



Important Factors in Surface EMG Measurement

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EMG Introduction

Small electrical currents are generated by muscle fibres prior to the production of muscle force. These currents are generated by the exchange of ions across muscle fibre membranes, a part of the signaling process for the muscle fibres to contract. The signal called the electromyogram (EMG) can be measured by applying conductive elements or electrodes to the skin surface, or invasively within the muscle. Surface EMG is the more common method of measurement, since it is non-invasive and can be conducted by personnel other than Medical Doctors, with minimal risk to the subject.

Measurement of surface EMG is dependent on a number of factors and the amplitude of the surface EMG signal (sEMG) varies from the μV to the low mV range (Basmajian & DeLuca, 1985). The amplitude and time and frequency domain properties of the sEMG signal are dependent on factors such as (Gerdle et al., 1999):

- the timing and intensity of muscle contraction
- the distance of the electrode from the active muscle area
- the properties of the overlying tissue (e.g. thickness of overlying skin and adipose tissue)
- the electrode and amplifier properties
- the quality of contact between the electrode and the skin

In most cases, information on the time and intensity of muscle contraction is desired. The remainder of the factors only exacerbates the variability in the EMG records, making interpretation of results more difficult. Nevertheless, there are methods to reduce the impact that non-muscular factors have on the properties of the EMG signal. For example, much of this variability in the sEMG signal can be minimized through:

- using the same electrodes and amplifier (i.e. same signal conditioning parameters)
- ensuring consistency in the quality of contact between the electrodes and the skin

Within subjects, the variability of the sEMG signal can also be reduced in consecutive recording sessions by placing the electrodes over the same skin location. In addition, there are other methods of normalizing the EMG signal to reduce the variability both within and between subjects. Many of the most important issues relating to the acquisition and analysis of the sEMG signal were recently addressed in a multi-national consensus initiative called SENIAM: Surface EMG for the Non-Invasive Assessment of Muscles (www.rrd.nl/projects/content/file_100.htm) (Freriks and Hermens, 2000).

Measuring and accurately representing the sEMG signal depends on the properties of the electrodes and their interaction with the skin, amplifier design, and the conversion and subsequent storage of the EMG signal from analog to digital form (i.e. A/D conversion). The quality of the measured EMG is often described by the ratio between the measured EMG signal and unwanted noise contributions from the environment. The goal is to maximize the amplitude of the signal while minimizing the noise. Assuming that the amplifier design and process of A/D conversion exceed acceptable standards (see below and Gerdle et al., 1999), the signal to noise ratio is determined almost exclusively by the

electrodes, and more specifically, the properties of the electrode – electrolyte – skin contact.

The remainder of this document outlines the factors influencing the characteristics of the EMG signal, with an emphasis on mechanisms to increase the consistency and accuracy of the sEMG signal. For more detailed information please refer to the sEMG methods chapter “Acquisition, Processing and Analysis of the Surface Electromyogram”, in the recent textbook (1999) entitled “Modern Techniques in Neuroscience Research” (Eds. U. Windhorst & H. Johansson).

Sources of Noise

Before we can develop strategies to eliminate unwanted noise we must understand what the sources of noise are. The two types of noise are ambient noise and transducer noise.

Ambient Noise

Ambient noise is generated by electromagnetic devices such as computers, force plates, power lines etc. Essentially any device that is plugged into the wall A/C (Alternating Current) outlet emits ambient noise. This noise has a wide range of frequency components, however, the dominant frequency component is 50Hz or 60Hz, corresponding to the frequency of the A/C power supply (i.e. wall outlet).

