Biomedical Research 2017; Special Issue: S1-S7 *ISSN 0970-938X*
www.biomedres.info

Review of surface electrode placement for recording electromyography signals.

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Abstract

Background: Surface Electromyography (SEMG) signal has used in monitoring muscle activities. It has been widely applied in many areas, such as body member prosthesis, noise cancellation for brain-computer interface, and robotics. The SEMG acquisition method for collecting the signal with low-noise has extensively investigated in the last decade. The objective of this study is to review the recent works on electrode position and identify avenues for future research.
Methods: A review of the relevant literature published between 1986 and 2015. This study commences with the basics of SEMG and recent methods for electrode position.
Result: The different noises affecting SEMG signal include the spread of the innervation zone, cross-talk from neighbour muscles, electrode size, and location of electrode placement. Moreover, electrode placement or displacement effect SEMG signal in both time and frequency domain.
Conclusion: Although several SEMG studies examined the effects of electrode position and internal electrode distance on forearm muscles, only a few studies addressed the methodological difficulties of the electrode position. In the majority of studies, electrodes were placed without the specific symptoms of the points along the length or shape of the muscle. Moreover, IED varied in different studies.

Keywords: Electrode placement, Inter electrode distance, SEMG electrode, Surface electromyography.

Accepted on July 13, 2016

Introduction

Many techniques have been developed to monitor muscle behavior and movements; these methods include electromyography (EMG) [1,2], mechanomyography [3,4], and electroencephalography [5,6]. Surface Electromyography (SEMG) has recently applied in other areas, such as in hand prosthesis [7,8]. SEMG signals are also involved in monitoring the muscle activities of artificial body members [9], removal of noise from the brain-computer interface [10,11], and robotics exoskeleton [12]. Furthermore, SEMG can detect motor unit (MU) functions when these cells are active [13].

EMG signals can be recorded using invasive and non-invasive methods, with the latter referred to as SEMG [14,15]. Invasive techniques utilize needle electrodes to monitor EMG signals directly from the muscles. By contrast, SEMG collects data using surface electrodes placed on the skin [16,17]. SEMG technique has considerable advantages over the invasive method, including the easier detection of SEMG signal over the skin and more comfort for subjects [18,19]. Thus, recognizing muscle behavior through SEMG detection is more feasible. A raw SEMG signal has peak-to-peak amplitudes of 0-2 mV with a band frequency ranging from 0 Hz to 1000 Hz [19]. However, the band frequency of SEMG, which includes significant information, ranges from 20 Hz to 500 Hz [20]. Raw SEMG signals have low amplitude; thus, the SEMG signal can be affected by many types of noises such as ambition noise or combines with them [21].

The impedance of the body skin reduces the amplitude of SEMG signals and induces noise. The noise generated from the skin is caused by fat between the muscle and skin and the blood flow in minuscule vessels under the skin [22]. Other powerful noises include environmental noise that mainly comes from the environment, as well as electromagnetic radiation sources, electrical power wires, and fluorescent lamps during recording [23]. Various significant noises that affect SEMG are from the subcutaneous tissue layers [24], the spread of the innervation zone (IZ) [25], crosstalk from neighboring muscles [26], electrode size, and electrode position [27,28]. Electrode position can significantly mislead the description of a statistical and spectral factor of SEMG, thus affecting SEMG evaluation [29,30].

Muscle physiology

The muscles of the human body are divided into three categories, namely, skeletal, cardiac, and smooth muscles; each muscle group has its own characteristics [31]. Smooth muscles are non-striated and self-acting because humans cannot control their movements. Smooth muscles are tissues that basically form supporting blood vessels and the walls of hollow organs, such as the stomach [32]. Cardiac muscle or heart muscle is

one of the major muscle groups, which is independent of the neural network [33]. The heart muscle is contracted automatically in the walls and histological foundation [34]. The most important muscle category consists of skeletal muscles that are found in the majority of muscle tissues [35]. These muscle groups are attached by the tendon to the bone [36]. In contrast to cardiac and smooth muscles, skeletal muscles are known as the voluntary muscle group. Humans can control skeletal muscles to make movements for a daily living because these muscles are under the control of the nervous system [37].

Skeletal muscles generate force and movement. Their structural unit is the muscle fiber [38]. The construction group of muscle fibers is the muscle myofiber or muscle cell. A myofiber has an approximately cylindrical shape with a diameter a few microns meters (10-100 μm) and a few millimeters to a few centimeters in length (1.5 mm to 30 cm) [39]. Many myofiber bundles or fascicules are spliced by tissue in muscle. The fascicule arrangement in a muscle is associated with muscle power and its motion limitation. The muscle fibers contract to move or produce a force.

