



# A review on crosstalk in myographic signals

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## Abstract

**Purpose** Crosstalk in myographic signals is a major hindrance to the understanding of local information related to individual muscle function. This review aims to analyse the problem of crosstalk in electromyography and mechanomyography.

**Methods** An initial search of the SCOPUS database using an appropriate set of keywords yielded 290 studies, and 59 potential studies were selected after all the records were screened using the eligibility criteria. This review on crosstalk revealed that signal contamination due to crosstalk remains a major challenge in the application of surface myography techniques. Various methods have been employed in previous studies to identify, quantify and reduce crosstalk in surface myographic signals.

**Results** Although correlation-based methods for crosstalk quantification are easy to use, there is a possibility that co-contraction could be interpreted as crosstalk. High-definition EMG has emerged as a new technique that has been successfully applied to reduce crosstalk.

**Conclusions** The phenomenon of crosstalk needs to be investigated carefully because it depends on many factors related to muscle task and physiology. This review article not only provides a good summary of the literature on crosstalk in myographic signals but also discusses new directions related to techniques for crosstalk identification, quantification and reduction. The review also provides insights into muscle-related issues that impact crosstalk in myographic signals.

**Keywords** Crosstalk · Electromyography · Mechanomyography · Signal contamination

## Abbreviations

ADM Abductor digiti minimi  
APB Abductor pollicis brevis  
ARV Average rectified value

BB Biceps brachii  
BE Branched electrode  
BSS Blind source separation  
BP Bipolar  
BRA Brachialis  
BRD Brachioradialis  
CCC Cross-correlation co-efficient  
CS Corrugator supercillii  
DD Double differential  
ECU Extensor carpi ulnaris  
ECR Extensor carpi radialis  
ED Extensor digitorum  
EDC Extensor digitorum communis  
EDM Extensor digiti minimi  
EI Extensor indicis  
EMG Electromyography  
ES Erector spinae  
FCR Flexor carpi radialis  
FCU Flexor carpi ulnaris  
FDP Flexor digitorum superficialis  
FDS Flexor digitorum profundus  
FES Field electrode stimulation  
GL Gastrocnemius lateralis

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GM	Gastrocnemius medialis
ICA	Independent component analysis
IED	Inter electrode distance
IEMG	Integrated EMG
IL	Iliopsoas
LD	Latissimus dorsi
MF	Median frequency
MMG	Mechanomyography
MUAP	Motor unit action potential
OO	Orbicularis oculi
PL	Peroneus longus
PP	Peak to peak
PT	Pronator teres
RAEO	Rectus abdominis internal oblique
RF	Rectus femoris
RMS	Root mean square
sEMG	Surface EMG
SOL	Soleus
SA	Sartorius
TA	Tibialis anterior
TS	Triceps surae
TB	Triceps brachii
TMS	Transcranial magnetic stimulation
TAIO	Transversus abdominis internal oblique
VI	Vastus intermedialis
VL	Vastus lateralis
VM	Vastus medialis
wEMG	Wired EMG
ZM	Zygomaticus major

## Introduction

Surface electromyography (sEMG) is a powerful tool that has been extensively used to provide insights into muscle physiology (Rudroff et al. 2008) and motor control and for the evaluation and diagnosis of neuromuscular diseases (Jonkers et al. 2004) and pain analysis. sEMG also provides more information on global muscle activity than fine-wired EMG (wEMG) (Mezzarane and Kohn 2009). Mechanomyography (MMG) is the mechanical counterpart of sEMG and provides equally useful information regarding muscle function under a variety of experimental conditions (Than et al. 2016; Orizio et al. 1999; Tosovic et al. 2016).

Surface electrodes, which are the sensors used in sEMG, are safe and easy to handle (Ali et al. 2013). Although surface electrodes provide a better approximation of the activity of superficial muscles, they cannot be used to detect selective signals from small and deep muscles due to the problem of crosstalk (Benhamou et al. 1990). Even the signals from superficial muscles are contaminated by crosstalk from muscles adjacent to and beneath the target muscle (Pérot and Mora 1993). Thus, myographic signals detected over

the skin surface are often mixtures of signals generated by multiple active muscles, and this phenomenon is generally referred to as crosstalk (Mesin 2018). Thus, it is sometimes not possible to identify the activity of individual muscles, particularly when the muscles are small and close to each other (Farina et al. 2008). In most cases, such closely spaced muscles do not work independently but contribute their specific role to the total activity. It is thus important to recognize the exact role of a muscle in a particular activity (Farina and Merletti 2004). Such findings could be helpful in many applications, including sports training (Ganter et al. 2007), rehabilitation (Brink-Elfegoun et al. 2007), and prosthetic control (Hussain et al. 2018; Xie et al. 2009). Hence, methods to identify, quantify and eliminate the unwanted signals from the main signal must be devised.

A few review articles in the literature discuss some important aspects of crosstalk in myographic signals. In particular, crosstalk in sEMG signals has been discussed as a problem that produces antagonist activity in quadriceps and hamstrings (Kellis 1998). sEMG crosstalk considerations were highlighted in pelvic floor muscles by Flury et al. (2017). Blind source identification was reviewed as a tool to reduce crosstalk in sEMG signals by Holobar and Farina (2014). Hug (2011) recently discussed crosstalk in sEMG as a drawback of the technique when studying muscle coordination.

To the best of our knowledge, crosstalk in myographic signals has not been previously reviewed, and thus, a review of previous studies on this issue is urgently needed. The current review highlights the available methods to identify, tools to quantify and techniques to reduce crosstalk in myographic signals in relation to various muscle issues. Our findings will provide insights for optimally resolving the problem of crosstalk in myographic signals in terms of equipment manoeuvres and offline computer techniques. Various areas of research related to this problem are highlighted in this review article, which shows the potential of this field.

Original research articles related to the problem of crosstalk in myographic signals were selected from the literature based on pre-decided inclusion and exclusion criteria. The combination of keywords used for the initial search of the SCOPUS database and the detailed selection criteria are shown in Fig. 1. After a careful screening, a total of 59 potential articles on crosstalk in electromyographic and mechanomyographic signals were selected. These 59 studies were then critically analysed and divided further into four topics, namely, crosstalk identification, crosstalk quantification, crosstalk reduction and muscle issues in myographic signals, to provide a better understanding of the issue.