Transducer Noise

Transducer noise is generated at the electrode – skin junction. Electrodes serve to convert the ionic currents generated in muscles into an electronic current that can be manipulated with electronic circuits and stored in either analog or digital form as a voltage potential. There are two types of noise sources that result from this transduction from an ionic to an electronic form:

- D/C (Direct Current) Voltage Potential: caused by differences in the impedance between the skin and the electrode sensor, and from oxidative and reductive chemical reactions taking place in the contact region between the electrode and the conductive gel (Gerdle et al., 1999)
- A/C (Alternating Current) Voltage Potential: generated by factors such as fluctuations in impedance between the conductive transducer and the skin. One effective method to decrease impedance effects is to use Ag-AgCl electrodes. This electrode consists of a silver metal surface plated with a thin layer of silver chloride material. (Duchene & Goubel, 1993)

The goal with EMG measurements is to maximize the signal to noise ratio. Technological developments have decreased the level of noise in the EMG signal. The most important development was the introduction of the bipolar recording technique. Bipolar electrode arrangements are used with a differential amplifier, which functions to suppress signals common to both electrodes. Essentially, differential amplification subtracts the potential at one electrode from that at the other electrode and then amplifies the difference.

Correlated signals common to both sites, such as from power sources and electromagnetic devices, but also EMG signals from more distant muscles are suppressed. Moreover, the D/C components such as the over-potential generated at the electrode skin junction will be detected with similar amplitude (see below) and will therefore be suppressed.

In contrast, signals from muscle tissue close to the electrodes will not be correlated and will be amplified (Gerdle et al., 1999). The advent of bipolar recordings with differential pre-amplification has enabled the recording of the full EMG bandwidth while increasing the spatial resolution (i.e. the size of the recording area). This also has the effect of increasing the signal to noise ratio.

One remaining factor is how the quality of the electrode – skin contact impacts the process of differential amplification in bipolar EMG measurements. The electrode – skin contact is quantitatively defined by the resistance of the skin and underlying tissues, in addition to the capacitance of the electrodes. It is commonly called electrode – skin impedance. The electrode – skin impedance can be measured quantitatively, such as with the BISIM impedance measurement device offered by Bortec.

The Importance of Skin – Electrode Impedance

Consistency in impedance is critical for the reliability of EMG measurements. Modern pre-amplifier design (i.e. high input impedance) has reduced the importance of measuring EMG with a low level of electrode – skin impedance. While the absolute level of muscle impedance is not a critical factor, the stability in impedance over time and the balance in impedance between electrode sites have a considerable effect on the signal to noise ratio of the measured EMG signal (Freriks and Hermens, 2000), both in terms of noise levels and spatial resolution.

The balance in impedance between electrode sites is important to minimize noise components. The impedance at each site does not have to be perfectly balanced, however, they should be relatively similar. The level of impedance balance is rather arbitrary, depending on the properties of the differential pre-amplifier in use, among other factors. The impedance determines the energy levels of the electrical signal measured at each electrode site (i.e. the view of the muscle and environment that the electrode measures).

As the impedance becomes increasingly different between electrode sites, so too does the signal strength entering the process of differential amplification. Differential amplification only cancels common signal components. For example, if the energy of power-line noise is different, some of the noise will remain in the signal following the process of differential amplification (Gerdle et al., 1999). Similarly, the D/C voltage potential will be different and part of it will not be cancelled. If the pre-amplifier does not have sufficient D/C noise suppression in the residual D/C component, once amplified, can lead to pre-amplifier instability, inaccuracy and saturation.

The general rule is the more balanced the electrode – skin impedance between electrode sites, the lower the noise and as a result the higher the signal to noise ratio. Given the

complexity of the EMG signal, it is difficult to predict or measure to what extent imbalanced impedance alters the properties of the EMG signal. Suffice it to say that by achieving a similar balance in impedance is the best way to increase the reliability of EMG measurements.

It is also important that the impedance remains consistent over the duration of the measurement session. For the reasons similar to those above, the signal to noise ratio will wander if the impedance drifts during measurement, as will the spatial resolution of the recorded EMG signal. Recent evidence demonstrates that the relative level of electrode – skin impedance has a significant effect on the energy of the measured EMG signal. That is, low impedance (<10 kOhm) resulted in a high level of energy for EMG frequency components under 100 Hz as compared to high electrode – skin impedance (>100 kOhm).

