

Multi Channel Surface EMG

Detection and Conditioning

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Abstract: The electromyogram is a compound signal comprising the electrical activity of the motor units activated asynchronously during voluntary muscle contractions. The temporal and spatial evolution of EMG can be sampled by surface electrodes. The basic principles and concepts about sEMG signal conditioning, spatial filtering, and spatial sampling are introduced and discussed.

1 INTRODUCTION

The electromyogram (EMG) is a compound signal comprising the electrical activity of the motor units (MU) activated asynchronously during voluntary muscle contractions. The summation of action potentials of active MUs generates, on the skin surface, an electrical field; the surface EMG (sEMG). Temporal and spatial evolution of this field might be sampled by surface electrodes appropriately positioned above active muscle regions. The properties of the detection system as well as the characteristics of the circuits for the conditioning of sEMG influence its quality and informative content.

2 sEMG CONDITIONING

The electrode skin interface properties change continuously due to its sensitivity to environmental, chemical and mechanical factors which affect electrical properties. A collection of common disturbing events and unpredictable interfering signals are: a) motion artifacts; b) mechanical vibrations of cables with consequent variation of capacitance, electric charges, and voltage drop; c) power line interference coupling; d) ground loops; e) fluctuations of electrode polarization; f) charge distribution variability on skin layers;

Mechanical solutions and fabrication methods have been studied to design surface electrodes with

low polarizable level and low noise floor within EMG frequency bandwidth.

Several articles and technical notes about bio-potential circuit implementations (AFE, Analog Front End) were published. Different approaches and solutions were presented to properly detect bio-potentials characterized by low amplitude (order of microvolt), extremely low frequency band (under 1kHz), high DC offset (up to $\pm 0.5\text{VDC}$) and low SNR ([5dB – 35dB]). General design criteria were published for bioelectric data acquisition systems (R.R. Harrison, 2007), (Bernhard Fuchs, 2002). System-on-Chip based approaches were also proposed (N.V. Helleputte, 2008) for advanced biomedical applications such as miniaturized and implantable sensing amplifiers (Wang 2006, R.R. Harrison 2003, T. Denison 2007, R. Rieger 2006) and wearable electronic sensors (L. Yan 2009). Table I reports the main properties of typical surface EMG signal.

Table 1: EMG Signal characteristics for a typical detection system based on Ag/AgCl electrode with wet conductive gel.

Property	Value	
	Min	Max
EMG bandwidth (BWEMG)	20Hz	500Hz
EMG Peak Amplitude	100 μV	5mV
Total RMS Noise Voltage (σ_{EMG})		10 μVRMS