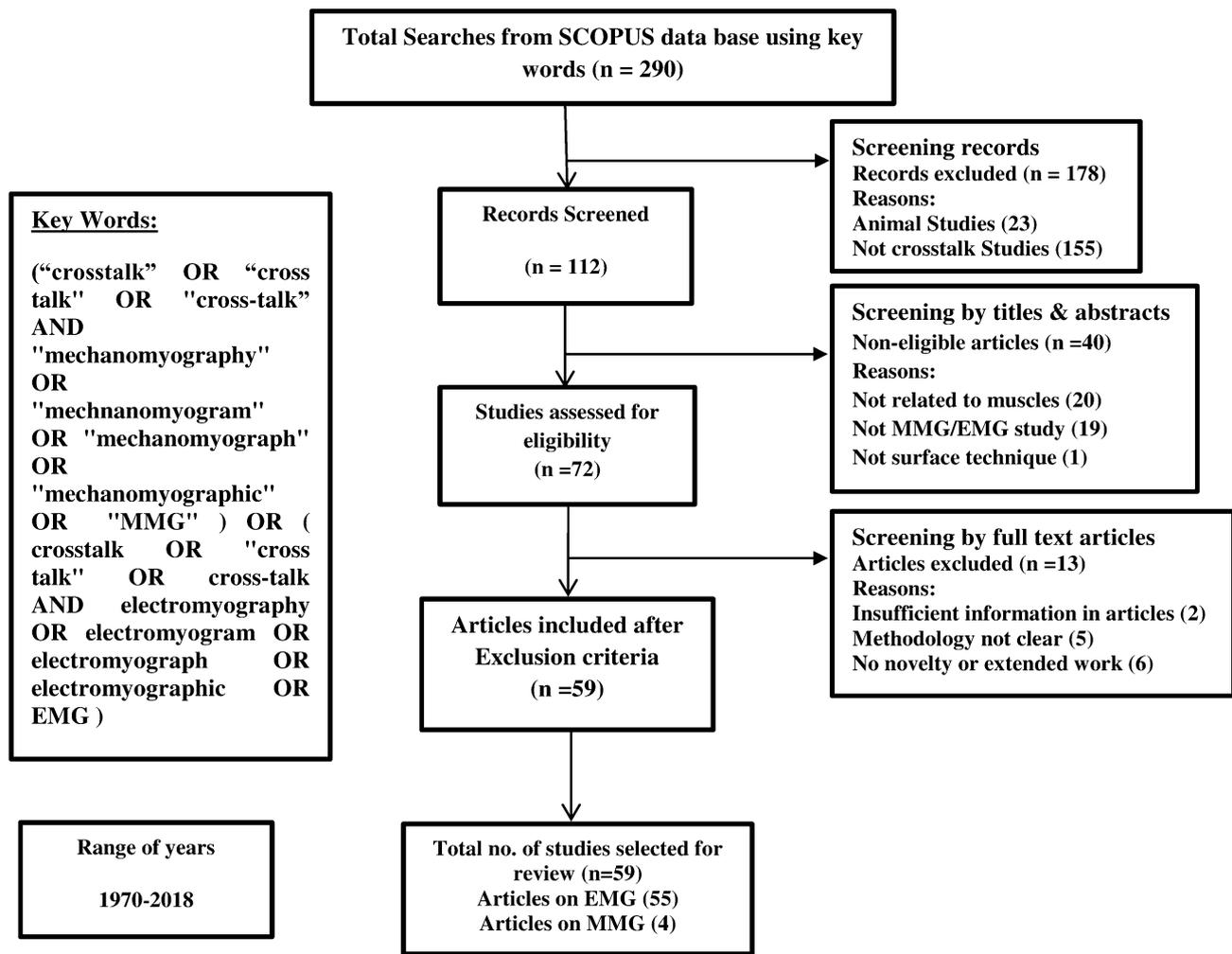


Fig. 1 Flow chart for selection of records on crosstalk studies in myographic signals

## Crosstalk identification

The first step in resolving the problem of crosstalk is its identification, i.e., determining whether this phenomenon exists when a particular muscle is performing a certain activity. Many articles in the literature discuss the identification of crosstalk among muscles, which shows the importance of this area of research. A list of abbreviations for the names of all the muscles is provided at the start of this review. As detailed in the literature, different methods have been developed for crosstalk identification, and these methods are discussed in detail in the following section and are listed in Table 1.

### Crosstalk identification through simultaneous wEMG and sEMG recordings

Many researchers have developed different methods to identify crosstalk and separate it from the original myographic

signals. One of these methods to identify crosstalk in sEMG signals involves the recording of both surface and wEMG from the same muscle during a particular activity.

sEMG and wEMG signals from rectus femoris (RF) and vastus lateralis (VL) during different muscle activities were recorded simultaneously by Nene et al. (2004), Byrne et al. (2005), Shahid et al. (2005) and Barr et al. (2010). All these researchers obtained higher muscle activity with sEMG compared with wEMG. This difference appears to indicate the presence of crosstalk but could also be due to the limited area detected by wEMG, which does not completely monitor all motor units.

In addition to simply a comparison of the sEMG and wEMG amplitudes, similarities in the appearance of motor unit action potentials (MUAPs) from the muscles also provides evidence of the possible presence of crosstalk (Shahid et al. 2005). For instance, a similar appearance of MUAPs in RF and VL is observed during hip flexion, even though RF is responsible for hip flexion and VL does not participate

**Table 1** Reported studies on crosstalk identification

No.	Methods	Muscles	References	Observations	Future work/limitations/suggestions
1.	Parallel recording of wEMG and sEMG	RF, VL	Nene et al. (2004), Byrne et al. (2005), Shahid et al. (2005), and Barr et al. (2010)	Higher muscle activity is detected by sEMG compared with wEMG sEMG shows biphasic activity at all speeds due to crosstalk The similar appearance of MUAPs in sEMG signals of the VL and RF during hip flexion depicts crosstalk in VL and vice versa for both muscles during knee extension	The effect of the type of muscle contraction on the relationship between sEMG and wEMG was not addressed
2.	Functional resistance test	GA, SOL, TA, PL	Ginn and Halaki (2015) Winter et al. (1994)	Different LD muscle activities were obtained with sEMG and wEMG during shoulder flexion and abduction FRT revealed negligible crosstalk in muscle pairs composed of muscles with different functions (SOL/PL and SOL/GL)	Single IED was used for crosstalk reduction A common drive to agonist muscle pairs negate the use of FRT to identify crosstalk
		SOL, TA	Mezzarane and Kohn (2009)	Crosstalked H-reflex from the target muscle was observed in a remote muscle	Mathematical derivations are invalid if a non-homogeneous crosstalk ratio is obtained during the EMG and silent period from the target to the remote muscle A third muscle named brachioradialis was not discussed
		BB, BRA, BRD	Staudenmann and Taube (2015)	The muscle activity of BRA can be clearly distinguished from the activity of BB using sEMG during a flexion + supination task	
		OO	Akamatsu et al. (2015)	The placement of electrodes on the central lower eyelid reduced the crosstalk in the sEMG signal due to clenching and head shaking	Artefacts are considered to indicate crosstalk in this study; hence, a specified experimental protocol that isolates the observed muscle activity should be developed
3.	External stimulation	FCR, FCU, ECR, ECU	Selvanayagam et al. (2011)	The maximal value of sEMG crosstalk during both voluntary and stimulated contraction is 39.4%, and a lower value of 3.7% is obtained with wEMG	A comparison of stimulated and voluntary sEMG crosstalk should be verified on larger muscles or leg muscles also
4.	Frequency-based method	RF, VI, VL, VM, BF	Watanabe and Akima (2009) and Saito et al. (2013)	A negligible effect of crosstalk from the VL on VI was observed during isometric contractions using the MF response and selective cooling of the VI	The negligible effect of crosstalk from VL on VI through this MF cooling index should be verified during dynamic contractions
		IL, SA	Jiroumaru et al. (2014)	A negligible effect of crosstalk from the SA was observed on the IL during isometric hip flexion using the MF response and selective cooling of the SA	The same experimental settings should be verified using dynamic contractions

**Table 1** (continued)

No.	Methods	Muscles	References	Observations	Future work/limitations/suggestions
5.	Miscellaneous methods	FCR, FDS, ECR, EDC  TA, SOL  ECR, ECU, EDC	Ridderikhoff et al. (2005)  Jensen et al. (2012)  Gallina et al. (2017)	Contralateral homologous forearm extensors exhibited involuntary mirrored movements due to neural crosstalk  The conduction velocity due to crosstalk was one order of magnitude higher than the conduction velocity of the original reflexes  HD sEMG showed that conventional sEMG signals obtained from the ECR during TMS exhibit crosstalk from other muscles, particularly under resting conditions	There is insufficient reasoning for why the results obtained for extensors are different from those obtained for flexors  Voluntary contraction should be considered in experimental protocols to ensure the detection of original muscle activation  sEMG arrays should be used in future stimulation protocols to observe the innervation zone

in hip flexion activity. This finding might indicate that the signals observed in VL are due to the activity of RF. Similarly, during knee extension, in which VL plays a vital role, the MUAP orientation of RF is similar to that found for VL. Although this effect could be due to crosstalk in the sEMG signal of RF due to the activity of VL, it could also be attributed to low-level contractions of RF. Hence, the recorded sEMG signals in this study do not depict the actual activity of the target muscle but rather register the recruitment and activation of other MUAPs. The above-mentioned studies concluded that the simultaneous recording of both sEMG and wEMG can be used to identify crosstalk in sEMG signals. Hence, the identification of crosstalk in sEMG could be a first step for the useful application of this tool for the assessment of muscle activity (Barr et al. 2010).