In contrast, for EMG signal frequency components between 100 and 150 Hz, low electrode – skin impedance resulted in a lower signal energy level than the measurements with high impedance (Hewson et al., 2002). Other findings support these results (Duff et al., 2002), indicating the spatial resolution (i.e. the electrical view into the muscle) is altered with changes in electrode – skin impedance. Therefore, it is very important that the impedance remains consistent throughout the measurement session. For more information, see Gerdle et al., 1999.

Skin Preparation

The electrode – skin interface generates a D/C voltage potential, mainly caused by a large increase in impedance from the outermost layer of skin, including dead skin material and oil secretions. This D/C potential, common to all electrodes, can be minimized with proper skin preparation. In fact, the quality of contact is typically reduced by at least a factor of 10 with proper preparation (Merletti and Migliorini, 1998). The SENIAM initiative recommends that the skin be adequately prepared (www.rrd.nl/projects/content/fil_100.htm).

Cross Talk

It is important to recognize that the bipolar sEMG is not always a selective representation of the electrical activity of a single muscle directly underlying the recording electrodes. With smaller muscles the electrodes may overlook the electrical activity of one or more neighboring muscles and their signals may crosstalk with the sEMG from the desired muscle. While signal sources close to the electrode will dominate the recorded sEMG signal, more distant sources from other muscles may experience crosstalk (Gerdle et al., 1999).

The distance for effective electrode measurement is the radius about the electrode where the amplitude of signal contributions is larger than the standard deviation of the signal noise (Gerdle et al., 1999). The amplitude of the bipolar sEMG signal decays

exponentially with increased distance from the recording electrode (Day, 1997). This is due to the fact that muscle fibres, subcutaneous fat and skin are anisotropic and act as a spatial filter with low pass frequency properties, where an increase in the distance between the muscle fibre and electrode increases the filtering effect. Effectively this means that less and less signal will be measurable from progressively more distant electrical sources; and similarly, that the frequency of sEMG contributions become progressively lower (i.e. shift in frequency spectrum to lower frequencies) (Lindstrom & Magnusson, 1977).

Crosstalk can be avoided by choosing the appropriate size of the electrodes conductive area and the appropriate inter-electrode distance. Decreasing the size of the conductive area reduces the effective sEMG measurement distance (i.e. depth). Similarly, decreasing the inter-electrode distance decreases the effective recording distance and shifts the EMG bandwidth to higher frequencies (Lindstrom & Magnusson, 1977). The SENIAM initiative has information on recommended electrode placement procedures for different muscles and muscle areas (www.rrd.nl/projects/content/fil_100.htm).

sEMG Normalization

The voltage potential of the sEMG signal detected by the electrodes strongly depends on several factors, varying between individuals and also over time within an individual. Thus, the amplitude of the sEMG itself is not useful in group comparisons, or to follow events over a long period of time (Mathiassen, 1997). The fact that the recorded EMG amplitude is never absolute is mainly due to the fact that the impedance varies between the active muscle fibres and electrodes and is unknown (Gerdle et al., 1999).

Therefore, when comparing amplitude variables between measurements, normalization of some kind is required, i.e. the sEMG converted to a scale that is common to all measurement occasions. Normalizing the signal amplitude with respect to force or torque is a commonly used technique. Typically, the EMG is related to a maximal contraction, or a submaximal contraction at a known level of force. For other examples and types of signal normalization please see the papers by Mathiassen et al. (1995, 1997) and Merletti et al. (1995).

