored if study recruited 10 to 20 participants, while 2 and 0 scores were given if the number of recruited participants were between 5 to 9 and fewer than 5 swimmers respectively. This quality checklist was assessed by the same reviewers independently and if disagreement occurred, a coordinator would take part and discuss with two reviewers to solve the disagreement. Afterwards, the summation of scores was calculated for each study and the final score of the quality assessment was presented in percentage (%), to cancel out the effects of non-applicable (NA) items. The checklist was shown in Table 1.

Results

Article selection process

The procedures and flow of the article selection process was shown in Figure 1, with reference to the Guidelines of PRISMA during the article retrieval. After comprehensive search from 7 online databases, in total 1956 articles were found. After title, abstract, full-text screening, and removal of duplicate articles, 13 articles were extracted.

Table 1. 10 Items of Quality Assessment Checklist. Original checklist was designed by Kmet and his team (2004), and this study adopted a revised version that presented in Martens' systematic review (Kmet et al., 2004; Martens et al., 2015b). Reviewers would score each item with 0, 1, 2 or NA if the item was not applicable for that study. The summation of scores was calculated for each study and the final score was presented in percentage.

No.	Question	Score
1	Question/Objective sufficiently described?	0, 1, 2
2	Study design evident and appropriate?	0, 1, 2
3	Connection to a theoretic framework/wider body of knowledge?	0, 1, 2
4	Subject characteristics sufficiently described?	/
4a	Age (Mean and Standard Deviation)	0, 1, 2
4b	Gender	0, 2
4c	Swimming/Activity Level of participants	0, 1, 2
5	Data collection methods clearly described and systematic?	/
5a	Research Protocol	0, 1, 2
5b	Type of EMG system	0, 1, 2
5c	Studied muscles	0, 1, 2
5d	Unilateral or Bilateral	0, 1, 2 or NA
6	Data analysis clearly described and systematic?	/
6a	EMG filters	0 or 2
6b	Normalization Method	0, 1, 2
6c	Data Processing Protocol	0, 1, 2
7	Some estimate of variance is reported for the main results?	0, 1, 2 or NA
8	Conclusions supported by the results?	0, 1, 2
9	Number of participants sufficient to draw conclusions?	0, 2, 4 ,6
10	Statistical analysis is described and appropriate?	0, 1, 2 or NA

Reviewers would score each item with 0, 1, 2 or NA if the item was not applicable for that study. The summation of scores was calculated for each study and the final score was presented in percentage.

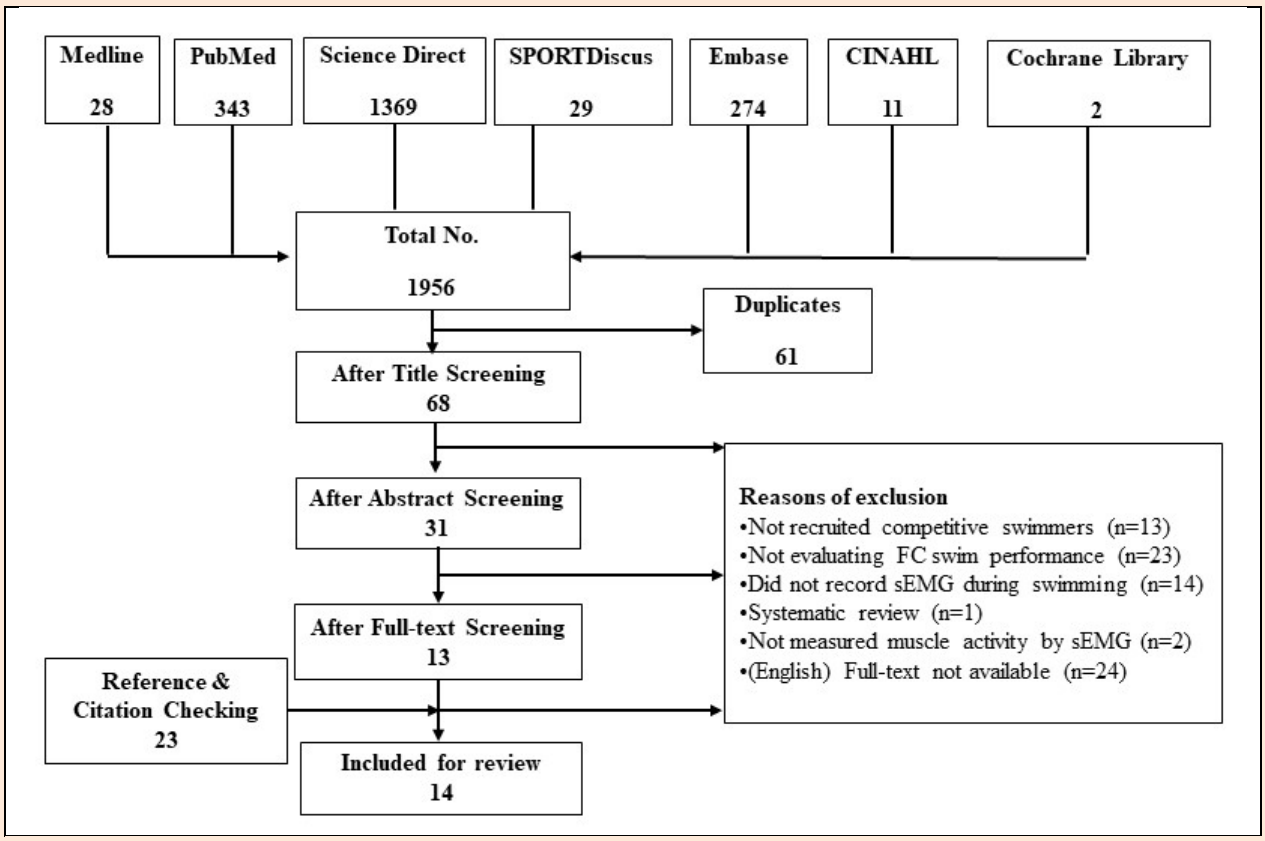

Figure 1. The flow of article selection process. The flow of article selection process was according to the Guidelines of PRISMA, 7 online databases were comprehensively searched, in total 1956 articles were found. After the review and selection by 2 independent reviewers, ultimately 14 articles were eligible for including in this review study

Additionally, 25 articles were retrieved from reference and citation checking, and 3 article was eligible to include in our review study. Therefore, 16 articles were finally eligible for reviewing in this study. Reasons of exclusion were as the follows: no (English) full text were available (n = 24), not evaluating FC swimming performance (n = 23), did not record muscle activity during swimming (n = 14), did not recruit competitive swimmers (n = 13), did not

measure muscle activity by sEMG (n = 2) and study was a systematic review (n = 1).

Research Q1: What muscles are involved in different swimming phases?