Muscle origin is the attachment of the muscle to the bone, which is fixed and does not move during contraction. Muscle origin typically has more mass, and it is more stable when the muscle is contracted compared with the other muscle end. The skeletal muscles are connected to the bone by the tendon in an area called insertion zone. Movements occur at the joint muscles; thus, the insertion zone is usually distant from the distal portion of the muscle about the muscle origin to facilitate the movement [40]. Tendon is a strong band tissue connection, which usually links one end of the skeletal muscle to a joint or bone and is capable of tolerating the tension. Furthermore, the tendon has been considered to transmit forces. This link allows tendons to modulate forces reactively during movements and provide stability when muscles are in the rest mode [41].

Tendons are nonessential in performing the same practical role, with some tendons typically positioned in the limbs. Moreover, tendons can save and regain energy during the high performance. For example, when a human walks, the Achilles tendon stretches and the joint ankle flexes. After this action, the stored elastic energy will be released when the foot plantar flexes. The stretching of the tendon allows the muscle to increase its force when the muscle acts with less or without any change in length [42]. The nervous system controls each muscle function in the muscle IZ. Involuntary muscles, such as heart muscles, have IZ by the autonomic nervous system and skeletal muscles by the external. The point at the end of the nervous system (innervation point of voluntary muscles) is called the motor unit (MU) [43]. MU includes a fiber of the motor nerve, and all of the fibers of the muscle have their innervate point.

Motor unit action potential

When a human decides to move his body parts, such as leg, hand, and neck, the motor cortex, which is a part of the brain, produces a signal [44]. The generated signal of the motor cortex leads to the particular skeletal muscle through the neural network. The neural network is a functional entity of interconnected motor neurons. The motor neurons at the end of the neural network are connected to the muscle. Motor neurons or MUs are attached to the myofibrils. The power of muscle contraction must determine the number of activated MUs [43]. For example, to perform the same function, a few numbers of MUs are required to lift a piece of paper from a table. However, large amounts of MUs would be required to lift a hardback book. The size of the MU population depends on muscle size [45]. Small muscles have small MUs. Some minor muscles have a number ratio of muscle per number of MUs of 1:1. Larger muscles are required for harmonious and fine motor operations that require less control. For example, the large gluteus maximus has a ratio of 1:20, which indicates that each MU is responsible for activating 20 muscle fibers. During the activity of a large muscle, which is appropriated for power and force, a motor fiber is requested to fire a muscle fiber group together. However, fine tuning is necessary for controlling the motions of a smaller group [45].

All of the muscle fibers from the same MU contract or relax approximately at the same time [46]. Furthermore, if the MUs of muscle fibers are activated to contract the muscle, the fibers will be in the maximum contraction [47]. This condition is called the all-or-none law. MU is basically a functional unit in the myofibrils that induce muscle contraction.

Surface electromyography

The contraction of the muscle is fundamentally driven by the electrochemical process. The degree of muscle contraction is controlled by the frequency of nervous impulses. The pulse travels through the spinal cord to activate the muscle fiber. Sodium and potassium channels open in response to a stimulus, thereby triggering the active response of excitable membranes in the nerve and muscle fibers. The polarizing and depolarizing actions in opening sodium and potassium channels produce the myoelectric signal [48]. This process is called motor unit action potential (MUAP). MUAP is the final and fastest event in the myofibril, which rapidly increases and decreases the electrical potential through a cell membrane. MUAP activation can be monitored under electrodes. The surface electromyography (SEMG) is a technique for detecting, collecting, and monitoring the myoelectric signal over the muscles using electrodes [49].

Methodology and Materials

This paper investigates significant diversified studies performed through 1995 to 2016, and it emphasizes mostly on the newly published articles including various effect of electrode placement/ displacement on signal processing, methods of finding exactly electrodes location as well as a place of electrode over different muscles.

Electrode placement

Various studies demonstrate that electrode placement over a muscle exhibits significant efficacy on the specification of the recorded SEMG signals [29,30,50-60]. The changing distances between the electrodes showed different complicated shapes of action potential from both the intra and extracellular action potentials of isolated frog muscle fibers. However, there is no significant difference between various recording placements for intracellular action potentials [61]. This process is related to the presence of the end of the muscle fiber based on a further correspondence of the recorded data. The muscle fibers can be considered an invariant system for the time shifter because of the distance between the muscle fiber and electrode site [61]. Moreover, the response to the signal during recording the SEMG could be altered. Accordingly, a surface electrode is more responsive to the primary signal compared with the micro electrode.