Types of Electrodes

Two types of surface electrodes are commonly in use:

- Dry electrodes in direct contact with the skin
- Gelled electrodes using an electrolytic gel as a chemical interface between the skin and the metallic part of the electrode

Dry Electrodes

“Dry electrodes are mainly used in applications where geometry or size of electrodes does not allow gel” (Gerdle et al., 1999). Bar electrodes and array electrodes are examples of dry electrodes. With dry electrodes it is common to have the pre-amplifier circuitry at the electrode site, due in part to the high electrode – skin impedance associated with dry electrodes. As such, dry electrodes (typically >20g) are considerably heavier than gelled electrodes (<1g). This increased inertial mass increases the difficulty in maintaining electrode fixation, as compared to gelled electrodes.

Gelled Electrodes

Gelled electrodes use an electrolytic gel as a chemical interface between the skin and the metallic part of the electrode. Oxidative and reductive chemical reactions take place in the contact region of the metal surface and the gel. Silver - silver-chloride (Ag- AgCl) is the most common composite for the metallic part of gelled electrodes. The AgCl layer allows current from the muscle to pass more freely across the junction between the electrolyte and the electrode. This introduces less electrical noise into the measurement, as compared with equivalent metallic electrodes (e.g. Ag). Due to this fact, Ag-AgCl electrodes are used in over 80% of surface EMG applications (Duchene & Goubel, 1993).

Gelled electrodes can either be disposable or reusable. Disposable electrodes are the most common since they are very light. Disposable electrodes come in a wide assortment of shapes and sizes, and the materials comprising the patch and the form of the conductive gel varies between manufacturers. With proper application, disposable electrodes minimize the risk of electrode displacement even during rapid movements.

SENIAM Recommendations for Bipolar sEMG Electrodes

The SENIAM initiative (www.rrd.nl/projects/content/fil_100.htm , Freriks and Hermens, 2000) has recommendations for construction of bipolar sEMG electrodes (sensors) including:

- Electrode shape
- Electrode size
- Inter-electrode distance
- Electrode material
- Electrode construction

Electrode Shape

- The “electrode shape is defined as the shape of the conductive area”. Electrodes come in several shapes from circular to square to bar shaped electrodes. The practical implication is that the surface area for each electrode site (i.e. bipolar) should be the same, so the input impedance at each site is similar and common

mode disturbance is limited. “SENIAM has found no clear and objective criteria for a recommendation for electrode shape”.

Electrode Size

- The “electrode size is defined as the size of the surface of a conductive area of a sEMG electrode”. SENIAM recommends that the “size of electrodes in the direction of the muscle fibres is maximum 10mm”.
- “Upon an increase of the size perpendicular to the muscle fibres (bar electrodes perpendicular to the muscle fibres), it is expected that the view of the electrodes increases. No quantitative data on the extent of this effect on the sEMG characteristics is available at the moment.”
- “Upon an increase of the size in the direction of the muscle fibres, it can be shown that this has an integrative effect on the sEMG signal, increasing the detected amplitude and decreasing the high frequency contents.”
- “The European inventory showed that circular electrodes with a circular diameter of 10mm are most preferred.”
- “For bipolar sensors, in general, the size of the electrodes should be large enough to record a reasonable pool of motor units, but small enough to avoid crosstalk from other muscles.”

Inter-Electrode Distance

- “Inter-electrode distance is defined as the center to center distance between the conductive areas of electrodes.”
- “The influence of the inter-electrode distance on the pick up area and crosstalk is a relevant item in the literature.”
- SENIAM recommends applying “the bipolar sEMG electrodes around the recommended sensor location with an inter-electrode distance of 20mm”.
- “When bipolar electrodes are being applied on relatively small muscles the inter-electrode distance should not exceed $\frac{1}{4}$ of the muscle fibre length. In this way unstable recordings, due to tendon and motor end-plate effects can be avoided.”

Electrode Material

- “SENIAM recommends to use pre-gelled Ag/AgCl electrodes.”
- “The electrode material which forms the contact layer with the skin needs to realize a good electrode skin contact, a low electrode-skin impedance, and a ‘stable’ behavior in time (that is, with respect to impedance and chemical reactions at the skin interface).”
- “An inventory has shown that different types of materials are used: Ag/AgCl (silver/silver-chloride), AgCl (silver-chloride), Ag, Au etc.”
- “Electrodes are mostly combined with electrode gel.”
- “Electrode gel and paste are used to reduce the electrode-skin impedance.”