The presence of crosstalk in latissimus dorsi (LD) was identified by the parallel recording of sEMG and wEMG signals during shoulder flexion and abduction tasks by Ginn and Halaki (2015). Compared with wEMG, sEMG showed higher activation of the LD during tasks in which this muscle is not highly activated, such as shoulder flexion and abduction. In contrast, sEMG and wEMG showed the same activation level during those tasks in which LD actively participates, such as shoulder extension and adduction. The researchers suggested that this difference could be due to the presence of crosstalk in sEMG signals. In addition, sEMG crosstalk has been attributed to the nature of this detection technique, which has a larger detection area compared with that of wEMG. Thus, the sEMG signal obtained contains signals from muscles other than the LD. Erector spinae (ES), which is located beneath the LD, could be a source of crosstalk in the LD signal obtained with sEMG. The researchers further suggested that the recording of LD activity with an IED less than 25 mm might decrease the amount of ES crosstalk.

**Crosstalk identification using a functional resistance test (FRT)**

An even simpler method to identify crosstalk involves the use of a FRT, in which a specific muscle or group of muscles is isolated and the recordings of non-active muscles are then examined (Winter et al. 1994). A FRT was performed by Mezzarane and Kohn (2009) by isolating the SO muscle. The subject was asked to contract the specified muscle only while the sEMG signals were being recorded from apparently non-active neighbouring muscles. However, the drawback of this approach is that the voluntary activation of a specified muscle without the activation of synergists or even antagonists cannot be ensured.

Staudenmann and Taube (2015) found that a high amount of crosstalk is not observed in the brachialis (BRA) muscle due to the activity of the biceps brachii (BB). For this

purpose, the following two-step task was performed: pure elbow flexion followed by elbow flexion superimposed by forearm supination. The researchers observed a lower level of crosstalk in the BRA signal during the second step and concluded that BRA activity can be distinguished from BB activity. Although this study shows that the FRT approach provides better results, this finding is due to the anatomical behaviour of the muscles.

Crosstalk in the orbicularis oculi (OO) muscle was investigated by Akamatsu et al. (2015) during eye blinking for prosthesis design. This crosstalk could be due to artefacts, such as clenching, speaking, ocular movement and shaking head, and can result in misinterpretation of the activity of the OO muscle during eye blinking. Although the researcher placed the sEMG electrodes on optimal locations to reduce crosstalk, a protocol that can isolate the activity of the OO muscle could be designed but to validate the application of an eye prosthesis.

### Crosstalk identification using a stimulated protocol

Another approach to identify crosstalk is to electrically stimulate the target muscle and observe the effect of its activity on non-target neighbouring muscles. This approach was used by Selvanayagam et al. (2011), who concluded that the same level of sEMG crosstalk is obtained with both voluntary and stimulated protocols. The maximum sEMG crosstalk for six forearm and hand muscles obtained during both voluntary and stimulated contractions was 39.4%. In contrast, the wEMG signal showed a lower level of crosstalk for the same muscles, namely, 3.7%. Thus, the problem of crosstalk in stimulated EMG activity is as critical as it is in voluntary contraction.

Although electrical stimulation can selectively stimulate a group of target muscles, locating the muscles that are activated is difficult. Second, reflex and external stimulation can provide an overestimation of muscle activation because the muscle activation is not manual. The results of this type of experiment are not applicable for voluntary contractions because the volume conductor properties of externally stimulated muscle are different from those during voluntary contractions. However, voluntary contractions are of vital importance for estimating the natural activity of a muscle in many situations (Lowery et al. 2003).

### Frequency-based crosstalk identification method

Another crosstalk identification tool is investigating the median frequency (MF) response recorded during the selective cooling of muscles. The MF decreases with decreases in the muscle temperature. Hence, the muscles that are likely to cause crosstalk on a target muscle can easily be cooled using an external source. A decrease in

the MF of a non-target muscle accompanied by a sustained MF of target muscle indicates a lack of crosstalk effect from the non-target muscle on the target muscle. Watanabe and Akima (2009) found that the MF of the VL decreased during cooling at a rate of 4.2% per 1 °C, but the MF of the VI remained same. Similarly, comparable results were observed by Watanabe and Akima (2009), who found that the MF of the BFS decreased 2.8–3.0% during each 1 °C decrease in the skin temperature with no change in the MF of the VI. Hence, muscles neighbouring the VI have a negligible crosstalk effect on the VI. Jiroumaru et al. (2014) observed a similar pattern of sEMG activity in hip muscles. The MF of sartorius muscle (SA) found that the MF of the SA decreased by 1.2% during each 1 °C decrease in temperature with no change in the MF of the iliopsoas muscle (IL), which shows that the SA has a negligible crosstalk effect on the sEMG signal of the IL.

### Miscellaneous

The literature details other methods for the identification of crosstalk in myographic signals. Conduction velocity was used as a measure of sEMG crosstalk by Jensen et al. (2012). These researchers claimed that this method can be used to identify and quantify crosstalk in sEMG signals. This method requires further investigation before it can be effectively applied to estimate crosstalk during reflex detection.

Another method for the identification of crosstalk in sEMG signals involves the use of HD sEMG, which uses a grid consisting of a larger number of very small electrodes working simultaneously. This method is becoming increasingly popular as an alternative tool to conventional sEMG because it yields accurate results. A comparison of sEMG and HD sEMG signals from the extensor carpi radialis (ECR) muscle was used by Gallina et al. (2017) to identify crosstalk in conventional sEMG. These findings showed that conventional sEMG supplements ECR muscle activity to a high extent during a transcranial magnetic stimulation (TMS) protocol, particularly when the muscle is at rest, and this exaggerated signal indicates crosstalk from other forearm muscles. Hence, the use of HD sEMG in conjunction with conventional sEMG can identify crosstalk in sEMG signals obtained in TMS experiments.

Another type of sEMG crosstalk in the contralateral homologous limb due to activity from forearm muscles was identified by Ridderikhoff et al. (2005), and this phenomenon is termed as neural crosstalk. Involuntary mirrored movement was observed in the forearm extensors of the contralateral homologous limb, but this phenomenon was not observed in the forearm flexors. Further investigation is needed to analyse sEMG neural crosstalk using a variety of experiment protocols.

## Crosstalk quantification

After crosstalk has been identified in myographic signals, the next step is its quantification. Three types of indices are used to investigate the magnitude of crosstalk in sEMG signals: the amplitude-based index, the power-based index and the correlation-based index. These indices have advantages and disadvantages, as discussed in detail in the forthcoming sections and listed in Table 2. The quantification of crosstalk in myographic signals is a crucial step toward the elimination of this unwanted signal content.

### Amplitude-based crosstalk quantification methods

The amplitude-based index has been calculated in the literature using three different amplitude measures: (i) average-rectified value (ARV), (ii) peak-to-peak (PP), and (iii) root mean square (RMS). These three measures have been employed to calculate the ratio of the signal amplitude with crosstalk to that without crosstalk.

Koh and Grabiner (1992) used the sEMG amplitude ratio to quantify crosstalk between the biceps femoris and the VL. A similar ratio was used by Van Vugt and Van Dijk (2001) to quantify crosstalk in an agonist-and-antagonist muscle pair. Farina et al. (2002) also used the same index for stimulated and non-stimulated muscles. These researchers compared amplitude-based and cross-correlation coefficient-based indices and found a poor correlation between the two entities. Based on these findings, the researchers concluded that amplitude-based indices are more reliable than CCC because they use information on the pure signal without crosstalk.