Effect of electrode placement on SEMG amplitude

The amplitude of the SEMG signal can be affected by electrode placement or displacement. For example, Chris Jensen et al. described the efficacy of the electrode position on the amplitude of the SEMG signal over the trapezius muscle during arm flexion and abduction. This study indicated that the maximum amplitude was provided in the midpoint between the acromion and spine of the seventh cervical vertebra, and also the slight displacement decreased the SEMG amplitude [62]. The surface electromyography for the non-invasive assessment of muscles (SENIAM) project, which was presented for 22 various muscles, proposed to place electrode between IZ and TZ over studied muscles [63]. However, the SENIAM project excludes the forearm muscles for wrist movements, which are used for daily life activities.

After SENIAM project, the works of Hermens et al., and Farina et al. concluded that the IZ and Tendon Zone (TZ) are unsuitable for electrode placement. Because the SEMG signals, which were collected from both IZ and TZ, were unstable and unsubstantial when they were estimated in terms of magnitude [64,65]. Amplitude and Magnitude of SEMG signal calculated as average rectified value (ARV) and the mean and median frequency (MNF and MDF). Studies show that the SEMG signal has different amplitudes and values of spectra feature for various electrode positions and inter-electrode distances [66,67]. One example study is that Wong et al. examined the SEMG activities of different muscles from various electrode positions [68]. They normalized the collected the SEMG signals and compared amplitudes using root mean square and ANOVA. The results indicated that the electrode area of SEMG significantly affected the SEMG amplitude.

Effect of IZ and TZ location on SEMG signal

SEMG signals are extremely sensitive to small electrode position, particularly when the detection area is close to the IZ or TZ [65]. Nishihara et al. also demonstrated that the IZ shifted during the activities [69]. Spearing MUAPs is another difficulty of electrode placement, and can be detected over superficial muscles using the linear electrode configuration. Shifting an electrode 15 mm over the muscle may define differences in the variable estimation of SEMG. Current studies investigated the effect of distance between electrode position and IZ or TZ [70]. Electrode placement and IZ location on the torque-related patterns of responses for normalized and absolute SEMG amplitudes and mean power frequency can be affected [70].

A recent study analyzed the effect of electrode displacement in detecting SEMG signal using wavelet methods [71]. Wavelet technique was adopted to verify the differences between electrode placement over IZ and far away from IZ. Studies showed that all levels of isometric torque from the distal electrode configuration, which were selected far away from IZ, exhibited more intensity values than the SEMG signals that were acquired over IZ in 2 to 110 Hz frequency band. However, the results indicated that the lack of a significant difference in the frequency of 110 Hz. Thus, the electrode placement over IZ can affect the SEMG signals in low frequency [71].

Effect of electrode types on SEMG signal

The square or circular shape of the electrode did not significantly change the result of SEMG recording [72]. However, this study demonstrated that the mean frequency and peak-to-peak amplitude depend on the internal electrode distance and the depth of the fiber over the electrode site. Also, mathematical simulation indicates that the tissue of muscle could not function as a low pass frequency filter using either a point or rectangular electrode [73]. The electrode species, linear electrode position, and terminal phases (reflecting the excitation extinction) in MUPs, the high frequencies in the power spectrum of MUP, and the distance between MU and the electrode can change the value of cross-talk during SEMG signal recording. Hence, using high-pass filtering or differential detecting techniques could remove the in-depth cross-talk produced by MUPs. Furthermore, electrode position should correspond to the muscle anatomy to reduce the effects of cross-talk. Thus, the amount of cross-talk is significantly smaller during signal detecting using a bipolar electrode above the end-plate or beyond deep muscles.

The various electrode configurations, such as regular double differentiation, longitudinal double differentiation, transversal double differentiation, and 2-D multi-electrode shows the different value of cross-talk. Studies show that demonstrated that 2-D multi-electrode configuration exhibited higher signal and lower cross-talk compared with other types [74]. Moreover, using multi-electrode shows the cross-talk effect off neighboring muscles through both 1-D and 2-D multi-electrodes during recording SEMG signals from a single MU that were selected as a convolution of intercellular AP, and the realization area could not define electrode specification depending on the uptake on the source properties.