Among 16 included studies in this review, 13 papers investigated muscle activity during swimming phase, including performing in 100m (Puce et al., 2021; Rouard and Clarys, 1995; Stirn et al., 2011) or 200m FC swim (Figueiredo et al., 2013a; Figueiredo et al., 2013b; Ikuta et al., 2012; Lauer et al., 2013), 25m swim (Martens et al., 2015a; 2016) or semi-tethered swim (Caty et al., 2007), and swimming in the flume with arms only or flutter kick in competitive swimmer only (Lomax et al., 2014; Matsuda et al., 2016). One study has investigated and compared the trunk muscle activity during both sprinting (4 x 50m FC) and middle-distance (400m) swim (Andersen et al., 2021). For the start and turn phases, muscle co-activation patterns of underwater dolphin kick have been investigated in both Kobayashi's and Yamakawa's studies (Kobayashi et al., 2016; Yamakawa et al., 2017) and only one paper (Pereira et al., 2015) has explored and described the electromyographic performance of 4 different flip turns of FC swim.

Concerning the selection of body parts for investigation, the most frequently investigated was the upper body (n = 11), lower body (n = 8) and then followed by the trunk muscles (n = 5), the total number is more than 14, as some papers investigated more than one body part in their research. Most of the studies conducted their measurement in unilateral side (n=12) and mainly investigated right side's muscles (n = 8) (Andersen et al., 2021; Caty et al., 2007; Figueiredo et al., 2013b; Ikuta et al., 2012; Lauer et al., 2013; Lomax et al., 2014; Stirn et al., 2011; Yamakawa et al., 2017) , but some studies did not clearly mention what side they were investigated (n = 5) (Figueiredo et al., 2013a; Kobayashi et al., 2016; Matsuda et al., 2016; Pereira et al., 2015; Rouard and Clarys, 1995). While 2 studies conducted bilaterally (n = 2) (Martens et al., 2016) (both left and right muscles selected), however, some studies (Pereira et al., 2015; Puce et al., 2021) investigated the side according to their hand dominance.

With regard to the quantity of muscle selection, the highest number of muscles included was Ikuta's study (Ikuta et al., 2012) that authors selected 11 muscles to evaluate the muscle fatigue during 100m FC, while the least number was 2 muscles selected in 6 studies (Caty et al., 2007; Lauer et al., 2013; Lomax et al., 2014; Martens et al., 2015a; 2016; Matsuda et al., 2016) with different study objectives. With respect to upper body parts, in total 12 muscles were selected among those included studies. Biceps Brachii (BB; n = 5), Triceps Brachii (TB; n = 7) and Pectoralis Major (PM; n = 6) were the muscles that frequently selected for investigations. Shoulder muscles, like Latissimus Dorsi (LD; n = 5), Upper Trapezius (UT; n = 2) and 3 parts of Deltoid (Anterior: n = 3; Middle: n = 2; and Posterior: n = 1) were chosen, while wrist or forearm muscles including Flexor Carpi Ulnaris (FCU; n = 3) Flexor Carpi Radialis (FCR; n=2) and Extensor Carpi Ulnaris (ECU; n = 1) were selected for investigation.

Regarding to lower body part, 5 muscles from thighs and lower legs were commonly selected. Rectus Femoris (RF; n = 7) and Biceps Femoris (BF; n = 8) of the thigh muscles were the most frequently selected either for evaluation of dolphin kicks in underwater phases or flutter kick during swimming phases, and only 1 study (Pereira et al., 2015) involved one more muscle, Vastus Lateralis (VL), to evaluate flip turn performance. While in the lower legs, two muscles were selected: Tibialis Anterior (TA; n=4) and Gastrocnemius (GAS; n = 4). With regard to the trunk muscles, most of the included studies investigated the muscle activity of Rectus Abdominis (RA; n = 5) and Erector Spinae (ES; n = 3), only 1 study (Andersen et al., 2021) also recruited Internal Oblique (IO) and External Oblique (EO) for evaluating torso twist during FC swim. Table 2 gave the summary on selected muscles for investigation in swimming and start and turn phases respectively.

Research Q2: What kinds of participants were mostly be investigated in existing literature and What information on certain types of participants are insufficient?

All studies presented participants' age, height, and weight. Some studies also presented with arm span, percentage (%) of adipose tissue, swimmers' personal best time in different FC events. But only few have mentioned whether they have recruited FC specialists (Figueiredo et al., 2013a; Puce et al., 2021; Stirn et al., 2011), the FINA points (Martens et al., 2015a; 2016; Yamakawa et al., 2017), years of experience in swimming (Figueiredo et al., 2013a; Martens et al., 2015a; 2016; Stirn et al., 2011) or training hours per week (Pereira et al., 2015; Yamakawa et al., 2017), to give more participants' information for reference.

The number of participants recruited in 16 studies was ranged from 7 (Caty et al., 2007) to 20 (Ikuta et al., 2012; Matsuda et al., 2016) swimmers. Concerning the competitive level of participants, most of the swimmers were described as competitive (n = 8) (Andersen et al., 2021; Figueiredo et al., 2013a; Martens et al., 2015a; 2016; Matsuda et al., 2016; Rouard and Clarys, 1995; Stirn et al., 2011; Yamakawa et al., 2017), international (n=3) (Caty et al., 2007; Figueiredo et al., 2013b; Lauer et al., 2013) and national levels (n=1) (Pereira et al., 2015), only some recruited collegiate or university swimmers (n=3) (Ikuta et al., 2012; Kobayashi et al., 2016; Lomax et al., 2014) that with regular trainings per week.

The mean age of swimmers was from 16.0 to 33.0 years old, mostly recruited adult swimmers, who were aged from 20 to 21. But rarely recruited young or master swimmers, only 2 papers recruited younger swimmers for their study, i.e., around 16 to 17 years old and 1 paper recruited master swimmers for investigation (Puce et al., 2021). Also, most of the participants recruited were male swimmers, only some studies have recruited female swimmers (Kobayashi et al., 2016; Lomax et al., 2014; Pereira et al., 2015; Puce et al., 2021; Yamakawa et al., 2017), while one study did not report the gender of their participants (Matsuda et al., 2016). Lastly, only few studies have provided information about their swimming performance in different FC events, including personal best or recent competition results in FC, or whether they were FC specialist etc.

Table 2. Summary of the number of arms, shoulders, legs and trunk muscles selected and investigated in swimming, in start and turn phases. Most of the studies investigated muscles from upper body, and then lower body, few of the studies conducted the investigations in trunk muscles, and mostly were investigated with unilateral side.