Campanini et al. (2007) used another amplitude-based crosstalk index, which they defined as the ratio of the area of the normalized envelope outside the expected activation phase of the muscle to the area of the entire normalized envelope. The benefit of this approach is that the crosstalk index does not account for muscle coactivation. The ratio of the sEMG crosstalk RMS to the sEMG RMS was calculated by Mezzarane and Kohn (2009) for the quantification of crosstalk in the target muscle; in this approach, H-reflex was used to stimulate the target muscle. H-reflex induced a silent period in the target muscle, and its effect was observed on non-target muscles. However, the mathematical derivations used in this study become invalid if a non-homogeneous crosstalk ratio is obtained during the EMG and silent period from the target to a remote muscle.

The key limitation of amplitude-based indices is that they require a crosstalk-free signal (Kong et al. 2010). Hence, employing this technique is difficult, and researchers avoid using them in their calculations. Despite the

difficulty of their operation, an amplitude-based index is beneficial because it does not account for muscle coactivation.

### Power-based crosstalk index

The utility of blind source separation (BSS) as a crosstalk quantification tool is evident in the literature. Farina et al. (2008) derived a power-based index using BSS to calculate crosstalk in sEMG signals. The power of the signal outside the interval of activation of the associated muscles was computed relative to the total signal power as a measure of crosstalk before and after BSS (Farina et al. 2008). This index of crosstalk is peculiar in the sense that more overlapping is associated with a smaller crosstalk index. This choice of crosstalk index is preferable over others because it quantifies the signal power outside the activation interval of a muscle. Hence, this approach could be used to quantify crosstalk in practical applications in which selective muscle activation is performed to record the EMG activity of several muscles.

### Cross-correlation-based crosstalk quantification methods

The cross-correlation coefficient (CCC), which is another method used to quantify crosstalk (Lowery et al. 2003), is based on the fundamental assumption that the shapes of the waveforms from both muscles under consideration for the calculation of crosstalk are the same. Although there are some arguments against this quantification approach, this technique has widely been adopted by researchers due to its ease of operation and reliability.

CCC ranges from 0 to 1, where 0 indicates no common signal between two muscles and 1 shows 100% commonality in signals. A convenient division of this range from 0 to 1 might be used to represent the level of association between signals. In cross-correlation analyses, a value less than 0.30 is thought to indicate a specific, isolated signal free of crosstalk. Marshall and Murphy (2003) considered a cross-correlation less than 0.30 to indicate a low association between signals, whereas a CCC between 0.30 and 0.70 represents a moderate relationship between the signals, and a CCC greater than 0.70 shows a strong relationship between the signals.

This technique has been adopted by Jensen et al. (2012), Marshall and Murphy (2003), Frahm et al. (2012), and Mogk and Keir (2003), among many other research groups. Jensen et al. (2012) quantified crosstalk in withdrawal reflexes from TA and SOL and evaluated the conduction velocity and maximal correlation coefficient from the correlograms. The conduction velocity due to crosstalk was one order of magnitude higher than the conduction velocity of the original reflexes.

**Table 2** Reported studies on crosstalk quantification

No.	Methods	Muscles	References	Observations	Future Work/Limitations/Suggestions
1.	Amplitude-based crosstalk index	VL, VM, RF  TA, TS	Koh and Grabiner (1993) and Farina et al. (2002)  Van Vugt and Van Dijk (2001)	Both types of crosstalk indices (amplitude- and correlation-based indices) show a poor correlation  When crosstalk was computed from the ratio of the EMG activity recorded during pure agonist activation to the EMG activity during pure antagonist activation, the DD electrode configuration yielded the best reduction of crosstalk among a variety of spatial filters tested	CCC is not indicative of crosstalk, but amplitude-based indices are not always suitable because they require information on the pure signal without crosstalk  A configuration of closely spaced bipolar electrodes might not be suitable for extracting some global information regarding the state of the muscle
		TA, PL, GM, GL, SOL	Campanini et al. (2007) and Mezzarane and Kohn (2009)	An increase in the crosstalk index was obtained as the electrodes on the TA were moved from the medial to the lateral location. An opposite trend was found for the PL, and a uniform trend was found for the GM, GL and SO	The crosstalk index does not account for muscle coactivation
		FDS, FDP, FCR, FCU	Kong et al. (2010)	Relatively larger magnitudes of crosstalk were observed with %RMS compared with $R^2$	The study was limited to static grip and forearm flexors
2.	Power-based crosstalk index	FCR, PT	Farina et al. (2008)	The ratio of the power of the signal before BSS to the power of the signal after BSS (outside the activation interval), which is used as a power index of crosstalk, yielded a reduction of 25% after BSS	A comparison of the crosstalk indices obtained with various degrees of overlapping between the muscles could provide greater justification of the index

Table 2 (continued)

No.	Methods	Muscles	References	Observations	Future Work/Limitations/Suggestions
3.	Cross-correlation-based crosstalk index	VL, VM, RF	Farina et al. (2002)	Both types of crosstalk indices are poorly correlated	CCC is not indicative of crosstalk, but amplitude-based indices are not always suitable because they require information on the pure signal without crosstalk
		None (a model was used in this study)	Lowery et al. (2003)	Cross-correlation is not a good measure of crosstalk because it does not account for coactivation	The results of the study require validation using real muscle data
		TAIO, RAE0	Marshall and Murphy (2003)	The CCC was low between the rectus abdominis and transversus obliquus, which are internal oblique muscles	The limitations for the use of CCC were not considered
		ECU, EDC, EDR, BRD, FCU, FDP, FDS, FCR	Mogk and Keir (2003), Islam et al. (2014a, b), and Islam et al. (2015)	CCC was shown to be a powerful tool to calculate the percentage of the common signal	Only one trial per condition was conducted, and fatigue was not monitored by Mogk and Keir (2003)
		TA, SOL	Jensen et al. (2012) and Frahm et al. (2012)	The conduction velocity due to crosstalk was found one order of magnitude higher than the conduction velocity of the original reflexes	No other crosstalk index was employed for the comparison of indices Voluntary contraction should be considered in the experiment to ensure detection of the activation of the original muscle

Farina et al. (2002) compared the CCC and amplitude-based indices for the quantification of crosstalk and found that CCC is not a good indicator of sEMG crosstalk. The effect of a volume conductor (skin, fat, muscle, bone) on myographic signals depends on the muscle (Beck et al. 2010). To this effect, the shared variance among forearm muscles obtained using CCC is 40–60% in EMG (Mogk and Keir 2003) and 30–70% in MMG (Islam et al. 2014a, b). This similarity in the shared variance indicates that CCC could be used as an alternative crosstalk quantification tool. However, according to De Luca (1997), if the percentage of the common signal between the muscles is greater than 60%, there is high probability that the contamination originates from the co-contraction in the muscles rather than crosstalk.

## Crosstalk reduction

After identification and quantification of crosstalk in myographic signals, the next step is to get rid of these unwanted signals. For this, many techniques have been adopted by researchers, some are based on precautionary measures during experiment and some are off-line techniques. The details of these techniques are listed in Table 3 and discussed below.

### Electrode geometry/interelectrode distance (IED)

Methods for crosstalk reduction using electrode manoeuvres include using electrodes with a smaller surface area, using a closer interelectrode distance, or introducing temporal and spatial filters during EMG processing, and many studies have used these methods (Winter et al. 1994; Van Vugt and Van Dijk 2001; Yung and Wells 2013).