Several studies investigated the multi- electrode configuration for the human gait. Campanini et al. recorded the SEMG signal

during gait by using 2-D, 4 × 3 grid electrodes were placed over the different muscles [75]. The SEMG was specified by its peak value, and time instant corresponded to the maximum value. The results demonstrate that the SEMG intensity of muscle activities during gait depended on the electrode position. Furthermore, the findings indicated that the best electrode position could reduce the cross-talk values while detecting the activated muscle where the IED is 20 mm in both directions.

No	References	year	No. Subject	Muscle	IED	Position
1	Gydikov et al. [61]	1986	Simulation	Frog muscle fibres	Mono Electrode	Terminal taper part of the fibres.
2	Jensen et al. [62]	1993	10	upper trapezius	20 mm	lateral and the dip region
3	Farina et al. [65]	2001	7	Lower limb	5-10 mm	Far from IZ
4	Farina et al. [72]	2002	Simulation	Motor Unit	20 mm	Far from IZ
5	Dimitrov et al. [73]	2002	Simulation	Motor Unit	Mono Electrode	end-plate region or beyond deep muscles
6	Dimitrov et al. [74]	2003	Simulation	Motor Unit	2 dimensional multi-electrode (BiTDD)	end-plate region
7	Castroflorio et al. [66]	2005	13	jaw elevator	10-15 mm	Far from IZ
8	Wong et al. [68]	2006	8	Lower limb	20 mm	Far from IZ
9	Campanini et al. [75]	2007	10	Lower limb	20 mm	Not mentioned
10	Beck et al. [70]	2008	10	Lower limb	30 mm	Far from IZ
11	Beck et al. [71]	2009	10	Lower limb	30 mm	Far from IZ
12	Barbero et al.*	2012	0-40	Upper and lower limb	Depends on muscle	Between IZ and TZ
13	Rodriguez et al. [30]	2015	20	Lower limb	36 mm	Between IZ and TZ

*This study investigated the IZ area using array electrode over different muscles.

Although several SEMG studies examined the effects of electrode position and internal electrode distance on forearm muscles, only a few studies addressed the methodological difficulties of the electrode position. In the majority of studies, electrodes were placed over a bully area without the specific symptoms of the points along the length or shape of the muscle. Moreover, the inter-electrode distance varied in different studies. The reviewed publications summarized in Table 1 indicate the electrode position, inter-electrode distance, and a number of subjects.

Quantitative studies on the sensitivity of the signal feature extracted from the SEMG signal on the recording type, including electrode position and inter-electrode-distance, for forearm muscles related to wrist movements are scarce. This limitation is significantly crucial for the repeatability of the results and the feasibility of comparing the data from various studies.

Discussion and Conclusion

Although several SEMG studies examined the effects of electrode position and internal electrode distance on forearm muscles, only a few studies addressed the methodological difficulties of the electrode position. In the majority of studies, electrodes were placed over a bully area without the specific symptoms of the points along the length or shape of the muscle. Moreover, the inter-electrode distance varied in different studies. The reviewed publications summarized in Table 1 indicate the electrode position, inter-electrode distance, and a number of subjects.

Quantitative studies on the sensitivity of the signal feature extracted from the SEMG signal on the recording type, including electrode position and inter-electrode-distance, for forearm muscles related to wrist movements are scarce. This limitation is significantly crucial for the repeatability of the results and the feasibility of comparing the data from various studies.

This literature survey was conducted to provide necessary information about SEMG signals and electrode position. The results indicated the critical importance of electrode placement or displacement in performing the variable estimation of SEMG. Several studies estimated the differences in frequency, amplitude, and velocity conduction over various electrode positions and IED. This work focused on surveying methods to demonstrate the effect of electrode position and IED. At the end of the discussion on the electrode position, a review of the most significant effects of the belly, IZ, and TZ area in the frequency and time domain of SEMG signal detecting was conducted.

Despite the abundant SEMG studies on the electrode position and internal electrode distance on forearm muscles, only a few studies have addressed the methodological difficulties of the electrode position. In the majority of studies, the electrodes were placed over a bully area without the specific symptoms of the points along the length or shape of the muscle. Moreover, the inter-electrode distance varied in different studies. Hence,

finding IZ and TZ over the skin is the main difficulty of presented methods. Guideline for electrode placement needs to be developed independently of IZ and TZ locations in the future.

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