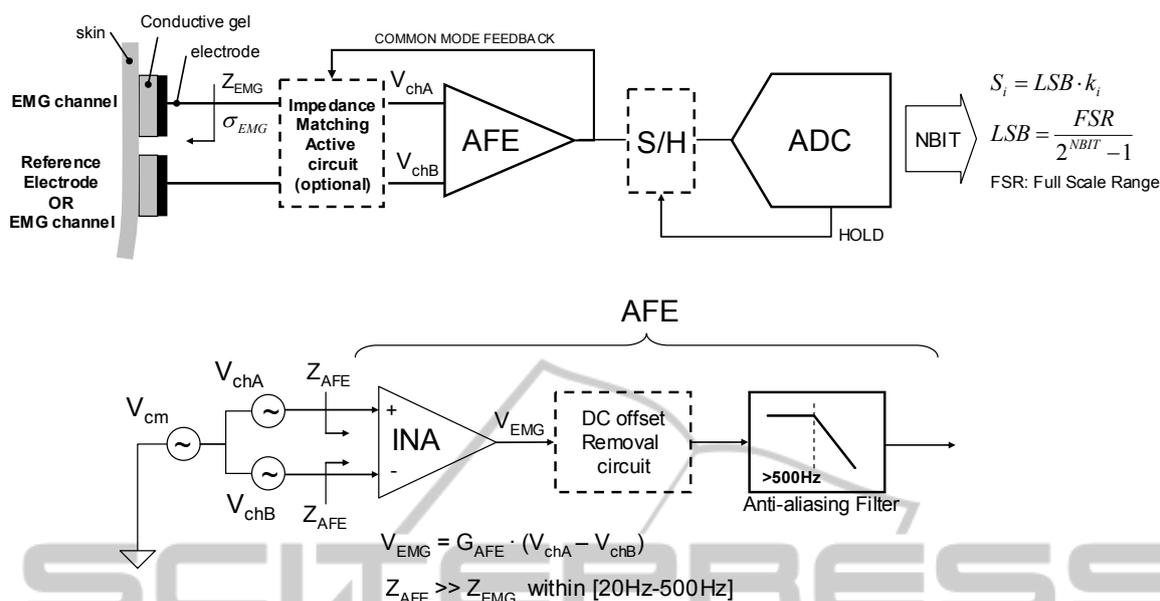


Figure 1: Summary of one channel EMG amplifier chain until the digitizing process. Three main blocks describe the full signal conditioning flow. The dotted blocks are optional and point out to specific improvement of the amplifier. The impedance matching circuit minimizes the mismatch between the equivalent impedances of the electrode-gel-skin contacts in order to reduce the false differential voltage detection (voltage divider effect). An example of Analog front End amplifier (AFE) implementation is reported by functional blocks. Specifically, a monolithic Instrumentation amplifier (INA) performs the differential signal extraction and amplification ($V_{EMG} = Gain \cdot [V_{chA} - V_{chB}]$). The common mode trend V_{cm} of the input signals is rejected the common mode component V_{cm} principally caused by power line interference coupling and motion artefacts. Specifically, low noise amplifier chain (AFE) and high resolution digitizing process (ADC) are strictly required to design a high resolution EMG detection system according to EMG signal characteristics and Electrode-Gel-Skin properties.

The most important building block for EMG recording is the signal conditioning chain (see Figure 1). Integrated circuits selection, configuration and dimensioning should be performed in order to maximize the signal quality until the digitizing process.

The primary aspects to handle during EMG amplifier design are:

- Efficient techniques for removal of DC due to electrode polarization effect.
- Very flat Differential Voltage gain within EMG bandwidth.
- High accuracy voltage gain setting (<1%) and good linearity within full voltage dynamic.
- Low gain mismatch among channels (<0.5%).
- AFE transfer function with very low group delay within EMG frequency band.
- Very high Common Mode Rejection within EMG bandwidth (CMRR > 90dB).
- High Power Supply rejection (PSRR > 80dB).
- Very high Input impedance ($|Z_{AFE}| > 100M\Omega$) within EMG frequency band.

- Negligible referred-to-input Total Noise floor level with respect to Electrode-skin interface noise σ_{EMG} (e.g. $1\mu V_{RMS}$ within EMG bandwidth [20Hz-500Hz]).
- Very low harmonic distortion of the EMG Power spectrum.
- High accuracy (<0.05%), very low noise (<3 μV_{PP}) voltage reference for A/D conversion.
- Programmable sampling frequency (>1ksp/s/ch) and simultaneous digitizing process of EMG signals.
- High performances, optical isolating interfaces to guarantee patient safety (IEC-60601).

Secondary aspects should also be evaluated, to optimize the circuit performances. The main characteristics to be focused on are: a) Low power and low voltage operating conditions (e.g. Battery based power supply system); b) Innovative small-sized integrated circuit suitable for wearable medical device development; c) Use of advanced materials and new technologies to improve the behaviour of the electrode-gel-skin interface.

3 ELECTRODE CONFIGURATION AND LOCATION

The importance of a standardization of electrode configuration and location for the reproducibility and correct interpretation of sEMG measurements has been widely recognized. The European concerted action SENIAM showed that a large variety of sensors, sensor placement procedures, and equipment are used in the European laboratories to detect sEMG signals (Hermens et al. 1999) and this is still one of the major issues in clinical surface EMG.