Changes in the interelectrode distance (IED) can vary the crosstalk in sEMG signals. Zipp (1982) studied the effects of the electrode geometry on sEMG crosstalk during elbow flexion and extension tasks by testing the crosstalk from the BB and triceps brachii (TB) with three different IEDs, including 150, 35 and 15 mm. The study found that closely spaced bipolar (BP) electrodes can reduce crosstalk by up to 75%. However, a closely spaced BP electrode configuration is not suitable for fetching global information about the state of a muscle. Winter et al. (1994) identified crosstalk in sEMG signals from the vastus lateralis (VL) and vastus medialis (VM). These researchers investigated the effects of changes in the electrode geometry and the mathematical differentiation of the signal on the amount of crosstalk and found that closely spaced electrodes with a smaller area and mathematical differentiation of the sEMG signal can reduce the signal crosstalk by up to 80%. The findings reported by Farina et al. (2002) for IED and crosstalk for the VL, VM and RF are also consistent with those obtained by Zipp (1982) and Winter et al. (1994). Later, De Luca et al. (2012)

observed the effect of the IED between bar- and disk-type sEMG sensors on crosstalk. The crosstalk in sEMG signals from the tibialis anterior (TA) and triceps surae (TS) was quantified for IEDs of 10 and 22 mm, and the results showed that a spacing of 22 mm yielded a greater amount of crosstalk. Hence, a sensor spacing of 10 mm is optimal for studying gait.

The studies conducted to date demonstrated consistent effects of the IED on sEMG crosstalk. However, this observation of reducing crosstalk by decreasing the IED was contradicted by Frahm et al. (2012), who found increases in sEMG crosstalk from the TA and soleus (SOL) muscles with decreases in the IED during nociceptive withdrawal reflex in humans. This finding suggests that the methods used for sEMG reflex recording in this study should be reconsidered.

### Electrode configuration/spatial selectivity

Various electrode configurations were tested in previous studies to identify the optimal configuration for crosstalk reduction. Koh and Grabiner (1992) compared two different electrode configurations, including BP and double differential (DD), for reducing crosstalk in sEMG signals originating from the VL and hamstrings. These researchers found that the BP reduced sEMG crosstalk in hamstrings to 17.1% of the ARV, while the DD reduced the crosstalk to 7.6% of the ARV. A year later, Koh and Grabiner (1993) compared three different electrode configurations, namely, single differential (SD), DD and branched electrode (BE), for reducing crosstalk in sEMG signals originating from the gastrocnemius medialis (GM) and TA. Crosstalk was reduced to 12% in the case of the SD and to 5% in the case of the DD and BE. Van Vugt and Van Dijk (2001) made similar observations by comparing six different electrode configurations to reduce crosstalk in sEMG signals originating from the TA and TS. The findings reported by Farina et al. (2002) strongly support the previous observations regarding spatial selectivity. All the above-mentioned studies concluded that the DD electrode configuration with the BE, which has a less complicated structure, is the best choice for crosstalk reduction. Viljoen et al. (2007) found comparable results for dynamic contractions but demonstrated that the normal double differential (NDD) electrode configurations are better when investigating isometric contractions.

Mesin et al. (2009) conducted a model study to observe the effect of subcutaneous fat on EMG crosstalk using the SD, DD and NDD configurations. NDD was more suitable for reducing crosstalk with increases in skin conductivity and subcutaneous fat, whereas the SD was more suitable for a shorter fibre length. Guerrero et al. (2017) improved the NDD design using operational amplifiers, and this model was found to be better for crosstalk rejection. The above-mentioned studies indicate that the problem of crosstalk in

**Table 3** Reported studies on crosstalk reduction

No.	Methods	Muscles	References	Observations	Future work/limitations/suggestions
1.	Interelectrode distance	BB, TB VI, VM, VL, RF TA, TS, SOL	Zipp (1982) Winter et al. (1994) and Farina et al. (2002) De Luca et al. (2012) and Frahm et al. (2012)	BP electrodes with an IED of 15 mm can reduce crosstalk by up to 75% Closely spaced electrodes with a smaller area and mathematical differentiation of the sEMG signal can reduce the signal crosstalk by up to 80% Crosstalk contamination on TA was 23% for single-differential disk sensors with a spacing of 22 mm, 17% for single-differential bar sensors with a spacing of 10 mm, and 8% for a 10-mm double-differential bar sensor	A closely spaced BP electrode configuration is not suitable for fetching global information of the state of a muscle Both practical and theoretical interpretations of crosstalk are significant The methods used for sEMG reflex recordings should be improved because crosstalk is of major concern in this field
2.	Electrode configuration	VL, VM, RF, Hamstrings MG, TA TA, TS	Koh and Grabiner (1992) and Farina et al. (2002) Koh and Grabiner (1993) Van Vugt and Van Dijk (2001)	BP reduced the sEMG crosstalk in hamstrings to 17.1% of the ARV, and DD reduced the crosstalk to 7.6% of the ARV SD reduced crosstalk in sEMG signals by up to 12% MVC, whereas both DD and BE reduced the crosstalk to 5% MVC The DD and BE electrode configurations gave the best crosstalk reduction, i.e., up to sixfold, in EMG activity	The application of DD for muscles with highly active neighbouring muscles is challenging A comprehensive comparison of the three methods used is required The practical application of BE should be clarified
3.	Filtering	BB, TB ECU, ECR, EDC	Viljoen et al. (2007), Mesin et al. (2009), and Guerrero et al. (2017) Nazarpour (2005) Mesin (2018)	The use of the DD configuration during muscle shortening and Laplacian filter during muscle force simulation yielded the best crosstalk rejection The use of an adaptive filter as a crosstalk suppression pre-processor improved the sEMG signal classification rate by 6.1% By increasing the SNR to 2 dB, the developed spatiotemporal filter significantly reduced crosstalk in sEMG signals	Parameters that distinguish muscle shortening and contraction force need to be identified before this model can be applied to human muscle The decrease in the correct classification rate for elbow extension and flexion with more obvious muscle activity is questionable Limited information was considered for the training set at low contraction levels

Table 3 (continued)

No.	Methods	Muscles	References	Observations	Future work/limitations/suggestions
4.	ICA/BSS	APB, ADM, FDS, EDC, ECU	Vuskovic and Li (1996) and Kilner et al. (2002)	BSS reduced the signal crosstalk by more than 78%	Signals from other muscles were ignored, and cross-correlation was thus not fully removed
		FCR, PT	Naik et al. (2006) and Farina et al. (2008)	ICA is unable to identify the number of independent sources, but the BSS model with optimized wavelet yielded the best reduction of crosstalk	The experimental results need to be improved considering the convolutive nature of the EMG signal
		FDS, FDP, ECU, ECR	Kong et al. (2010)	BSS reduced the overall crosstalk in forearm muscles by 33%	Crosstalk still observable in flexors such as PL because thumb muscles may also contribute to crosstalk
		TA	Naik et al. (2013)	The Amari index (a measure of the unwanted signal content) was significantly reduced after signal reconstruction	To achieve crosstalk removal, the developed ICA filtering approach can be applied to sEMG prior to biomedical signal processing
		EI, EDM	Léouffre et al. (2013) and Dogadov et al. (2015, 2016)	The signal-to-crosstalk ratio of the MUAP model was significantly higher than those obtained with the beamformer and BSS algorithms	The muscle force should be reconstructed from sources separated using the proposed algorithm to verify its validity

sEMG signals can be partially improved using a differential pair of electrodes with different configurations and modification of the traditional design.

## Filtering

An adaptive crosstalk suppression filter was proposed by Nazarpour (2005) for reducing crosstalk in sEMG signals. The results could be of more interest if the amount of crosstalk was specifically noted for the BB and TB. The researchers also proposed an algorithm to classify the sEMG signal, and its accuracy for sEMG signals with and without crosstalk was confirmed. The overall classification accuracy was improved by 6.15% after crosstalk suppression. However, a decrease in the correct classification rate for elbow extension and flexion is questionable because muscle activity is more pronounced during these tasks. No further experimental work was performed using this technique, which could be of great interest for researchers.

Recently, Mesin (2018) developed a spatiotemporal filter to reduce sEMG crosstalk in signals from forearm muscles. Both experimental and simulated results showed that the developed filter increases the SNR of the signal to 2 dB in comparison to that obtained with the SD and DD techniques. Thus, crosstalk was reduced to a significant amount (Mesin 2018).