				Arms						Shoulders						Legs					Trunk	
Author (Year)	Swimming Phase		No. of muscles	BB	TB	BRR	FCU	FCR	ECU	PM	UT	LD	AD	PD	DM	RF	BF	TA	GAS	VL	RA	ES
Rouard et al (1995)	Swimming	100m	6	V	V	V	V					V	V									
Stirn et al (2011)		100m	3		V					V		V										
Ikuta et al (2012)		200m	11	V	V		V			V		V	V	V		V	V	V	V			
Figueiredo et al (2013)		200m	8	V	V			V		V	V					V	V	V				
Figueiredo et al (2013)		200m	7	V	V			V		V	V					V	V					
Lauer et al (2013)		200m	2	V	V																	
Martens et al (2015a)		25m	2												V						V	
Martens et al (2016)		25m	2												V						V	
Caty et al (2007)		25m semi-tethered	2				V		V													
Matsuda et al (2016)		Flutter Kick	2													V	V					
Lomax et al (2014)		Arms only	2							V		V										
Yamakawa et al (2017)	Start & Turn	Dolphin Kick	6													V	V	V	V		V	V
Kobayashi et al (2016)		Dolphin Kick	6													V	V	V	V		V	V
Pereira et al (2015)	Turn	Flip Turn	4														V	V	V	V		

Abbreviations: AD: Anterior Deltoid; BB: Biceps Brachii; BF: Biceps Femoris; BRR: Brachioradialis; DM: Deltoideus Medialis; ECU: Extensor Carpi Ulnaris; ES: Erector Spinae; FCR: Flexor Carpi Radialis; FCU: Flexor Carpi Ulnaris; GAS: Gastrocnemius; LD: Latissimus Dorsi; PD: Posterior Deltoid; PM: Pectoralis Major; RA: Rectus Abdominis; RF: Rectus Femoris; TA: Tibialis Anterior; TB: Triceps Brachii; UT: Upper Trapezius; V: Investigated muscles; VL: Vastus Lateralis

Research Q3: What were the objectives of the study through measurement of muscle activity of competitive swimmers?

After reviewing those eligible articles, we have summarized the purposes of the study (including primary and secondary purposes) into 4 categories (Table 3), as some studies have included more than 2 purposes (n = 5) (Figueiredo et al., 2013b; Ikuta et al., 2012; Martens et al., 2015a; 2016; Yamakawa et al., 2017), thus the total number of articles was over 16.

Investigation of the muscle activation pattern and its variability: Most of the studies (n = 8) (Andersen et al., 2021; Figueiredo et al., 2013b; Ikuta et al., 2012; Martens et al., 2015a; 2016; Matsuda et al., 2016; Pereira et al., 2015; Yamakawa et al., 2017) aimed to investigate the muscle activation pattern in different groups of swimmers, by using sEMG in different swimming phases in FC swim, including underwater dolphin kick in the start phases, flip turns performance in turn phases and swimming phases in different conditions (whole body swim, arms only and flutter kick only). Apart from measuring the muscle activity, 2 studies (n = 2) (Martens et al., 2015a; 2016) have aimed to measure the variability of muscle activity between or within competitive swimmers, to see any variations and to assess the similarity in the muscle activation patterns between and within swimmers with different characteristics.

Investigation of the co-contraction of muscles: Another topic that mostly investigated was co-contraction (coactivation) patterns of muscles (n=5) during underwater dolphin kick (n=1) (Kobayashi et al., 2016), and flutter kick (n=1) (Matsuda et al., 2016) and during FC swimming (n=3) (Caty et al., 2007; Lauer et al., 2013; Rouard and Clarys, 1995). For underwater dolphin kick, 3 pairs of muscles were selected, including RA and ES in trunk, RF and BF in thigh and TA and GAS of lower legs. While for flutter kick, only RF & BF in lower leg muscles were chosen. Lastly, for swimming phases, co-activation of wrist (ECU and FCU), and elbow (BB and TB) were investigated.

Investigation of muscle fatigue: 4 studies were targeted to investigate the muscle fatigue during FC swim. 2 studies evaluated the muscle fatigue during 100m (Stirn et al., 2011) concerning upper arms and trunk muscles, while Figueiredo and his team (Figueiredo et al., 2013a) and also Puce and the team (Puce et al., 2021) have studied both upper and lower limbs muscles performance in 200m and 100m FC swim respectively. The last one has specifically investigated the effects of inspiratory muscle fatigue (IMF) on latissimus dorsi (LD) and pectoralis major (PM) and its impact on stroke performance during 20s arms only FC swim (Lomax et al., 2014).

Investigation of the relationship between muscle activity and swimming kinematics: Apart from measuring and evaluating muscle activity during FC swim as the main objective, two studies have secondary purposes in their studies. Authors would like to explore the relationships between the changes in muscle activity and relevant kinematic

parameters during FC swim. Yamakawa's study reported and correlated swimming velocity (SV), kicking frequency (KF) and amplitude (Yamakawa et al., 2017) with the co-activation pattern during dolphin kick. Another study aimed to examine the relationships between the changes in SV with changes in stroke kinematics and EMG data (Ikuta et al., 2012) during 200-m FC swim.

Table 3. Summary of the purposes, participants' characteristics, evaluated swimming phases and tests and score of quality assessment of each study. 4 categories of the study's purpose were summarised and most were aimed to investigate the muscle activation pattern during FC swim.

Author (Year)	Purpose	Participant characteristics	Phases	Test	Quality
Rouard et al (1995)	To document the co-contraction patterns of elbow and shoulder joints during rapid maximal-effort movement against drag	9M: Competitive FC specialists Age: 17.3±2.59	Swimming	4 X 100m FC	71%
Caty et al (2007)	To evaluate the wrist fixation and the recruitment of the forearm muscles during insweep and outsweep phases	7M: International Level Age: 22.6±2.7	Swimming	25m semi-tethered swim	79%
Stirn et al (2011)	To evaluate the peripheral muscle fatigue during 100m maximum effort FC swim in upper trunk and arm muscles by means of amplitude and frequency parameters	11M: Competitive Non-FC specialists Age: 22.0±2.9	Swimming	100m All-out FC	82%
Ikuta et al (2012)	To evaluate changes in muscle activity associated with physiological fatigue and decreases SV during 200m FC swim To examine the relationship between decreased SV and changes in kinematics or EMG between individuals	20M: University Team Age: 20.5±1.0	Swimming	200m FC (4 x 50m Swim)	79%
Figueiredo et al (2013)	To investigate and report kinematic and electromyographic changes during a maximal 200m FC.	10M: International Level Age: 21.26±2.4	Swimming	200m FC	84%
Figueiredo et al (2013)	To investigate how muscle fatigue evolves in 200m FC swim by means of an amplitude and frequency analysis	10M: Competitive FC specialists Age: 21.6±2.4	Swimming	200m FC	79%
Lauer et al (2013)	To apply coactivation index to prime movers of the elbow in FC & examine how it affected by stroke phases	10M: International Level Age: 20.8±2.3	Swimming	200m FC	79%
Lomax et al (2014)	To examine whether or not IMF-induced fatigue in the LD and PM muscles, and its impact on stroke kinematics during sprint swimming	6M, 2F: Collegiate Level Age: 22.0±5.5 (overall)	Swimming	20s Arms Only FC	71%
Martens et al (2015a)	To assess intra-individual variability of the EMG signal of bilaterally measured RA and DM; To describe the muscle activity by MVIC, in relation to upper limb stroke movements	15M: Competitive Age: 21.26±2.24	Swimming	25m FC	87%
Pereira et al (2015)	To describe and compare the kinematic, kinetic and electromyographic characteristics of 4 FC flip turns	9M, 8F: National Level Age: 19.5±2.6 (M); 16.0±2.8 (F)	Turn	Flip Turn: 4 Variants	82%
Kobayashi et al (2016)	To clarify muscle activation pattern between agonist and antagonist muscles in trunk, thigh and lower legs during underwater dolphin kick	13F: Collegiate Level Age: 20.2±1.7	Start & Turn	15m Dolphin Kick	68%
Matsuda et al (2016)	To compare muscle activation and co-contraction levels of rectus femoris and biceps femoris during flutter kicking between swimmers	10 Competitive, 10 Recreational Age: 20.0±0.9 (Competitive)	Swimming	Flutter Kick	76%
Martens et al (2016)	To investigate inter-individual variability in FC swimming; To determine if any EMG sub patterns using key features in a cluster analysis	15M: Competitive Age: 21.26±2.24	Swimming	25m FC	87%
Yamakawa et al (2017)	To clarify the effects of increased kick frequency on Froude efficiency and muscular activation patterns in trunk, thigh, and leg during underwater dolphin kick; To investigate the relationships between average swimming velocity or Froude efficiency and muscular activation pattern	8F: Competitive Age: 20.9±1.9	Start & Turn	15m Dolphin Kick	79%