3.1 Monopolar Detection

The ideal configuration for the detection of the potential distribution on the skin is to move on the skin a point electrode measuring the voltage with respect to a remote reference where the potential is zero (monopolar detection).

The monopolar detection provides the whole information which can be recorded from the detection volume but it is mainly used in research applications because of its lack of spatial selectivity (recording of the contribution of sources that are near or far from the electrodes) and its sensitivity to common mode signals. Spatial filtering techniques have been proposed to detect surface EMG signals

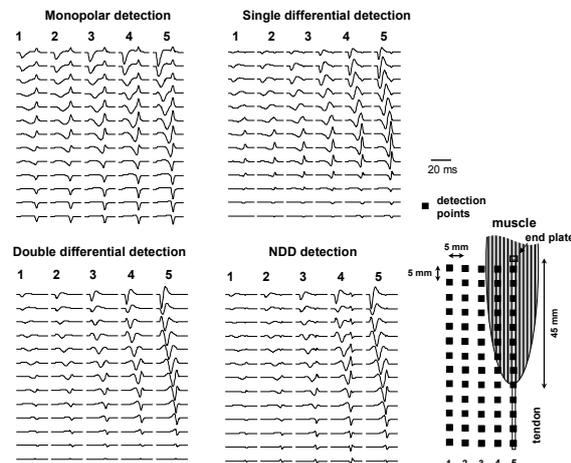


Figure 2: Example of the spatial selectivity of different spatial filters with respect to propagating and non propagating components. It is possible to observe: a) the higher spatial selectivity of NDD in transversal direction with respect to mono-dimensional spatial filters. 2) the enhancement of end-of-fiber effects in the case of NDD filter with respect to the reduction obtained by SD and DD filters.

enhancing the spatial selectivity of surface recordings by limiting the detection volume (Broman et al.1985; Disselhorst-Klug et al. 1997; Farina et al. 2002a).

3.2 Spatial Filtering

Spatial filters in surface EMG detection are based on the linear combination of signals detected by a number of electrodes placed over the skin with a defined geometry with the purpose of attenuating specific spatial frequencies with respect to others. One of the most common goals is the attenuation of non-propagating components of either physiological (such as the end-of-fiber effects and remote sources) or external origin (power line interference) which are present in the monopolar signals.

The effect of the spatial filter on the detected signal depends on the weights assigned to each electrode, on the geometry of the electrode configuration, on the electrode shape and size.

3.2.1 One-dimensional Spatial Filters

The simplest and most widely used spatial filter is the bipolar or single differential (SD), which records the difference between the potentials detected by two electrodes placed at a fixed distance (inter-electrode distance, IED).

Despite the simplicity of the bipolar configuration, the effect of its transfer function as a spatial filter requires an accurate analysis for a correct EMG detection and interpretation.

The differential detection system output depends on the spatial frequency of the input and sEMG spectral parameters obtained with different inter-electrode distances and electrode sizes cannot be compared (Fuglevand et al. 1992).

SD detection provides the rejection of common mode signals; a further enhancement of spatial selectivity can be achieved by using a more selective spatial filter.

One of the most important classes of spatial filters in sEMG recording is represented by the Laplace filters. The simplest Laplacian filter is the double differential (DD) filter that is constituted by three equally spaced electrodes, the central electrode weighted with a factor -2 and the others with $+1$.

More complex detection configurations to provide selectivity high enough to separate single motor unit action potentials (MUAPs) from the interference EMG signal are represented by two-dimensional spatial filters.

3.2.2 Two-dimensional Spatial Filter

The propagation of a MUAP along the muscle fibres results, on the skin surface, in a propagating two-dimensional distribution spatially low-pass filtered by the volume conductor. Since the optimal spatial filter is the one closest to the inverse of the volume conductor filter, two-dimensional spatial high-pass filters have been proposed (Disselhorst-Klug et al. 1997; Reucher et al. 1987a, 1987b).