## ICA/BSS

BSS is an algorithm that has been used to remove crosstalk in EMG signals originating from nearby muscles (Vuskovic and Li 1996). BSS is based on the assumption that the signals from distinct muscles are not correlated (Farina et al. 2008). BSS is blind to sources, which means that it separates the original EMG signal from crosstalk signals without prior knowledge of the signal mixture.

Signals produced after BSS do not necessarily show the same activities of the muscles that were recorded initially. BSS produces the same number of outputs as the inputs. For example, if BSS uses the recordings from five muscles as the input, five output signals will be obtained. However, each of the five recordings might contain signals from multiple muscles. BSS only guarantees that no two recordings will contain common activity, but an output recording might be a mixture of signals from multiple muscles (Kilner et al. 2002).

Kong et al. (2010) used the BSS technique to reduce crosstalk to 33% in sEMG signals originating from forearm muscles. Some degree of crosstalk can still be observed in a few flexors, such as the PL, because thumb muscles, which were not considered in the study, might also contribute to crosstalk. In a more recent study, Naik et al. (2013) developed an approach using independent component analysis

(ICA) to separate the sEMG recording sources. After signal separation, the sEMG signal was reconstructed using an unmixing matrix, which improved the quality of the sEMG signal. The researchers claimed that using this filtering approach, which is denoted fast ICA, prior to further signal processing of the sEMG signal can remove unwanted signal components, such as crosstalk. Léouffre et al. (2013) also suggested that focusing on electrode positioning and signal processing is important to make BSS more useful for sEMG signal analysis.

Dogadov et al. (2015) compared two different algorithms for reducing sEMG crosstalk. The ICA-based method (JADE) and a newly tested integrated sEMG (IEMG) were used to reduce crosstalk in sEMG signals from the EDM and EI. IEMG yielded a better signal-to-crosstalk ratio (1112 dB) than JADE (830 dB). The reason for the low performance of JADE is that the condition that the sources need to be independent was not adhered to in the study. Hence, IEMG provided better crosstalk reduction, as validated through reconstruction of the forces after source separation.

The researchers then proposed a new algorithm using interelectrode delay as a parameter for reducing crosstalk in sEMG signals. The peaks in MUAP propagation were detected from the sEMG signal originating from the EI and EDM during three different tasks of finger extension (Dogadov et al. 2016). The signal-to-crosstalk ratio obtained with the proposed algorithm was significantly higher than that obtained with conventional algorithms, including BSS and beamformer. However, the application of this algorithm needs to be validated. The muscle force should be reconstructed from the sources separated using the proposed algorithm to validate this technique.

BSS assumes a non-Gaussian amplitude distribution in the sEMG signals for the recovery of source signals. Nazarpour (2005) reported that the non-Gaussian amplitude distribution in sEMG signals does not hold for signals above 25% MVC. Thus, the use of BSS to reduce crosstalk in sEMG signals at higher force levels might not yield satisfactory results. However, another limitation identified by Naik et al. (2006) regards the use of ICA for sEMG crosstalk reduction even at low force levels. Using theoretical and experimental approaches, the researchers proved that the number of independent sources in sEMG recordings cannot be measured using Zibulevsky's sparse decomposition technique in ICA. The hypothesis that the number of sources should be less than the number of sEMG recordings was not confirmed. Hence, ICA was found to be an unsuitable technique for reducing crosstalk in sEMG, even at low force levels.

Crosstalk cannot be avoided completely, but there are a few techniques for reducing crosstalk in sEMG signals. Reducing the interelectrode distance, using the DD and NDD configurations for isometric and dynamic contractions,

respectively, and the filtration of signals are some obvious approaches for reducing crosstalk. Some techniques, such as filtration, the use of operational amplifiers in the DD mode, IEMG and MUAP-based reduction techniques, are a few of the open areas of research. Although much progress has been made, many questions remain unaddressed.

## Crosstalk and muscle issues

To date, crosstalk has been discussed from the point of view of the signal. In this section, we discuss the phenomenon from the physiological point of view. Certain muscle issues directly influence the crosstalk content in myographic signals, and these muscle issues are discussed in detail in the following section and are listed in Table 4.

### Muscle task/muscle activity

Crosstalk information could be muscle or even activity specific depending on the muscle or task performed by the muscle. In one study, the cross-correlation coefficient did not vary with changes in the level of isometric torque, and no consistent differences in crosstalk among the superficial quadriceps femoris muscles have been detected (Beck et al. 2010). Thus, the crosstalk in MMG signals detected from the superficial quadriceps femoris muscles provides independent information about each muscle (Beck et al. 2010). The crosstalk magnitude in MMG signals originating from the forearm muscles (ED, ECU and FCU) during a grip force task ranges from 2.45 to 62.28% (Islam et al. 2014a), and this wide range shows the independence of crosstalk from muscle activity.

Facial pacing is the process of reanimating a disabled facial muscle. The muscle activity measured from a healthy muscle using sEMG was reproduced with a disabled muscle using field electrode stimulation (FES) (Rantanen et al. 2016). To check the validity of applying sEMG in facial pacing, four different facial movements, namely, smile, frown, lip pucker and eye blink, were performed by the subjects. The crosstalk between the muscles involved in these four activities was measured under normal and chewing conditions. The crosstalk in sEMG signals during all four facial movements without chewing was in an acceptable range. Hence, sEMG is suitable for facial pacing, but the problem of crosstalk from the masseter, which is a chewing muscle, needs to be resolved. Hence, it can be concluded that crosstalk should be considered in a case-by-case basis and depending on the activity because crosstalk depends on many factors, including the type of activity being performed and the muscle physiology.

**Table 4** Reported studies on crosstalk and muscle-related issues

No.	Methods	Muscles	References	Observations	Future work/limitations/suggestions
1.	Muscle task	VL, VM, RF ED, ECU, FCU ZM, OO, CS	Beck et al. (2010) Islam et al. (2014a) Rantanen et al. (2016)	Crosstalk does not show an increasing trend with increasing muscle torque Crosstalk increases with increases in the gripping force Chewing increases the crosstalk effect during all tested muscle activities	No other crosstalk index was employed in the comparison of indices using MMG data The skin fold thickness, which could influence crosstalk, was not considered Masseter (chewing) causes misinterpretation of the sEMG signal, and this topic should be addressed in the future
2.	Postural setting	ECU, EDC, EDR, BRD, FCU, FDP, FDS, FCR	Mogk and Keir (2003), Kong et al. (2010), and Yung and Wells (2013)	A change in forearm orientation does not impact sEMG crosstalk	The relationship between sEMG crosstalk and muscle activity in the longitudinal direction should be studied using the same experimental settings in the future
3.	Muscle force level	ED, ECU, FCU	Kong et al. (2010) and Islam et al. (2014a)	Crosstalk increases with increases in the gripping force	The skin fold thickness, which could influence crosstalk, was not considered
4.	Co-activation	VL, VM, hamstrings	Koh and Grabiner (1992)	Crosstalk reductions to 17.1% in the lateral hamstrings and 11.3% in the medial hamstrings were obtained	Co-activation should be separated from crosstalk
5.	Synergists	TA, MG, LG, SOL ED, ECU, FCU	Raiteri et al. (2015) Islam et al. (2014b)	Muscle co-contraction and crosstalk are successfully distinguished from each other for the lower limb muscles Crosstalk in synergist pairs is higher than that in antagonist pairs	In future studies, agonist torque in an ankle should not be corrected based on antagonist sEMG Muscle fatigue was not considered
6.	Agonist/antagonist	VL, VM, Hamstrings ECR, ECU, FCR, FCU	Koh and Grabiner (1992) Kong et al. (2010), Yung and Wells (2013), and Islam et al. (2015)	The antagonist activity of the hamstring and the crosstalk found in hamstring signals are affected by excitation of the quadriceps The crosstalk in an agonist pair is greater than that in a pair of antagonist muscles	Co-activation is distinct from crosstalk A clearer understanding of the biomechanical function of muscles is required to interpret the results
7.	Muscle size	Model study Model study FDS, FDP, ECR, ECU ED, FD	Viljoen et al. (2007) Mesin et al. (2009) Kong et al. (2010) Urbanek and van der Smagt (2016)	ARV increases with increases in muscle shortening SD is suitable for crosstalk reduction when the fibre length is shorter Digit-dedicated flexors show increased crosstalk than wrist-dedicated flexors Three-dimensional reconstruction of imaging EMG provides information of muscle geometry	The effects of muscle shortening and contraction force cannot be distinguished in real time The spatial filter should be selected based on the signal (a change in anatomy changes the signal) The results should be verified using different postural settings High-speed computing and advanced instrumentation for sEMG are required to minimize the electrode size and thus obtain a better imaging EMG algorithm