Unit - m: metre. **Abbreviations -** DM: Deltoideus Medialis; EMG: Electromyography; F: Female swimmers; FC: Front crawl/Freestyle; IMF: Inspiratory Muscle Fatigue; M: Male swimmers; MVIC: Maximum Isometric Voluntary Contraction; N/A: Not applicable, PM: Pectoralis Major; RA: Rectus Abdominis; SV: Swimming Velocity

Table 4. Summary of which muscle investigated, measured biomechanical parameters and normalization method of each study. Various method for EMG data normalization method were adopted, and clearly described the procedures in most of the included studies. Some relevant biomechanical parameters also measured as secondary outcomes, i.e., stroke length (SL) and stroke frequency (SF) and so on.

Author (Year)	Main Purpose	Swim Test	Muscles Investigated	Biomechanical Parameters	Normalization of EMG Data
Rouard et al (1995)	Co-contraction	4 X 100m FC	**Unilateral:** Side - Not Mentioned Upper Limbs: BB, TB, FCU, BRR, LD, AD	N/A	Dynamic Peak: % of $iEMG_{max}$
Caty et al (2007)	Co-contraction	25m semi-tethered swim	**Unilateral:** Right Side Upper Limbs: FCU, ECU	Power(W)	Dynamic Peak: % of $iEMG_{max}$
Lauer et al (2013)	Co-contraction	200m FC	**Unilateral:** Right Side Upper Limbs: BB, TB	Elbow angular velocity(deg/s)	Dynamic Peak: % of $iEMG_{max}$
Matsuda et al (2016)	Co-contraction	Flutter Kick	**Unilateral:** Side - Not Mention Lower Limbs: RF; BF	Velocity(m/s), Kick time(s), Kick length(m/kick), Max. angular velocity(deg/s)	Dynamic Peak: Peak Value from 10 kick cycles
Yamakawa et al (2017)	Co-contraction**	Dolphin Kick	**Unilateral:** Right Side Trunk: RA, ES Lower Limbs: TA, GAS, RF, BF	Average SV(m/s), Froude Efficiency, KF(Hz), Kick Amplitude(m), Average & Max. Vertical Toe Velocities(m/s), % of downward & upward kick phases	Not mentioned
Martens et al (2015a)	Intra-variability of muscle activity	25m FC Swim	**Bilateral Sides:** Upper Limbs: DM Trunk: RA	N/A	MVIC & Dynamic Peak
Martens et al (2016)	Inter-variability of muscle activity	25m FC Swim	**Bilateral Sides:** Upper Limbs: DM Trunk: RA	N/A	MVIC
Ikuta et al (2012)	Muscle activation pattern**	200m FC	**Unilateral:** Right Side Upper Limbs: FCU, BB, PM, LD, TB, AD, PD Lower Limbs: TA, GAS, RF, BF	SV(m/s), SL(m) AAV of shoulder flexion	Not mention
Figueiredo et al (2013)	Muscle activation pattern	200m FC swim	**Unilateral:** Right Side Upper Limbs: FCR, BB, TB, PM, UT Lower Limbs: BF, RF	SV(m/s), SF(Hz), SL(m), KF(Hz), Hand angular velocity(rad/s) Elbow & shoulder angles(deg)	Dynamic Peak: % of $iEMG_{max}$
Pereira et al (2015)	Muscle activation pattern	Flip Turn	**Side:** Not Mention Lower Limbs: GASM, TA, BF, VL	Time of each phase of turn(s), Horizontal velocity of COM(m/s), Initial Rolling Distance(m)	MVIC
Kobayashi et al (2016)	Muscle activation pattern	15m dolphin kick	**Unilateral:** Side – Not mention Trunk Muscles: RA, ES Lower Limbs: RF, BF, TA, GAS	Average SV(m/s), KF(Hz), Kick amplitude(m), % of downward & upward phases	Dynamic Peak: Peak Value of 3 kick cycles
Stirn et al (2011)	Muscle Fatigue	100m FC	**Unilateral:** Right Side Upper Limbs: TB, PM & LD	SV(m/s), SL(m), SR(stroke/min)	Not mentioned
Lomax et al (2014)	Muscle Fatigue	20s arms only FC	**Unilateral:** Right Side Upper Limbs: PM, LD	SR(cycles/min)	Not mentioned
Figueiredo et al (2013)	Muscle Fatigue	200m FC	**Unilateral:** Side – Not mention Upper Limbs: FCR, BB, PM, UT, TB Lower Limbs: TA, RF, BF	SF(Hz), SL(m), SV(m/s)	Dynamic Peak: % of $iEMG_{max}$

Unit: cycle/min: cycle/minute; deg: degree; deg/s: degree/second; Hz: Hertz; m: meter; m/kick: meter/kick; m/s: meter/second; s: second; stroke/min: stroke/minute; rad/s: radian/second; W: Watt. Abbreviations - AAV: Arm angular velocity; AD: Anterior Deltoid; BB: Biceps Brachii; BF: Biceps Femoris; BRR: Brachioradialis; COM: Centre of Mass; DM: Deltoideus Medialis; ECU: Extensor Carpi Ulnaris; EMG: Electromyography; ES: Erector Spinae; FC: Front crawl/ Freestyle; FCR: Flexor Carpi Radialis; FCU: Flexor Carpi Ulnaris; GAS: Gastrocnemius; GASM: Gastrocnemius Medialis; $iEMG_{max}$: Maximum value of integrated electromyographic data; KF: Kick frequency; LD: Latissimus Dorsi; MVIC: Maximum Voluntary Isometric Contraction; N/A: Not applicable; PD: Posterior Deltoid; PM: Pectoralis Major; RA: Rectus Abdominis; RF: Rectus Femoris; SL: Stroke Length; SR: Stroke Rate; SV: Swimming Velocity; TA: Tibialis Anterior; TB: Triceps Brachii; UT: Upper Trapezius; VL: Vastus Lateralis. **: Secondary purpose: investigation of the relationships with the kinematics parameters with EMG data.