Reucher et al. proposed the normal double differentiating filter (NDD-filter) realized by five cross-wise arranged electrodes whereby the central electrode is weighted with the factor -4 and the surrounding electrodes with the factor $+1$. NDD-filter improves the spatial selectivity in all directions (Figure 4), and allows the separation of the activities of single MUs even at maximum voluntary contraction (Reucher 1987a, 1987b). Moreover the 2-D systems are less sensitive to fiber orientation and the electrode placement is less critical with these types of filters.

3.2.3 Spatial Filtering and Inter-electrode Distance

The inter-electrode distance (IED) is regarded as one of the most relevant properties of the sEMG detection systems. Although it affects sEMG signal characteristics, a high variability and a wide range of values for IEDs (4-48 mm) can be found in literature (Hermens 1999).

In literature it has often been suggested that a decrease of inter-electrode distance (IED) would increase the spatial selectivity of the detection system. In literature no evidence can be found for this. Roeleveld (Roeleveld et al. 1997a) performed an experimental study investigating the effect of the IED variation (from 6 to 84 mm) in the bipolar detection on the contribution of motor unit potentials to the surface EMG. The contribution of superficial and deep motor units to the recorded SEMG signal was found to be unrelated to IED as long as $IED < 40$ mm while for IED exceeding 40 mm the contribution of deeper motor-units to SEMG is greater than the contribution of superficial ones.

3.2.4 Detection System Orientation and Location on the Muscles

The orientation defines the direction of a mono-dimensional detection system with respect to the direction of the muscle fibers; the *location* defines the position of the detection system on the muscle.

The SD and DD detection systems are usually placed in the direction of the muscle fibers but they could also be placed in the transversal direction. When electrodes are arranged parallel to the muscle fibres, the filters are referred as longitudinal (LSD and LDD) while when arranged transversally to the muscle fibers, the filter is known as transversal (TSD and TDD). LSD and LDD result in better longitudinal and poorer transversal selectivity with respect to TSD and TDD.

In literature, the most common locations of the detection system on a muscle are the following: a) in the center of the muscle, b) on the muscle belly; c) somewhere between the innervation zone and one tendon; d) on the motor point.

Although the transfer function of the spatial filter is independent of the electrode location on the muscle, the motor end-plates (where MUAPs generate) and the muscle-tendon junctions (where MUAPs extinguish) are two positions that must be carefully considered.

The signal generated by a single fiber and detected with a bipolar system placed along the fiber direction, symmetrically with respect to the end-plate of the fiber, provides a zero voltage. Since the innervations of MUs in a muscle are concentrated in one or two locations, this electrode location corresponds to signals that are small, noisy, and sensitive to small displacements between electrodes and muscle (Masuda et al. 1985) and must be avoided in practical applications. Similar observations apply to muscle-tendon junction. For this reason, the location of a pair of electrodes is critical and should be optimized by placing the electrodes between the innervation zone(s) and a muscle-tendon junction. Figure 3 depicts this situation and shows the importance of a correct electrode placement.

EMG global variables, such as amplitude, spectral characteristic frequencies, and estimates of conduction velocity, are heavily altered when electrode pairs are placed on or near the innervation zone (Jensen et al., 1993, Lateva et al., 1993, Roy et al., 1986).

These considerations imply the identification of the innervation zone(s) before the electrode pairs are applied: this task can be achieved by means of an electrode array.

3.2.5 Spatial Filtering and Cross-talk

The signal detected on a muscle and generated by another active muscle is referred as cross-talk. Many applications of sEMG require the simultaneous

detection of sEMG from many muscles to evaluate, for example, the muscular co-ordination pattern (Koh and Grabiner 1993; Winter et al. 1994). In these cases, it is mandatory to reduce the cross-talk from near muscles.

Spatial high-pass filters enhance the signals propagating along the fibers of MUs located close to the recording electrodes and suppress the contributions of more distantly located sources. At some distance from the sources the contributions due to end-of-fiber effects become predominant with respect to the propagating components because the latter decay in space more slowly than the first. It could be concluded that high-pass spatial filtering would reduce cross-talk and different kinds of spatial filters have been applied for cross-talk reduction. However, the experimental results have shown that cross-talk is not reduced by spatial high-pass filtering (van Vugt and van Dijk 2001).