Table 4 (continued)

No.	Methods	Muscles	References	Observations	Future work/limitations/suggestions
8.	Fat layer	Model study TAIO, RAE0	Kuiken et al. (2003) Marshall and Murphy (2003)	Reducing the subcutaneous fat layer decreases the EMG crosstalk Reducing the subcutaneous fat layer decreases the EMG crosstalk	The simulation-based results were not tested using real data The limitations regarding the use of CCC were not followed
9.	Direction of signal propagation	ED, FCU, ECU	Islam et al. (2014b)	Decreased crosstalk is observed in the transverse signal propagation direction	The results should be verified using a muscle stimulation protocol
10.	Neural crosstalk	FCR, FDS, EDC	Ridderikhoff et al. (2005)	The mirrored movement observed in contralateral limbs is known as neural crosstalk	No other study supporting this observation of EMG crosstalk has been reported

## Postural setting

The postural setting also affects the evaluation of sEMG crosstalk. During a static grip task, digit-dedicated flexors show relatively greater amplitudes of sEMG crosstalk than wrist-dedicated flexors. This finding could be due to the neutral position of the wrist during the task (Kong et al. 2010). However, a change in the forearm orientation, ranging from pronation and supination to a neutral position, does not have a significant impact on crosstalk in sEMG signals from forearm muscles (Mogk and Keir 2003; Yung and Wells 2013). Hence, researchers should consider the subject's posture when designing an experimental protocol.

## Muscle force level

Crosstalk was also found to be strongly correlated with increasing grip force but weakly correlated with the forearm diameter and length (Islam et al. 2014a). The amount of crosstalk in both sEMG (Kong et al. 2010) and MMG signals (Islam et al. 2014a) has been found to increase with increases in the muscle effort.

## Co-activation/co-contraction

sEMG crosstalk and muscle co-activation are often confused with each other (Koh and Grabiner 1992). Hence, the corresponding correlation co-efficient should be considered when interpreting crosstalk. De Luca (1997) noted the following rule of thumb: a correlation of approximately 0.60 or higher might not indicate crosstalk between but rather co-contraction of adjacent muscles.

Crosstalk in sEMG signals could be distinguished from co-contraction using supersonic shear wave imaging. Ultrasound imaging provides a clearer picture of the biomechanical function of muscles compared with sEMG due to the presence of crosstalk in these myographic signals. Raiteri et al. (2016) found that the shear modulus, which serves as a measure of muscle force, is negligible during co-contraction, whereas sEMG simultaneously shows the muscle activity of the observed muscles. Hence, this observed muscle activity could merely be crosstalk in the sEMG signal rather than co-contraction. Raiteri et al. (2015) previously obtained comparable results for the TA, GM, GL and SOL muscles in the lower limb using ultrasound imaging and found a very small change in the length of fascicles compared with that found based on sEMG activity (7–23% MVIC across all four muscles). The sEMG activity also decreased as the IED decreased from 4 to 2 cm. The negligible change in the length of antagonist fascicles muscles and the decrease in sEMG activity with decreases in the IED clearly indicate that the antagonist sEMG activity in the lower limb is mainly due to crosstalk but not co-contraction. Hence,

it is important to distinguish between muscle crosstalk and co-contraction to eliminate crosstalk in myographic signals.

### Synergists

The crosstalk between muscles within a muscle group, which are called synergists, is expected to be higher than that between agonists and antagonists, particularly when examining individuals whose muscles cannot be clearly identified, such as untrained individuals and patients with muscle atrophies (Kellis 1998), because muscles, fat, tendons and even tissues between muscles act as low-pass filters (Islam et al. 2014b). Because synergists collaborate to perform a task, it is highly likely that the crosstalk between these muscles will be higher. It is also likely that agonists will yield higher crosstalk because these muscles are closer to each other than they are to antagonists.

### Agonist/antagonist

A significant amount of crosstalk was observed in inactive muscles with active neighbours (Lowery et al. 2003). Crosstalk is a major concern during the recording of signals from relatively inactive muscles that are physically near highly active muscles (Koh and Grabiner 1992). For example, the amount of crosstalk found in the hamstring muscle during 100% MVC excitation of the quadriceps affects the interpretation of antagonistic hamstring activity during knee extension (Koh and Grabiner 1992). Kellis (1998) proposed that an sEMG value for antagonist muscle activity that is less than 5% of MVC might be interpreted as crosstalk.

Muscles that are relatively close to each other exhibit high cross-correlation values. For example, crosstalk among flexors is larger than crosstalk between some flexors and an extensor. However, this finding is contradicted by the lower cross-correlation value observed between the FCU and FCR muscles by Yung and Wells (2013), and this difference might be due to the use of longer radial distances, which might even exceed 25 mm. Hence, the observations of the FCU and FCR at larger distances show lower crosstalk values. Hence, it can be concluded that crosstalk between an agonist and an antagonist muscle is lower than that among synergists.

### Muscle size

The forearm muscles showed greater crosstalk values than quadriceps muscles due to their smaller size and greater number of neighbouring muscles (Islam et al. 2014a; Beck et al. 2010). This finding also suggests that the quadriceps muscles, which are larger in size, are most likely to be further apart, which might also serve to reduce crosstalk. Viljoen et al. (2007) and Mesin et al. (2009) observed a reduction in crosstalk with muscle shortening during an activity.

Hence, a decrease in muscle size yields a decrease in sEMG crosstalk because muscle shortening refers to muscle contraction and not the anthropometric length.

The muscle size is important for the quantification of crosstalk in myographic signals. The fraction of crosstalk among forearm muscles is greater than that reported for leg muscles. The leg has a larger room for a smaller number of large muscles than the forearm. Hence, the proximity between muscles, the number of muscles and the muscle size contribute to the resulting crosstalk (Kong et al. 2010). Thus, the crosstalk in myographic signals from medium-sized muscles should be measured to obtain a clearer image of the effect of anthropometric parameters on crosstalk.

In addition to muscle size, information about the muscle location can also provide a better understanding of muscle activity. Crosstalk in sEMG is a major issue that hinders accurate assessment of a muscle, and to address this issue, a 3D reconstruction of the activity of forearm muscles was generated by Urbanek and van der Smagt (2016). This reconstruction of muscle activity was performed using sEMG signals from a substantial number of electrodes (64 electrodes) placed around the forearm. The reconstructed muscle activity generated with sEMG was then compared with the results obtained by ultrasound imaging. The depth of the muscle calculated with both techniques was highly correlated. Thus, the imaging EMG algorithm developed by Urbanek and van der Smagt (2016) was found to be an appropriate alternative to ultrasound imaging that also provides a safety edge from dangerous ultrasonic waves. This approach also constitutes a reliable method for locating the anatomical location of a muscle using sEMG, and this study encouraged the development of new instruments for EMG, namely, small-sized, closely spaced electrodes. The study also calls for high-speed calculations and computing requirements. The results clearly show that the muscle size is of utmost importance in the field of crosstalk, and sEMG, with appropriate modifications, can be used to estimate muscle size and shape.