Research Q4: What is the most commonly adopted method for sEMG data processing and how do they process the data collected?

In our study, as we only included the studies that using non-invasive sEMG for data collection, for those using fine wire or needle electrodes were excluded in our review study. 5 studies clearly mentioned that they used wireless sEMG technology (Kobayashi et al., 2016; Martens et al., 2015a; 2016; Puce et al., 2021; Yamakawa et al., 2017), and 2 studies reported they have used telemetric EMG devices (Rouard and Clarys, 1995; Stirn et al., 2011), and while the remaining studies did not clearly mention which type of sEMG they adopted (Table 4).

Various methods for EMG data normalization and processing methods were adopted in included studies. For data processing, most of the studies have mentioned they have done EMG signal rectification with band-pass filtering or smoothed by Root Mean Square (RMS) and also integration of rectified EMG per unit of time (iEMG/t) for eliminating the effect of phase duration. 8 studies (Andersen et al., 2021; Caty et al., 2007; Figueiredo et al., 2013a; Figueiredo et al., 2013b; Kobayashi et al., 2016; Lauer et al., 2013; Matsuda et al., 2016; Rouard and Clarys, 1995) have used dynamic peak as normalization method by finding the maximum value found during the tests and was set as 100%. While 2 papers (Martens et al., 2016; Pereira et al., 2015) adopted maximum voluntary isometric contraction (MVIC) methods that requested the participants to perform their maximal effort under the manual resistance, and the highest value found during the tests was marked as 100%. While 1 study (Martens et al., 2015a) has adopted both methods for EMG data normalization as authors aimed to compare any differences in EMG data between two methods, and however 5 studies (Ikuta et al., 2012; Lomax et al., 2014; Puce et al., 2021; Stirn et al., 2011; Yamakawa et al., 2017) did not describe or mention their normalization method clearly in methodology part.

Quality assessment: Apart from answering the research questions of this review paper, we have also evaluated the quality of each paper, with a 10-item checklist (Kmet et al., 2004; Martens et al., 2015). 10 items were assessed and % of the summation of score were presented. Among 16 studies, the highest score was 87% (Andersen et al., 2021; Martens et al., 2015b; 2016) and the lowest score was 68% (Kobayashi et al., 2016), which was a conference paper. In average, overall % of the summation of score was 79%. Most of the study loss their scores in item 4c, item 7 and item 9, that insufficient information about swimming level of participants, insufficient estimate of variance provided for the main results, i.e. 95% Confidence Interval, Standard Errors and number of participants recruited.

Discussion

This study summarized and reviewed the investigations about electromyographic data collected by sEMG, on starts, turns and FC swim of competitive swimmers and evaluated different research objectives of eligible studies. Also, we have also evaluated the quality of each article by a quality assessment tool on the clearness of reporting and description in their studies. This study might be the pioneer review paper that giving an overview on measuring muscle activity, specifically for FC stroke from the perspectives of different swimming phases, and also provide a more updated information on recent research topics by measuring muscle activity with sEMG during FC swim.

Research Q1: What muscles are involved in different swimming phases?

When considering muscles selection and swimming phases together, different phases have different targeted muscles for investigations. From the underwater phases of start, the lower limbs muscles were the main foci because of the dolphin kick and along with the investigation of the trunk muscles. Afterwards, the muscle activity of upper limbs muscles draws our attentions due to the importance of arms for each stroke, and some studies would also study lower limbs during the flutter kick, while limited information was available on discussing the trunk muscles activity of body roll, including the shoulder roll and hip roll when performing the alternative arms and legs movement and breathing actions. Lastly, when came across with the turning phases, lower limbs muscle activity became the focus again because of the importance of the legs to against the wall.

Most of the included studies investigated the muscle activity during swimming phases by sEMG, including arms only, flutter kick and whole body FC swim. Larger proportion of investigations put their focuses on evaluating the patterns or trace the changes in muscle activity during swimming, as swimming phases were the main parts of each event, that contribute most to the final time. Unfortunately, we observed insufficient investigations that concerning the start and turning phases. Among 16 included articles, only 2 papers have evaluated the muscle activity of underwater dolphin kicks and 1 paper studied the flip turn. However, with the positive contribution of start and turn in competitions and swimming time (Cossor and Mason, 2001; Morais et al., 2019), more research should be conducted for these two phases independently, in order to have more in-depth understanding about the muscle performance and activation pattern specifically for starts and turns. Thus, the coaching teams can prescribe more direct and specific interventions and trainings to bring improvement in performance in starts and turns (Marinho et al., 2020; Veiga and Roig, 2016), by referring to the evidence-based information. Moreover, with different muscle activation patterns in different phases, by collecting the muscle activity through sEMG, this might be beneficial to swimmers and also coaches to understand how we distribute and activate different muscles wisely in different phases, to reduce the chance of getting fatigue. For example, during underwater phases after start and turn, especially in sprinting distance events, for example, stay longer in underwater phase, in order to have more strength to perform explosive strokes during swimming phases. Hence, this further confirmed that there are some differences in muscle activation existed in different phases, different strategies might be performed by different swimmers in different races (Marinho et al., 2020). For example, during the gliding

phases after starts and turns, swimmers usually use gliding techniques to maintain body in streamline to minimize the drag force and also maximize the push off force and speed after the start from the block and after the wall contact in turns (Puel et al., 2012; Veiga et al., 2016), without additional energy or cost by swimmers (Naemi et al., 2010). Additionally, muscles from upper limbs and trunks are mainly contribute for this purpose, however, the changes and influences of different muscle activity in start and turns on the muscle activity and performance during swimming phases, are still lack of scientific evidence for proof, although optimisation of start and turn phases are important and should be emphasized in training (Born et al., 2021; Morais et al., 2019). Moreover, with regards to the present international regulations and rules, swimmers can swim 15m during the underwater phases after start and turns and with the recognition of the importance of start and turns from coaches to overall performance but with limitations to access relevant information (Thompson et al., 2022). Thereby, evaluating the muscle activation profiles during start and turn phases are highly recommended to reveal more information and give some insights for coaches to monitor the swimmers' performance and providing feedback and deploying appropriate training for performance enhancement with evidence-based data support.