This discrepancy between theory and practice is justified by the fact that the model used for the

description of spatial filter theory considered a potential distribution generated on the skin by a propagating MUAP neglecting the MUAP generation and extinction phenomena. It is known that the generation and extinction phenomena produce a non-propagating potential distribution on the skin surface, and spatial filters have different transfer functions with respect to propagating and non-propagating signals. Simulations of the filter responses to non-propagating potentials have shown that most of the spatial filters do not reduce them and in some cases they even enhance them (Dimitrova et al. 2002; Farina et al. 2002b). Figure 2 shows an example of enhancement of end of fiber potentials by NDD filter with respect to the reduction obtained by SD and DD filters.

Although different techniques have been tested to reduce crosstalk, this issue is not yet satisfactorily solved.

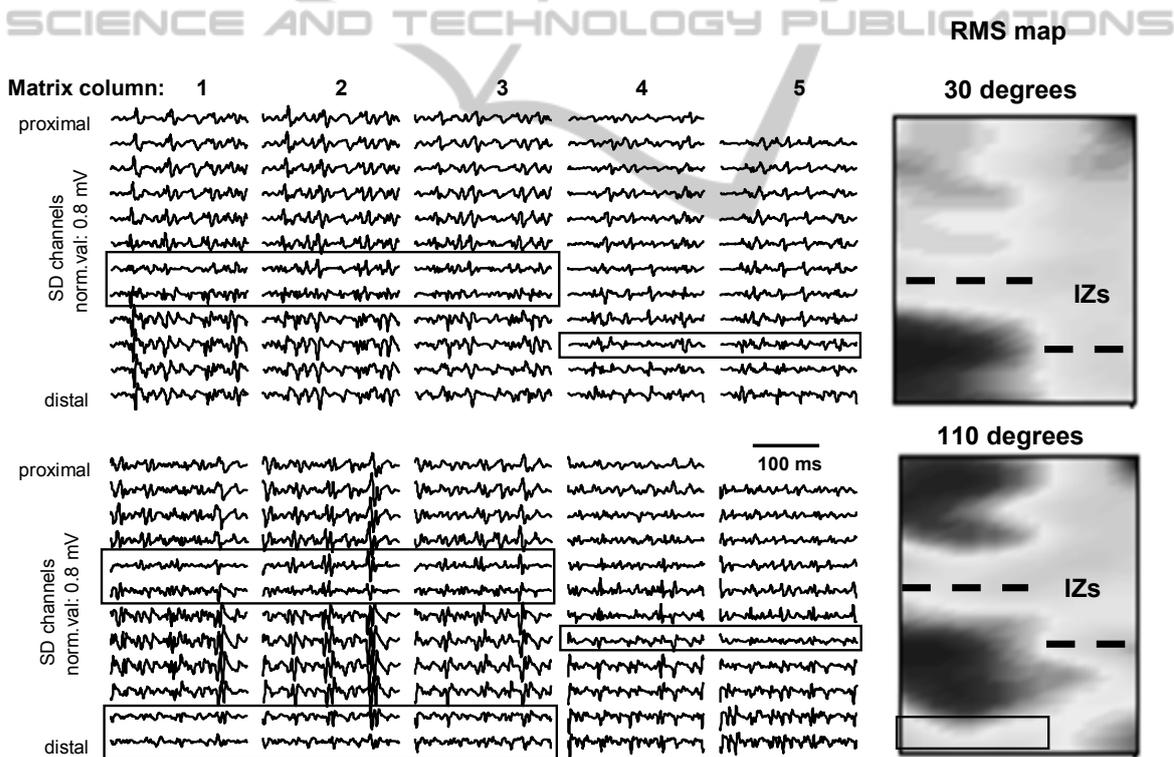


Figure 3: Example of topographical information obtained from multi-channel detection systems. sEMG signals have been recorded during an elbow flexion using a grid of electrodes (13 rows and 5 columns with one missed electrode, 8 mm ied) during a progressive elbow flexion. The SD SEMG signals (on the left) and the interpolated RMS distribution estimated on one epoch 250 ms long (on the right) are reported for two elbow angles (30 degrees on the top and 120 degrees on the bottom (0 degrees correspond to maximum extension)). The positions of the innervation zones and of the tendon are highlighted. From the images on the right it is possible to identify the two areas (left and right) of activity corresponding to the two heads of the biceps brachii and the different positions and shift of the innervation zones and tendon for the two biceps brachii heads.