- Disposable and reusable electrodes give similar performance; reusable electrodes have an increased risk of improper and inconsistent measurement characteristics through change impedance.

Electrode Construction

- Defined as “the (mechanical) construction which is used to integrate the electrodes, the cables and (if applicable) the pre-amplifier”.
- “SENIAM recommends a construction with a fixed inter electrode distance, built from light weight material.”
- “Cables need to be fixed using tape or an elastic band in such a manner that pulling artifacts can be avoided.”
- “If in fast dynamic contractions the sensor construction causes too much (movement) artifact due to the inertia of the construction, SENIAM recommends to fix the inter electrode distance using (double sided) tape or rings.”
- It is expected that the construction (and its mass) do not directly affect the sEMG characteristics. These are nevertheless some potential indirect effects which can disturb or interfere with the recorded sEMG pattern.
- “If the construction of the sensor is such that inter-electrode distance can vary during muscle contraction, this will modulate the amplitude, shape and width of the action potentials, and will consequently affect the interference pattern both with respect to its amplitude and frequency characteristics.”
- “If the construction of the sensor is such that electrodes and cables can move, there is the potential risk for movement artifacts (due to pulling of cables or inertia of the construction).”

Electrode Placement

The EMG signal provides a view of the electrical activity in a muscle(s) during contraction. The electrical view is highly dependent on where the electrode is overlying the muscle of interest. Since electrode placement determines the electrical view of a muscle, then it is important in EMG measurements to be consistent in the placement of the electrodes for a subject over consecutive recording sessions and between different subjects. When determining electrode placement, the use of the guidelines set forth in the international SENIAM initiative is highly recommended. One of the deliverables of this recent consensus initiative was the electrode placement procedures for 27 different muscle areas. Please see the SENIAM web-site (www.rrd.nl/projects/content/fil_100.htm) for further details or contact Bortec Biomedical Ltd.

The sensor location is defined as the position of the two bipolar sites overlying a muscle in relation to a line between two anatomical landmarks. The goal of sensor placement is to achieve a location where a good and stable surface EMG signal can be obtained. There are two general strategies for placement of electrodes. From the skin surface the electrode can be arranged longitudinally with respect to the long axis of the muscle and transversely, perpendicular to the long axis.

- Longitudinal: the recommendation is to place the bipolar electrode arrangement halfway from the distal motor end-plate (approximation – muscle mid-line) zone and distal tendon. The goal is to avoid the sensor overlying the innervation zone or tendon during the whole range of motion.
- Transverse: the recommendation is to place the bipolar electrode on the muscle so that each sensor is away from the boundary of the muscle recording area of interest. This can consist of the compartments of a large muscle and neighboring muscles underlying the area of the electrode. Typically, this means that the line between the centers of the electrode sensors is roughly parallel to the long axis of the muscle.

Signal Conditioning and Amplification

Advent of modern electronics and the process of differential amplification have enabled the measurement of EMG signals of low noise and high signal fidelity (i.e. high signal to noise ratio). With differential amplification, it is now possible to measure the full effective bandwidth of the EMG signal. Typical bandpass frequency ranges are from between 10 and 20Hz (high pass filtering) to between 500 and 1000Hz (low-pass filtering). High-pass filtering is necessary because movement artifacts are comprised of low frequency components (typically <10Hz). Low pass filtering is desirable to remove high-frequency components to avoid signal aliasing (see Gerdle et al., 1999). In the past, it was common to remove power-line (A/C) noise components (i.e. either 50 or 60Hz) by using a sharp notch filter. See Figure 1 below. There are problems with notch filtering because EMG has large signal contributions at these and neighboring frequencies. The result of notch filtering is the loss of important EMG signal information, so notch filtering should be avoided as a general rule.