From the review on muscle selection for investigations, according to Table 2, obviously, most of the study (11 out of 16 articles) were interested in upper limbs, including arms and shoulders muscles, due to the major contribution for forward movement from upper limbs, with around 85%, during FC swim (Deschodt et al., 1999). BB, TB, PM and LD were mostly selected, because of their main functions in forceful propulsion during each arm stroke (Pink et al., 1991). Not only upper extremities, lower limbs' muscles also have gained researchers' attention and more investigations were found. 8 included studies investigated lower limbs muscle activity during different parts of swimming, like dolphin kick during underwater phases, flip turn and legs kicking. Similar selection of muscles was observed that studies chose RF, BF, TA, GAS for investigations. Regarding to swimming phases, although the contribution of the legs would be far fewer than the arms, however, study proven that legs action also positively affect the swimming speed in FC (Gourgoulis et al., 2014) and also with increasing importance of the leg kicking on coaches' perceptions (Morris et al., 2019), more related studies should be conducted for investigating the muscle activity of lower limbs, including evaluating starts and turning phases. So that more information can provide for reference and finding out how legs muscles contribute to the swimming time and stabilization of body position.

Not only increase our attention to limbs' contribution on swimming performance, trunk muscles also played an important role during swimming for stabilization (Martens et al., 2015b), even though trunk muscles might not directly contribute to time performance. However, limited studies have involved trunk muscles in sEMG measurement, 5 studies have included trunk muscles for investigations, and mostly investigating the roles in starts or turning phases, but rarely in the swimming phases. Moreover, RA and ES were the mostly investigated trunk muscles and RA was the most frequently measured muscle in included studies. Without the participation of core muscles, the kinetic chain was not completed. Not only RA or ES should be selected for investigation, also other trunk muscles should be included, like IO and EO, only one study has investigated which focused on the torso twist during FC (Andersen et al., 2021). A limited knowledge about the engagement of trunk muscles, therefore, more attention should be put on the evaluation of the activity of trunk muscles, instead of just putting focus on the limbs, as trunk would contribute in maintaining stabilization of spine and controlling the posture in FC (Andersen et al., 2021; Martens et al., 2015; 2016). More scientific research should be conducted for finding activation pattern and the changes of muscle activity during different parts in swimming and different phases of arms or comparing the activation pattern between experienced and novice swimmers. This might give more inspirations to coaches and scientists on how to optimize the performance through understanding the role of trunk muscles by measuring the muscle activity.

Apart from the selection of muscles in a study, choosing which side for investigation should be one of the concerns too. About 75% of included studies (12 out of 16) investigated the muscle activity unilaterally, and in favour of selecting the right sides for investigation, no matter exploring the performance of FC swim, dolphin kicks or flip turns. However, differences in muscle performance might be existed between the left side and right side, and also the dominant and non-dominant sides, which have several studies found out there were differences in coordination, and propulsive forces (Barden et al., 2011; Dos Santos et al., 2013; Dos Santos et al., 2017; Morouço et al., 2015a). Previous research has found out that most of the swimmers have shown asymmetrical strength and also demonstrated that the side of breathing or the hand dominance would bring influences in arm coordination (Evershed et al., 2014; Seifert et al., 2005), hence this implied that asymmetrical muscle activation patterns would exist in swimmers. However, to the author's knowledge, there is no investigation has been conducted and examined about the effects of asymmetrical muscle activities and also, the consequences or detrimental effects of asymmetry in muscle activation, for short-term and long-term perspectives (Bishop et al., 2018) on swimmers. Future investigations of this relevant topic might help to provide more insight and information for planning and designing appropriate training or tests.

Research Q2: What kinds of participants were mostly be investigated in existing literature and What information on certain types of participants are insufficient?

Over 70% of study recruited male swimmers only as participants, while only 3 have recruited some female swimmers to participate in their investigations. This showed there is a bias towards on male swimmers, but insufficient attention for female swimmers was provided. Differences in performance will be existed due to the differences in the anthropometric characteristics, which would show some variants in muscle activity, or patterns between male and female swimmers. With the study found out that there were significant differences in tethered force performance (Morouço et al., 2015b), swimming performance and

relevant stroke parameters (Ferreira et al., 2015) between male and female swimmers, and also, regarding to the recent review study (Knechtle et al., 2020), their results further confirmed the performance gap between gender. Therefore, differences will be expected to exist between gender in muscle activity during swimming. Hence, with the consideration of the physiological and anthropometrical differences between male and female, not only overall performance should be analysed, gender effect might be considered during the data analysis, to assess the possibility of significant differences in muscle activations during different phases in FC swim. Moreover, in order to have more comprehensive understanding about the performance of female swimmers, more investigations on the muscle activation pattern of female swimmers will be beneficial to the planning of training programs for performance enhancement based on the evidence from female subjects instead of male subjects' research.

With respect to the age range of recruited participants, authors mostly focused their investigations on swimmers that aged 20 or 21, which limited the diversity of participants' characteristics in available evidence. However, according to a research (Rüst et al., 2014), there was significant interaction (age x gender) effect on swimming speed and age accounted for over 37% of FC swimming speed, and these might be influenced by the differences in maturation and puberty. With differences in growth velocity, male and female swimmers in different age groups, especially the young and adolescent swimmers might perform different patterns of muscle activity during swimming. Thereby, there is necessity to consider and then evaluate the muscle activity with different age population. Despite older and more experienced swimmers might perform in more stable and consistent movements during data collection, in order to support the cultivation of elite swimmers and talent identification and promote the development of systematic trainings for younger swimmers, more investigations for younger swimmers should be done. Thereby, to give more support in the screening or selection of swimmers in younger population and discover any insufficiencies by quantifying the performance and providing more evidence-based information for planning interventions are recommended.

Also, ambiguous information on whether the recruited participants were specialists in FC or not would affect the interpretation of the results. With more attention and focus on the performance of FC, no doubt that more interest will be put in this stroke than other types. However, without providing sufficient information about the swimming performance in FC, it is difficult to compare the results from different studies. As research found that different activation pattern in time or amplitude were found between different levels of swimmers, including co-activation patterns. Therefore, the information or characteristics of participants should be collected and reported in a more detailed manner, i.e., FINA Point, experience in competitive swimming recent personal best in FC etc., so that the readers can easily do comparison or references for swimmers with similar characteristics.

For the purpose of providing more comprehensive evaluation and optimization of swimming performance, previous research has demonstrated and suggested to consider multiple factors, including, anthropometrics, gender, age, or skill level/experience (Morais et al., 2021b; 2017) for comparison and evaluation. Therefore, without sufficient participants' information and variety of study population, this might limit our understanding of certain population and unable to use scientific evidence to support the planning of different trainings.

Research Q3: What were the objectives of the study through measurement of muscle activity of competitive swimmers and what are the implications of the results of sEMG measurement?

Investigation of the muscle activation pattern and its variability: Investigation the muscle activation pattern might provide a fundamental reference on which muscles involved in which time phases. Previous studies found out which muscles contribute most for forceful propulsion; however, mainly upper limbs have gained attention, which more studies have discussed their roles and the activity level during different swimming phases.

Although other muscles might not present with high activation or more active time in EMG data, but they also acted as stabilizer to reduce the drag force or served as a bridge for transmitting force by rotator cuff, trunk or pelvis and leg muscles. More attention should be given to appraise their contribution and more investigations to report and discuss their roles and importance in swimming performance will be highly recommended, and thus more available information can be provided to public.