3.3 Spatial Sampling

The surface EMG signal evolves in time and space, and it can be described as a three dimensional signal with one temporal and two spatial (the skin plane) dimensions. Sampling the EMG potential distribution by placing a number of detection systems in different locations over the skin allows studying how the surface EMG signal evolves in time and space.

If a spatial filter (one-dimensional (SD or DD), two-dimensional (NDD or other type)) is applied to each detection point, the potential distribution is spatially filtered and also spatially sampled.

3.3.1 Spatial Sampling in One Dimension: the Linear Arrays

The first systems performing a spatial sampling of sEMG were proposed by DeLuca, Merletti, and Masuda. They proposed linear arrays of electrode placed along the fiber direction to estimate the velocity of propagation of action potentials, to identify some anatomical characteristics such as the innervation zone location and the muscle fiber length and to investigate in detail the processes of generation, propagation, and extinction of the MUAPs along the muscle fibers.

Roeleveld et al. (1997b) proposed the use of two electrode arrays located both longitudinally and in the transversal direction with respect to the muscle fibers to estimate MU depth.

Linear electrode arrays have also been applied to obtain guidelines for the standardization of the sEMG recording when a global analysis of the signal is performed.

3.3.2 Spatial Sampling in Two Dimensions

The spatial distribution of voltage on the skin above the muscle can be detected with a grid of electrodes that provides two dimensional (2D) sampling in space. If the grid covers a large part of the muscle it provides spatial information that is largely independent of the temporal information. The time evolution of the voltage distribution on the skin can be tracked by sampling in time.

Multi-channel sEMG is an interesting non-invasive methodology to: 1) obtain muscle anatomical information (such as the location of innervation zones, tendon endings, and the direction of the muscle fibers), 2) to obtain a topographical representation of muscle activity, and 3) to decompose the surface EMG signal into the constituent single MU action potential trains if

electrode grids with small electrode sizes and inter-electrode spacing (High Density EMG, HD-EMG) are used (Zwarts et al. 2003).

3.3.3 Anatomical Information and Topographical Representation of Muscle Activity

The knowledge of fiber direction and innervation zone location is relevant, for instance, for defining the optimal locations for estimating EMG variables in isometric and dynamic contractions. The topographical representation of muscle activity allows studying the regional variations in the degree of muscle activation with time. This is particularly important in dynamic contractions. Figure 3 shows the distribution of single differential (SD) sEMG RMS at two different elbow angles of isometric contraction of the biceps brachii and demonstrates that a single sampling point is not representative of the spatially heterogeneous muscle activity and the activity it detects depends in a strong way on the geometrical factors.

The two dimensional spatial sampling obtained using HD sEMG detection systems results in a three dimensional signal, which can be used to reconstruct the 3-D potential distribution if the Nyquist limits are met in all the three dimensions.

3.3.4 Aliasing in Space

To meet the Nyquist theorem in space, the inter-electrode distance (IED) must be smaller than a threshold value. If we simplify the problem and we consider only propagating signals, the IED threshold value can be identified starting from the relationship $f_s = f_t/v$ between the spatial frequency (f_s , cycles/m), the temporal frequency (f_t , cycles/s or Hz) and the signal propagation velocity (v , m/s). If we consider 400Hz as the highest temporal frequency of sEMG and a propagation velocity of about 4m/s, the highest spatial frequency is 100 cycles/m. For the Nyquist theorem, the spatial sampling frequency should be higher than 200 samples/m, which means IED less than 5 mm. Some commonly used values of IED (10 mm or 20mm) imply aliasing in space but its consequences on the sEMG signals have not been investigated.

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