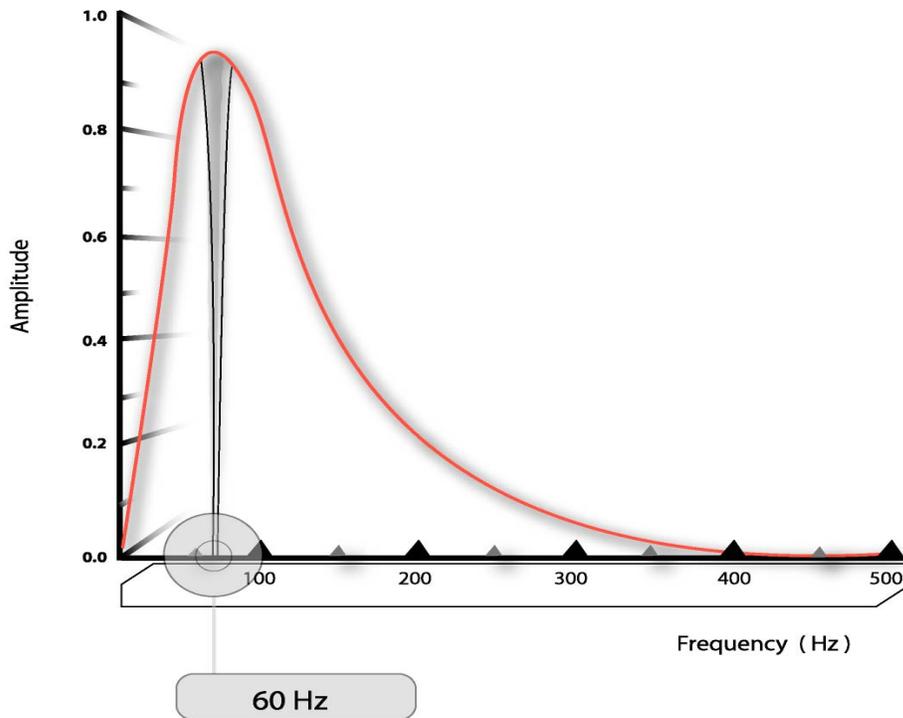


Figure 1: schematic representation of a typical sEMG power spectrum. The shaded area indicates the signal lost when notch filtering is used, in this case to eliminate 60Hz power source noise.

Amplification is also necessary to optimize the resolution of the recording or digitizing equipment (for more information see Gerdle et al., 1999). Amplifiers of high quality have adjustable gains of between, at least, 100 and 10 000 to maximize the signal to noise ratio of the EMG signal during each recording. This range of gains provides the sufficient range of amplifications for surface EMG signals which can range typically from 0 to 6mV peak to peak (Basmajian & DeLuca, 1985). The AMT-8 EMG System from Bortec Biomedical Ltd. has a gain range of between 100 and 15 000.

The quality of the EMG signal, in part, depends on the characteristics of the amplification process. While there may be several stages of amplification, the most important stage is often described as pre-amplification. Pre-amplification implies the first stage of amplification, close to the signal source. There are several important parameters in pre-amplifier signal conditioning of the EMG signal.

Properties of an ideal pre-amplifier

There are several important properties to consider in a pre-amplifier:

- High common mode rejection ratio
- Very high input impedance
- Short distance to the signal source
- Strong DC signal suppression

Common Mode Rejection Ratio (CMRR)

Bipolar electrode arrangements are used with a differential amplifier, which functions to suppress signals common to both electrodes. Essentially, differential amplification subtracts the potential at one electrode from that at the other electrode and then amplifies the difference. Correlated signals common to both sites, such as from power sources and electromagnetic devices, but also EMG signals from more distant muscles are suppressed.