Moreover, despite overall activation pattern for FC swim have been recognized, swimming techniques might be evolved, and the active time of the muscle might have changed also. Thereby, previous definitions might not be applicable in our new swimming generations, more up-to-date muscle activation pattern can be measured and compared with previous results would bring some inspirations for implementing or revising coaching strategies for swimmers.

Investigation of the co-contraction of muscles: Co-activation is a phenomenon of simultaneous activation of muscles surrounding a joint (Kellis, 1998). During a dynamic movement, reciprocal activation patterns are expected between the agonist and antagonist muscles, if co-activation patterns are demonstrated, researchers suggested that the movement is not efficient and no net movement is occurred (Winter, 2009). Therefore, researchers suggested that co-activation might affect the swimming performance, due to the prohibition of net movement when the agonist and antagonist muscles working together and thus, induced the inefficiency in swimming. With the concerns of the effects on swimming performance, 5 papers have investigated different muscle groups in different swimming phases by using sEMG to detect and quantify the co-activation of certain pair of muscles. These would assist on assessing the co-activation pattern and also evaluating the performance by comparing the patterns between athletes and also detecting the inefficiency during swimming.

With respect to the included studies, some studies observed the elbow and wrist co-activation patterns during swim, while some have investigated the patterns in trunk

or lower legs muscle during dolphin kick or flutter kick. Referring to the results from Yamakawa's study (Yamakawa et al., 2017), with the assistance of sEMG, the negative relationship was found between co-active phase of trunk muscles (RA-ES) and efficiency during the underwater dolphin kick. This finding serve as a pioneer but would bring inspiration to the fields about the non-reciprocal activation pattern between RA and ES might affect the swimming performance, but further investigations are recommended to verify the relationships. Moreover, with respect to the results from Matsuda (Matsuda et al., 2016), competitive levels of swimmers would also affect the co-activation patterns, as the results revealed that more competitive swimmers would show lower levels of co-activation pattern of RF-BF in flutter kicks than recreational swimmers. This implied that measuring muscle activity by using sEMG would also help to evaluate the performance by comparing the activation pattern between athletes, and so as to understand the strengths and weaknesses in certain phases, and that information might be helpful for planning trainings for improvement.

However, despite some findings suggested that co-activation in muscles might inhibit the dynamics movement, but co-activation might also bring contributions on performance by providing joint stabilization. According to the conference paper from Kobayashi (Kobayashi et al., 2016), the lower legs co-activation (TA-GAS) might be helpful for stabilizing the ankle joint to reduce the drag force during flutter kick. Apart from the lower limbs, the co-activation at writs and elbow muscles occurred surrounded the joints might aid the movement during insweep phase from different studies (Caty et al., 2007; Lauer et al., 2013; Rouard and Clarys, 1995). It seems possible that these results reflected that co-activation in BB and TB might also have a supporting role during swimming and to prepare for performing next stroke cycle during the recovery phases (Lauer et al., 2013). However, which pairs of muscles and in what swimming phases require co-activation for stabilization or overcoming the drag force might need further investigation for discussion and verification. Therefore, more investigations of co-activation pattern by using sEMG to collect the muscle activity of targeted pairs of muscles are recommended, to identify the appropriate co-activation pattern and level in certain pairs of muscles. Furthermore, as stated in previous research (Solomonow et al., 1988), training would reduce the co-activation level and thus, increase the efficiency and might bring positive effects on swimming performance. With the application of sEMG for measurement, this might facilitate the monitoring and evaluation of the training effects on the co-activation and swimming performance together.

However, the differences between experienced and novice swimmers were not well understood, not only in kicking, but also the arms stroke performance. Moreover, from our observation, unilateral sides (mainly right sides) of muscles were selected for investigations in 5 included studies, however, dominant hands or legs or more experienced swimmers might perform better with lower co-activation levels as shown in other activities (Furuya and Kinoshita, 2007). In order to confirm this phenomenon, more research can be done to investigate and prove this relationship and explore the extent of differences for different competitive levels of swimmers, which have similar suggestions from Caty's study (Caty et al., 2007). Apart from only measuring the levels of coactivation of different pairs of agonist and antagonist muscles, in different stroke phases, or different swimming parts, more exploration on the effects of co-activation on different swimming biomechanics, for example, the effects of the distance travelled by each stroke (stroke length), number of stroke per minute (stroke rate) and the propulsive force or drag of each stroke and also the relationship in between might also be an interesting topic to explore and find out what will be the effects on swimming performance.

Investigation of muscle fatigue: Fatigue is defined as "any exercise-induced loss of ability to produce force with a muscle or muscle group" (Taylor et al., 2006), the occurrence of muscle fatigue might bring negative effects on swimming performance, thus, attracted scholars to do investigation about this topic. Moreover, electromyographic data found to be valid measurement tool for monitoring the muscle fatigue in swimmers (Puce et al., 2021), therefore, more studies introduced the sEMG to explore and evaluate the muscle fatigue in swimming. We observed that authors would examine the muscle activity for 100m and 200m FC swim, with the similar observation from (Gonjo and Olstad, 2021) for conducting analysis or evaluation. These certain events might require anaerobic energy system, which would initiate fatigue responses, and thus more authors chose this distance for investigating the influence on swimmers' ability of muscle contraction. The muscle activity changes would be able to reflect by using sEMG for following the changes in muscle activation patterns, not just measuring the blood lactate concentration after the test, as the results found in Figueiredo's study (Figueiredo et al., 2013b). Furthermore, by measuring the muscle activity to evaluate the muscle fatigue, the results might help the coaches and swimmers recognized the weaknesses on certain muscles, and therefore, specific trainings and strategies can be prescribed to pinpoint the problems and to refine swimmers' performance.

For the investigations included in our review, not only measure the muscle activity, but they have also measured the changes in different kinematics parameters during swimming, including SV, SL, SR/SF and KF (Figueiredo et al., 2013a; Lomax et al., 2014; Stirn et al., 2011), and then correlating those parameters with the changes in muscle activity too. The results revealed that muscle fatigue mostly appeared in upper limbs, i.e. PM, LD and TB, and thereby affecting the stroke biomechanics, especially in SL (Figueiredo et al., 2013b), while the kick performance is relatively stable, without showing any signs of fatigue (Figueiredo et al., 2013a; Figueiredo et al., 2013b). By evaluating the muscle fatigue of both upper and lower limbs, which further confirmed that upper extremities contributed more during FC swim and lower limbs might act as a supporting role, i.e. maintain a better body position and thus, decrease the drag force to support the upper limbs.