### Fat layer

The effect of the subcutaneous fat layer on sEMG activity was indicated by finite element analysis (Kuiken et al. 2003; Marshall and Murphy 2003). The researchers observed that a larger fat layer is associated with a significantly reduced sEMG signal amplitude and an increased sEMG crosstalk between adjacent muscles (Kuiken et al. 2003; Marshall and Murphy 2003). An increase in the thickness of the fat layer will decrease the relative difference in the distance of the electrode from the intended muscle and the adjacent muscle, which would cause crosstalk. If the electrode is closer to the intended muscle, the relative contribution of that muscle to the EMG signal will be higher. Taken together, these

observations indicate that the fat layer acts as a spatial filter between the electrode and the muscle, which reduces the sEMG signal amplitude and increases crosstalk. However, the effect of the skin fold thickness (fat layer) on MMG crosstalk remains an open area of research (Islam et al. 2014a).

### Direction of signal propagation

The percentage of the common signal from forearm muscles depends largely on the direction of propagation of the MMG signal. Hence, during a variety of wrist postures, the transverse axis to the muscle fibre showed lower values of crosstalk in comparison to the longitudinal and lateral axes (Islam et al. 2014b). This finding might be due to the attenuation of the MMG signal in this direction. Due to the lower effect of crosstalk in the transverse direction, the measurement of MMG signals in this direction is more reliable during the assessment of muscle activity.

### Neural crosstalk

Occasional involuntary mirrored movements have also been observed in contralateral homologous forearm extensors, which could be due to neural crosstalk or even motor overflow (Ridderikhoff et al. 2005). Frequency and phase locking parameters have been found between EMG patterns of homologous extensors. These parameters were estimated using time-resolved spectral methods. However, no involuntary mirrored movements have been observed in contralateral homologous forearm flexors. In general, neural crosstalk might contribute to similarities in amplitude time-histories but should not contribute to correlations in the raw EMG signal.

### Crosstalk in MMG

Because it is a novel technique for the study of myographic signals, the problem of crosstalk in MMG has not been widely studied. MMG is a suitable alternative to EMG, particularly for the assessment of muscle fatigue and for the study of muscle contractile properties. The identification, quantification and reduction of crosstalk in MMG signals can result in better estimation of muscle activity using MMG. Techniques for crosstalk identification and reduction have not yet been developed for MMG signals. Useful findings regarding crosstalk in MMG signals from leg muscles (Beck et al. 2010) and forearm muscles (Islam et al. 2014a) show the potential of this area of research. Both of these research groups used CCC only for the quantification of crosstalk in MMG signals. Despite criticism, a cross-correlation-based method is used frequently, and the CCC is

considered the most powerful index for the quantification of crosstalk in both MMG and EMG signals (Islam et al. 2014a). The CCC should be used for obvious reasons: this method is less complex and requires only raw MMG signals from the muscles for the evaluation of crosstalk. The amplitude-based indices require signals without crosstalk (Kong et al. 2010), which are not available in the case of MMG.

The literature does not include any evidence of the application of a technique for the reduction and removal of crosstalk in MMG signals. BSS cannot be applied to MMG signals for crosstalk reduction because this approach requires the condition that the signals from multiple sources are not correlated, which is not true in MMG because the signals from neighbouring muscles are correlated (Kilner et al. 2002).

MMG signals are obtained from muscles and are often termed the mechanical counterpart of sEMG signals, and as myographic signals, they are susceptible to crosstalk. Thus, methods to identify, quantify and reduce crosstalk in MMG signals from a variety of muscles using various experimental protocols should be developed.

### Discussion

Based on the literature, it could be concluded that some crosstalk in myographic signals is unavoidable, particularly when the recorded signals originate from muscles located in close proximity. The simplest way to avoid crosstalk is the careful design of an experiment according to the functional resistance test (Mezzarane and Kohn 2009). However, this is not always feasible because a simple activity might involve multiple muscles, and this phenomenon can be avoided by carefully considering the sensor placement, inter-electrode distance, and electrode configuration. The offline filtration and reduction methods might be appealing, but their practical applications have some limitations. While performing an experiment on human subjects, one cannot avoid randomness in the resulting anthropometric data, and this randomness might enhance the effects of muscle-related issues of crosstalk. Thus, crosstalk must be avoided prior to data acquisition or during offline processing.

Crosstalk can be identified using sEMG and wEMG in parallel (Barr et al. 2010). However, this technique is not easy to implement due to invasive nature of wEMG. FRT provides an optimal image of myographic signals without crosstalk but is not useful for most experimental protocols due to diverse muscle activities. The identification of crosstalk in externally stimulated muscles is equally crucial to that during voluntary activation (Lowery et al. 2003). External stimulations might also stimulate synergist muscles, which might cause crosstalk. Crosstalk identification using frequency-based methods and HD EMG has shown

promising results (Gallina et al. 2017) and requires further exploration.

Two major types of crosstalk indices are described in the literature for the quantification of the percentage of common myographic signals: amplitude-based and CCC-based indices. The amplitude-based indices do not account for muscle coactivation, whereas CCC does not guarantee this differentiation (Farina et al. 2002). However, the first type is difficult to use because it requires a signal without crosstalk. To date, amplitude-based indices have not yet been used for MMG. The reliability of the second type, namely, CCC, was questioned by Gazzoni et al. (2004) and Farina et al. (2002), who claimed that the volume conductor affects the signals differently in different muscles and concluded that CCC is not a good indicator of crosstalk. Based on this argument, the percentage of the common signal in forearm muscles should be relatively small, but these muscles exhibit 40–60% and 30–70% crosstalk in sEMG and MMG signals, respectively (Mogk and Keir 2003; Islam et al. 2014a, b). Thus, it appears that the claim does not hold true for the quantification of crosstalk in forearm muscles using CCC. In view of these comments, CCC still has the potential to be employed as a suitable index for the quantification of crosstalk, even though CCC might not always depict crosstalk and could sometimes quantify some other mechanisms, such as motor unit synchrony (Islam et al. 2014a). Due to its ease of use, CCC could be used to quantify observations of crosstalk in certain applications in which accurate measurements of motor unit control are required, such as externally powered prosthetics.

Electrode manoeuvres and a variety of offline computer techniques have been employed for the reduction and removal of crosstalk in sEMG signals. A smaller interelectrode distance (Yung and Wells 2013) and the use of the DD electrode configuration (Mesin et al. 2009) were found to yield an optimal reduction in crosstalk. The ICA-based BSS technique has been successfully implemented for the same purpose (Farina et al. 2008). However, due to certain limitations even in the basic assumptions for the use of BSS, this approach was found to not be suitable for reducing crosstalk in myographic signals (Nazarpour 2005). The IEMG- and MUAP-based crosstalk reduction techniques have been employed successfully, but further exploration with different experimental settings and muscles is required.

## Conclusion

This review of crosstalk in myographic signals highlights significant problems regarding the identification, quantification and reduction of this phenomenon in relation to particular muscle issues. Crosstalk has an impact on myography techniques used for the assessment of muscle function.

Signals without contamination are desirable for clarifying the functions of individual muscles. Our findings revealed that crosstalk identification using a frequency-based method and a high-definition EMG technique are currently the most reliable methods. For quantification, both types of indices, CCC and amplitude-based indices, have advantages and disadvantages. The choice of quantification technique depends largely on the experimental set-up and muscle physiology. Electrode manoeuvres and computer techniques have been employed for the reduction of crosstalk in sEMG signals. The literature suggests that the integrated EMG and MUAP-based techniques are best suited for this purpose. Various muscle-related issues, including muscle activity, co-contraction, muscle size and fat layer, also have impacts on the level of signal contamination. A literature analysis exposed a need for further exploration of crosstalk quantification and reduction techniques, as well as the effects of a variety of muscle-related issues on both sEMG and MMG.

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## Compliance with ethical standards

**Conflict of interest** The authors of this article declare that they have no conflict of interest.

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