The common mode rejection ratio provides an index on the extent to which common signal components are attenuated from the signal. As such it is desirable to have the highest common mode rejection (CMR) possible. At the moment the best CMRR that can be realistically achieved with current technology is about 120 (dB/Octave @ e.g. 60Hz). The CMR is expressed in logarithmic form, thus an increase in CMRR from 90 (dB) to 110 (dB) is an increase of 100 x. See Table 1 for a conversion of the CMR in (dB) to a linear scale. The Bortec Biomedical pre-amplifiers achieve CMRR near 115 (dB @ 60Hz).

Formula: $A(\text{dB}) = 20 \log_{10}(A_0/A_1)$

dB	Linear Scale
3	1.41
5	
10	1.78
20	
50	3.16
70	10
80	316
90	
100	3160
110	
120	10 000
	31 600
	100 000
	316 000
	1 000 000

Table 1: Comparison of logarithmic and linear scaling, which indicates the level of suppression of signal components common to the bipolar leads input into the differential amplifier.

Input Impedance

It is very important that EMG pre-amplifiers have high input impedance. Input (i.e. source) impedance is typically less than 50 kOhms with gel electrodes and proper skin preparation. In order to measure a voltage accurately, the input resistance of the

measurement device should be considerably larger than the impedance at the skin¹. If not, the signal will be attenuated and distorted due to the effects of process called input loading.

For gel electrode recordings an input impedance in the tens of MOhms range is sufficient. For example, the pre-amplifiers from Bortec Biomedical Ltd. use active components with input impedance reaching 10GOhm. In contrast, for dry electrode recordings with a much higher skin-electrode impedance, into the thousands of KOhms (i.e. few MOhms), input impedances in the GOhm range (i.e. 10^{10} Ohms) are required to achieve an adequate signal to noise ratio.

Distance from Signal Source

One drawback with high input impedance is that power line noise, RF (radio frequency) noise and movement artifacts are introduced in the lead wires by means of capacitive coupling: the higher the input impedance of the pre-amplifier, the greater the impact of noise and movement artifact from lead wires. That is, with increased length of the leads the parasitic capacitance increases, thus the resulting coupled noise is increased. In other words, the long lead length combined with high impedance of the pre-amplifier results in reduced signal to noise ratio.

For gel electrode recordings with low electrode – skin impedance levels, these effects are minimal, provided a short lead length from the electrode to the pre-amplifier is used. Bortec Biomedical pre-amplifiers are specifically designed for a short lead length, to minimize the mass of the electrode assembly to the patch and the pre-amplifier clip attachment.

For dry electrode recordings, the pre-amplifier is typically housed with the electrode sensors minimizing the lead distance. This increases the mass of the electrode assembly attached to the subject, increasing the risk of inadequate fixation. Inadequate fixation can cause common mode disturbance in amplifiers and movement artifacts, which will effectively reduce the signal to noise ratio of the recorded EMG.

D/C Signal Suppression

It is important that pre-amplifier circuits have strong D/C component suppression circuitry. There are D/C components caused by factors involving skin impedance and the chemical reactions between the skin and the electrode and gel. Any difference in the D/C potential measured at the each of the electrode sensors will be amplified, which can lead to pre-amplifier instability or saturation. Such instabilities are often referred to as common mode disturbances.

The practical test of the D/C suppression capacity of a pre-amplifier is to bombard the pre-amplifier with D/C potential fields, by using measuring EMG in conjunction with

¹ The typical rule of thumb in electronics is for the input impedance of the pre-amplifiers to be at least 10 times the electrode – skin impedance: at least 100 times is required for high precision measurements.

D/C based electromagnetic motion capture equipment or when stimulating nerve or muscle with a magnetic stimulator.

The AMT-8 EMG System from Bortec Biomedical Ltd. is often used in the presence of equipment emitting high levels of D/C electromagnetic radiation. The decrease in the signal to noise ratio is surprisingly small indicating that the D/C suppression circuitry is effective.

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