Because the physiological changes, i.e., lactate accumulation, which would affect the ability of force production. With such huge negative effects on final performance, continuously monitoring the muscle activity during

swimming by sEMG, and combining the measurement of kinematic parameters are recommended (Stirn et al., 2011), since this would allow us to have better understanding on the gradual changes in different parameters in muscle fatigue. In addition, according to the definition of muscle fatigue (Taylor et al., 2006), the occurrence of muscle fatigue would affect the ability of force production, thereby, investigation the relationship with the continuous measurement in force production, as limited research is available on evaluating the force performance with the appearance of muscle fatigue (Aujouannet et al., 2006), so that we can monitor the progress of changes in both parameters and see any correlations exist between both changes and compare the results between different competitive levels of swimmers.

Moreover, inspiratory muscle fatigue also a new topic for evaluating the swimming performance, as there were research found out that it would affect the swimming speed in FC, i.e. breathing frequency, SL and SR (Lomax and Castle, 2011). Also, PM is engaged in breathing action with other respiratory muscles, it is interesting that to further investigate the relationship between the muscle activity of PM and the inspiratory muscles and also the information about IMF is scarce and more research about the IMF effects on swimming performance, including both kinetics and kinematics will be recommended.

Investigation of the relationship between muscle activity and swimming biomechanics: Notwithstanding that the ultimate target in competition will be swimmer can perform their fastest time, more attention might be focused on temporal parameters, but there are multiple factors would affect the time performance, i.e., kinetics and kinematics parameters including propulsive force of each stroke, swimming velocity or takeoff velocity from block start and body roll during swimming. Given that the importance of different biomechanical parameters on swimming performance (Barbosa et al., 2010; Kwok et al., 2021; Nicol et al., 2019), multi-factorial investigation analysis should be included in future. The relationships between the changes in stroke biomechanics, for instance, appearance of muscle fatigue would affect the stroke length and also the stroke rate, ultimately influence the swimming velocity (SV= SL x SR). The rationale behind and process of the decreased in force or speed along with the measurement of muscle activity should be recognized by conducting more research.

The above-mentioned asymmetrical muscle activation, and its relationships with the differences in relevant kinetics or kinematics parameters on swimmers that revealed in previous research (Carvalho et al., 2019; Cohen et al., 2020; Dos Santos et al., 2017; Pedersen and Kjendlie, 2006; Psycharakis and McCabe, 2011), more investigation to explore the influences and relationships would be recommended by measuring both sides' muscle activities in different phases for comparing and evaluating the asymmetries in measured parameters by calculating the index of asymmetry (Seifert et al., 2008; Carpes et al., 2010; Sanders et al., 2012) through the difference between the left and right side muscles or breathing and non-breathing side and presented as percentage (%), called symmetry index (SI; SI% = ((A-B)/(A + B))*2*100). This index might allow us to differentiate any asymmetry in swimmers and also to do the comparison between swimmers or groups.

Research Q4: What is the most commonly adopted method for sEMG data processing and how do they process the data collected?

With the rapid development of the technology, wireless sEMG should be more mature than before, and more investigations and research by this measurement tool could be done. According to the systematic review conducted by Martens and his team (Martens et al., 2015b), no wireless sEMG were used for investigation. After years of development, different studies have introduced the wireless technology for evaluating different purposes that related to muscle activity. As choosing sEMG as the measurement tool would reduce the limitations bring from wired methods, wireless technology even can generate a more natural and similar environment for swimmer to perform for data collection. In our review study, only one study (Puce et al., 2021) has adopted to use the wireless sEMG for measuring the muscle activity and confirm its validity and sensitivity. This represented that there are gaps in using the latest models of sEMG for monitoring or evaluation of muscle activity. Thus, more application of wireless sEMG in research field for swimming is highly recommended, for giving more updated information and insight on swimmers' muscle activity to relevant parties.

Regarding to data handling, most of the included articles have presented their data processing procedures, i.e., rectification or integration of EMG data, and the range of frequency (Hz) for data filtering using different software, according to the guideline from International Society of Kinesiological Electromyography, SENIAM and the Journal of Electromyography and Kinesiology. While for data normalization, MVIC and dynamic peak were the methods adopted mostly in 14 included studies. However, debate and argument still exist on choosing which normalization methods for EMG data (Burden, 2010), as each method has its own advantages and disadvantages Martens et al. (2015a) and researchers shall select the methods according to the research methodology and objectives.

Some might not suggest using MVIC as normalization method, we just assumed that the subject was performed with their maximal effort, and the same manual resistance and the same situation were provided during MVIC tests for each subject. Also, MVIC was performed on land while the data collection for swimming was conducted underwater, this might wrongly estimate the muscle activity collected from swimming tests, as participants performed in different conditions. Oppositely, using dynamic peak methods might limit the comparison between or within subjects in different trials, as the peak value was obtained from each test, therefore, many variables would affect the peak value obtained from each trial, i.e., conditions of swimmers, training effects and etc., despite there was no significant differences in the results between two normalization methods (Martens et al., 2015a). Until this moment, no conclusions were drawn on which method is the most appropriate for normalizing the EMG data for swimming, as both methods have its own limitations and advantages, but researchers should address their limitations in their study clearly and readers shall interpret the results with

cautions. In order to dispel the doubts, more investigations by using both normalization methods are suggested to assess any significant differences would exist in the results. Finally, constructing a guideline is suggested for providing a clearer direction and guidance for future investigations and authors shall carefully choose the best methods according to their objectives of each study and also the experimental procedures and criteria of each method for data normalization.

Quality assessment: We have also evaluated the quality of each article by an assessment tool on reporting the participants' information and number of participant recruitment, description on methods on data collection and processing and the presentation of their main results.

Most of the paper only provided age, height and weight, time of swimming events etc., however, rarely mentioned whether they were FC specialists and their years of experience, which might be important for coaches and sports scientists to reference and compare the results with their own athletes.

Conclusion

With the advancement and rapid development of technology, measuring muscle activity will be more accessible and convenient in a more natural environment, thus this might attract more swimmers to participate in scientific studies and reduce the time consumed during data collection with less complication procedures. Thereby, we should promote the quality of the study and thus, the result will be more generalizable to relevant swimming population.

With the support from the rapid development of technology for swimming performance monitoring and enhancement, we shall seize this opportunity to well-utilize those technologies on the swimming athletes. From this review study, we found that there is insufficient information about the muscle activity of legs and trunk muscles during FC swim, and not much investigation on starts and turning phases. With insufficient investigations and information on these two important phases, these might limit our understandings and hence, affecting the planning on relevant training and performance evaluation for swimmers in a more comprehensive approach.

Also, insufficient information on female is discovered, and most of the study only selected unilateral side for research. Therefore, we suggested that more investigations on muscle activation performance during starts and turns and study for women swimming population. Also, bilateral sides of muscle activity should be recruited for assessing any differences between sides. Lastly, more research about co-activation of muscles during swimming will also be recommended to see the effects on performance.

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Key points

- Biased investigations of upper limbs' muscles activity due to the important role in FC swim.
- More experiments should be conducted to evaluate muscle activity during starts and turns.
- Insufficient information about the muscle activity of leg and trunk muscles during FC swim.
- More exploration about the roles or contribution of muscle co-activation on swimming performance is highly recommended.

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